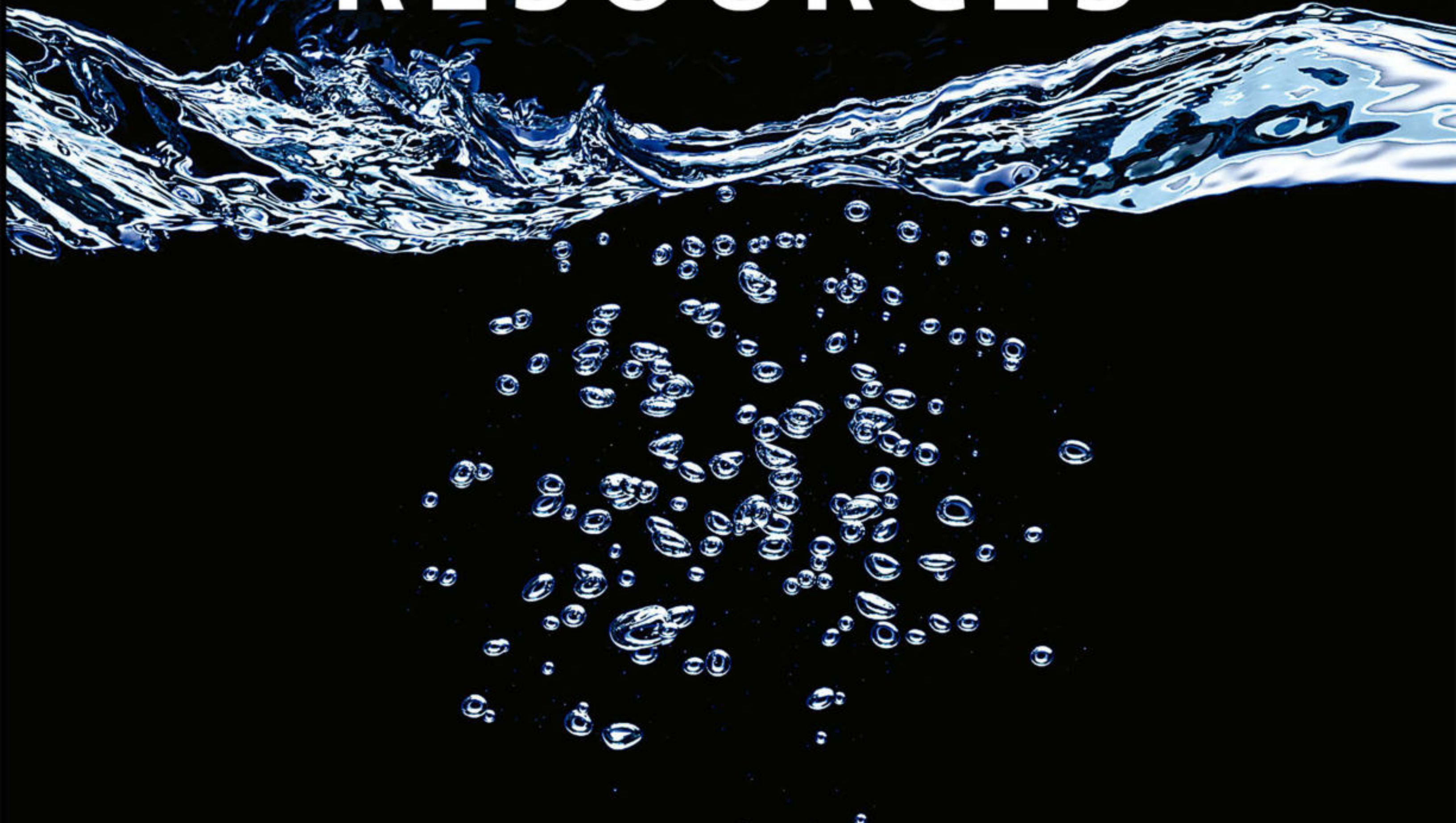
CANADA'S GROUNDWATER RESOURCES



Compiled and Edited by Alfonso Rivera

Chief Hydrogeologist, Geological Survey of Canada

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GROUNDWATER
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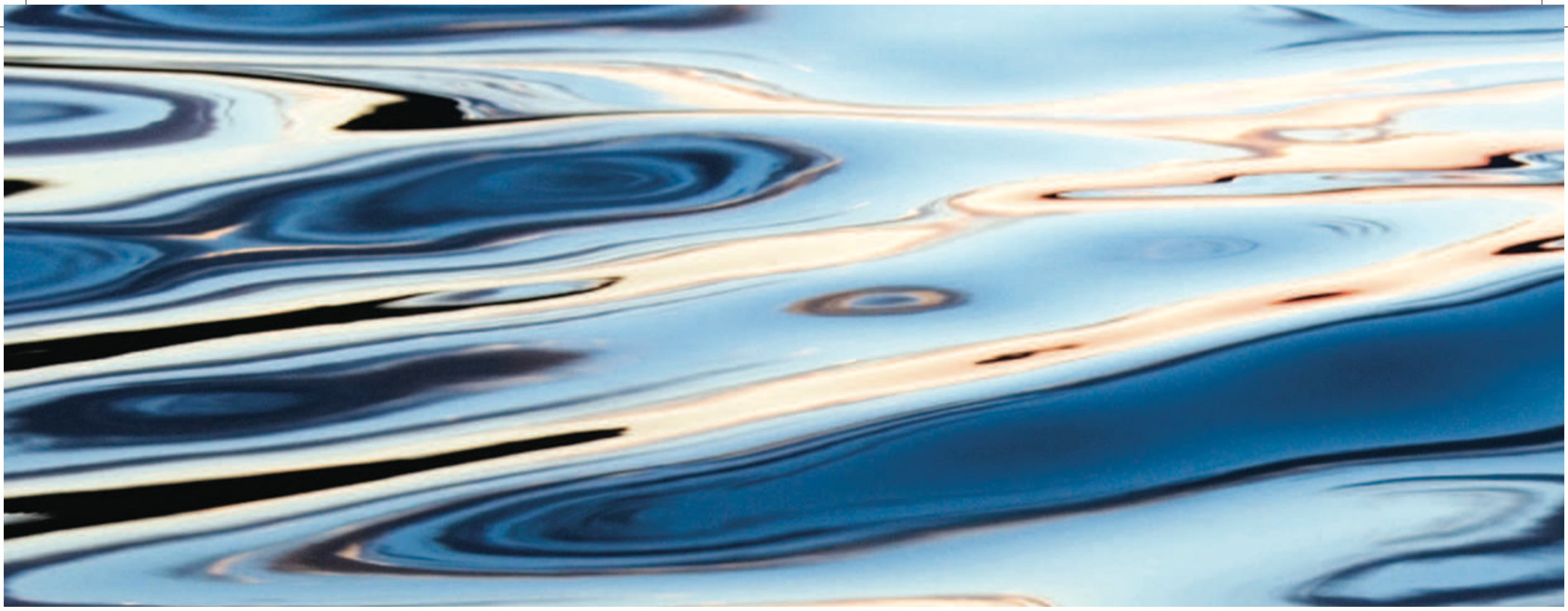
Alfonso Rivera
November, 2013



CHAPTER 3 AN APPROACH TO REGIONAL ASSESSMENTS OF GROUNDWATER

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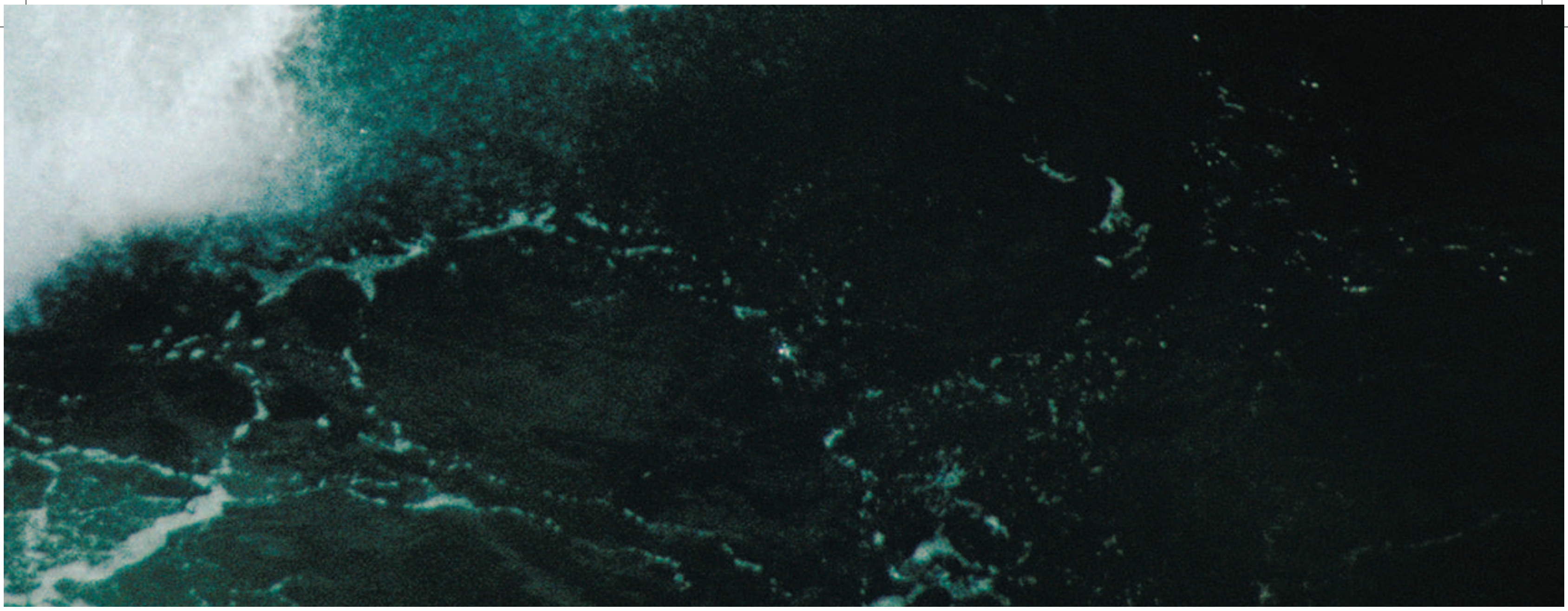

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FOREWORD

By Alfonso Rivera

Water scarcity in Canada is not as immediately serious as it is in many places elsewhere in the world. Nevertheless, failure to manage our water effectively may limit future social and economic development, and exacerbate long-term water scarcity concerns across this country.

Many scientists have predicted energy and water as the critical issues facing future generations. Today, we know that water has emerged as the critical issue—fresh water, at the Earth's surface, and fresh water underground (which scientists label as groundwater).

"Global pictures" are difficult to relate to the wide groundwater variations and problems encountered by Canadians in their everyday lives. Several years ago Burke and Moench (2000) noted that "the key to groundwater management generally lies in the local realities of hydrogeology and the socio-cultural patterns of water use, not in global statistics, agreements or statements."

Groundwater is essential for life in arid and semiarid regions. It is also important in humid regions, and is one of the fundamental requirements for maintenance of natural landscapes and aquatic ecosystems. Many of our most sensitive ecosystems (wetlands, found almost everywhere in Canada) are dependent on groundwater. Yet, groundwater remains a relatively unknown resource, one which is difficult for the public and for decision-makers to recognize and/or understand.

UNESCO's International Hydrological Decade (1965–1974) concluded that:

"The problem of finding water for man's needs is not a new one. What is new is the magnitude and extent of the accelerating demand."

Decades later, this axiom becomes even more relevant. Today, the question that requires an answer is this: do we know enough about the processes associated with freshwater resources in the inhabited and inhabitable parts of Canada to determine if these resources are adequate, in quantity and quality, to meet growing demand? We will explore possible answers to this question in our coast to coast regional analysis of Canada's groundwater availability and potential (Chapters 8 through 16).

Canada is considered a water-rich country (our many rivers and lakes comprise seven percent of the world's annually renewable surface freshwater supply). Our water resources, however, are not evenly distributed and their extent remains highly diverse due to widely varying climatic and geographical factors. Water resources across the country are also stressed by contamination, climate change, the increasing demands of growing population centres, and the sizeable needs of industry and agriculture.

Most fresh water—other than that frozen in glaciers—is found underground. In fact, all of Earth's water found in lakes and rivers (surface water) accounts for only a tiny fraction of the world's available freshwater resources (less than one percent). Ninety-nine percent of the Earth's freshwater supply is groundwater found in aquifers.

These numbers are for the world as a total entity.

Here in Canada, we do not know the ratio between available surface freshwater resources (all rivers and lakes), and groundwater in aquifers, although we believe there is more groundwater than surface water, as with the rest of the world. Should this hypothesis be confirmed, the consequences would be enormous, making groundwater a strategic resource in coping with climate change, droughts, and pollution.

The unknown resource

We do know that groundwater is one of our most important resources, one that supplies clean, abundant and relatively cheap fresh water to more than 10 million Canadians within all sectors. And our use of groundwater is increasing constantly. Why is it then that water studies in Canada, and the subsequent investments in water potential are directed toward surface water resources?

National surface water monitoring networks have been in existence since the early 1900s, involving multiple jurisdictions. To date, this country has no national network to monitor groundwater. Why? Is it because groundwater is out of sight, and the benefits of its use are not well understood?

Most groundwater extractions are done in isolation, without planning, at the regional or basin level. Nationally we have no idea of what our groundwater resources are. And, more importantly, groundwater scientists and professionals have not done a good job of developing, assessing, promoting, or even educating Canadians about what groundwater is, and its importance to the ongoing health of this country.

We need to change this oversight. The time to pay full attention to Canada's groundwater is now; the driving forces for change include increased public awareness, the threat of climate change, droughts, point and/or non-point pollution, decreases in surface water quality, water conflicts, inter-jurisdictional water concerns, and increased attention to international commitments (as in the Great Lakes transboundary aquifers situation).

How much groundwater do we have, and how much is available to Canadians and the ecosystems that depend upon it?

How much groundwater are we using; how much can we use; for how long; what are the time scales? Is our current resource use sustainable? Can we identify meaningful indicators of use or misuse at national, regional, and local scales?

What is the importance of groundwater in the Great Lakes Basin? As surface water levels within the Great Lakes continue to shrink, what new role will groundwater play in that ecosystem?

Groundwater is at the heart of a complex system which includes climate, hydrology, hydrogeology, ecology, hydrogeochemistry, and biology. These interrelated dynamics occur naturally throughout a number of cycles (water cycle and carbon cycle, to name two). Groundwater also influences or is influenced by anthropogenic issues such as land use, waste disposal, and overexploitation of aquifers (or over-pumping). Walkerton, water crisis, climate change, land use, droughts, water-energy, water bulk transfers, urbanization, transboundary aquifers… these were all keywords and issues in the front pages of every newspaper at the time this book was in preparation. And these are ongoing concerns for every Canadian today.

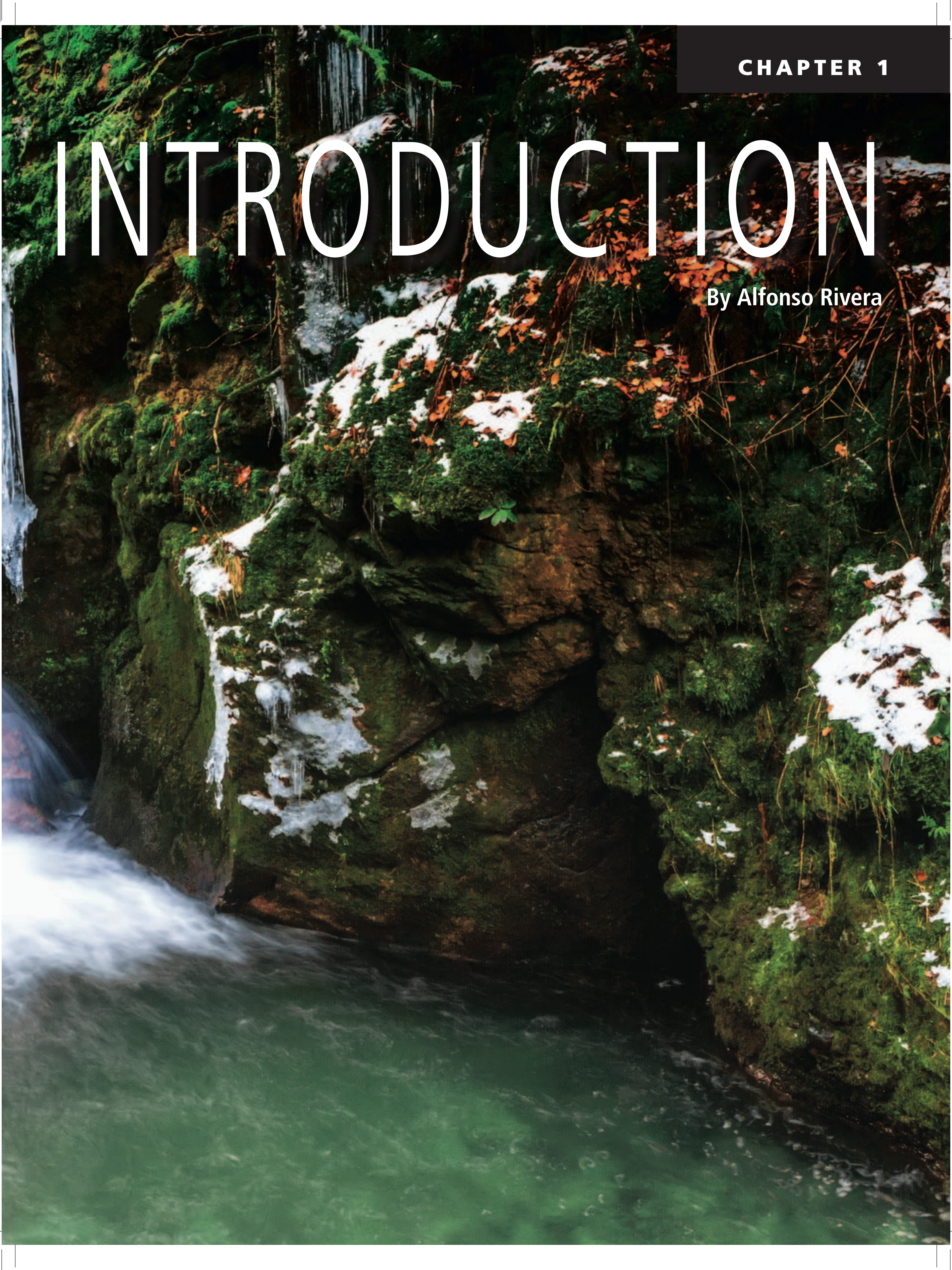
People reading this book will have many different perspectives on groundwater and its impact, be it scientific, management, legislative, or social and environmental, but as authors, we hope we are providing herewith a solid overview of this important resource and its impact both on our current livelihoods, and on possibilities or challenges faced in the future.

PART I:
INTRODUCTION

CHAPTER 1

INTRODUCTION

By Alfonso Rivera



1.1 BACKGROUND AND HISTORICAL PERSPECTIVES

1.1.1 A review of the literature

Canadian scientists have made many fundamental contributions to groundwater sciences, including physically-based distributed hydrological models (Freeze, 1974), the concept of nested flow systems (Tóth, 1963), research on groundwater contamination and remediation (MacKay and Cherry, 1989), groundwater resource evaluation and well hydraulics (pumping test analysis), the Q_{20} concept[1] (Farvolden, 1959), and innovative field and laboratory tracer tests.

These contributions notwithstanding, syntheses of scientific knowledge regarding Canada's groundwater resources are few. *Groundwater in Canada* (Brown, 1967), *Groundwater* (Freeze and Cherry, 1979), and *Hydrogeology* (Back et al., 1988) are the three most prestigious references on this topic.

Groundwater in Canada (1967)

Groundwater in Canada edited by I.C. Brown and published by the Department of Energy, Mines and Resources in 1967 was—and after more than 40 years still is—the latest comprehensive description of groundwater resources in this country. The book represents the last national groundwater state-of-knowledge report. Well written, *Groundwater in Canada* was very successful from a scientific point of view, and contained solid descriptions of Canada's groundwater resources through detailed delineation of this country's hydrogeological regions. Outside the Geological Survey of Canada, however, this book was not widely known, and it did not receive widespread distribution to water resource decision makers. In 1967, the federal government's mandate on groundwater research was centred on data gathering and well recording. These facts were reflected in Brown's book, which covers an extensive set of data with numerous tables and figures, as well as nine chapters with summaries describing six hydrogeological regions of Canada. These chapters on hydrogeological regions are what most resembles our current book. Our authors, however, were able to take advantage of the very strong collaboration between studies performed by provinces and universities, and studies performed by research institutions within the federal government over the past 10 years. Brown's book only included contributions from research within the federal government, and although *Groundwater in Canada* was a landmark publication of its time, it did not help to maintain and/or advance the status of groundwater within the federal or provincial governments because of its lack of public appeal and practical use.

The authors and contributors to *Canada's Groundwater Resources*, our current book, have tried to prepare the scientific material with the interested public, decision makers, and science and professional communities in mind. The vision and purpose of this new book is to provide a science-based overview and a collective understanding of Canada's groundwater resources in order to support sustainable use and protection. To that end, we have worked to depict the state of knowledge on groundwater resources at the regional scale, as well as knowledge gaps, although in many ways, our current synthesis can be considered a modern and expanded version of Brown's 1967 treatise.

Groundwater (1979)

When *Groundwater* by Freeze & Cherry (1979) was published, it became an instant classic in

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[1] The Q_{20} concept is based on a theoretical model for the flow of groundwater to a well completed in a confined aquifer. It assumes that if the well is to last 20 years, the drawdown curve from a pumping test must not have a greater drawdown than there would be available where it intersects the 20 year line on a time scale.

groundwater science. This book has been extensively used as a reference both in academia and in applied hydrogeology for three decades. Freeze and Cherry succeeded in compiling, and nicely summarizing, existing knowledge regarding the physical, chemical, and geological principles, characteristics and processes of aquifers and groundwater resources. Allan Freeze and John Cherry (both Canadians) were pioneers in perceiving the emerging of the full multi- and inter-disciplinary environmental science of groundwater, which integrated geology, hydrology, physics, chemistry, and engineering to a greater degree than had been done in the past. A great deal of the material presented in the book was derived from their own research in Canada while working at the University of British Columbia and the University of Waterloo. The excellent scientific material on groundwater presented by Freeze and Cherry cannot be equated and we made no attempt to do so in our own book, although we have presented brief descriptions of some scientific and/or technical groundwater concerns in our focus on thematic overviews as they apply to and for Canadian conditions. Freeze and Cherry's book remains the strongest source of comprehensive, thorough, and universal descriptions of the scientific and technical groundwater issues.

Hydrogeology (1988)

Hydrogeology edited by Back et al. (1988) and published by the Geological Society of America is one of the synthesis volumes of *The Decade of North American Geology Project* series initiated by the Geological Society of America. This book represents volume O–2 of that series, and describes in detail the hydrogeological conditions of the three North American countries, including four chapters specifically dedicated to aquifers and groundwater in Canada. *Hydrogeology* was prepared with strong emphasis on the geological aspects of hydrogeology, i.e., aquifers and groundwater, and represents a synthesis of the hydrogeologic understanding of the 1980s merged with principles and processes from other geology sub-disciplines. The book could be considered an expanded version of the classical USGS Water Supply Paper by Meinzer (published in 1923 as the first of a planned series of six papers on groundwater in the United States). Unlike that series, however, *Hydrogeology* is a compendium of a diversity of topics written by several authors from the three North American countries. *Hydrogeology* does not describe groundwater as a resource, nor does it discuss anthropogenic effects, whereas our volume does.

1.1.2 Historical progression on groundwater research

During the 1960s and 1970s, Canadian scientists used drainage basins (generally at shallow depths) as frameworks to study groundwater flow systems (Brown, 1967). As their knowledge increased, however, it became possible to define groundwater flow systems at greater depths. Studies were directed toward flow systems not defined by detailed surface topography but by general surface elevations, by geological knowledge, and by the hydrological properties of the rock through which the water flowed.

Also during the 1960s, distinguished Canadian scientists (Tóth, 1962; Freeze and Witherspoon, 1967), following previous works on *gravity-driven* groundwater flow, developed breakthrough theories of what became known as "hierarchically-nested flow systems." Scientists as early as the end of the 19th century had perceived the relationship between topography and groundwater flow patterns in unconfined aquifers. King (1899) and Hubbert (1940) noticed that a water table tends to be a subdued replica of its topography, and Hubbert (1940) suggested that topography could control groundwater flow patterns as high elevations become recharge areas and low elevations become discharge areas. Later, during the 1960s, Tóth (1963), and Freeze and Witherspoon (1967) developed mathematical models simulating the effects of topography on groundwater flow systems. Both models supported King and Hubbert's conclusions. These models also indicated that hilly topography could result in the formation of smaller local flow systems, with local recharge and discharge areas, within larger regional systems.

Those concepts shifted the paradigm of aquifer-bound groundwater flow to cross-formational water movement through hydraulically continuous drainage basins, and they were instrumental in redefining the scope of a single-issue water supply problem into the many-faceted Earth science discipline of modern hydrogeology (Tóth, 2009).

During 1980s, the focus of hydrogeology shifted from flow analysis to transport analysis, and from regional-scale to local, site-specific scale. By the end of the 1980s, several new scientific issues had arisen in response to the discovery of widespread groundwater supply contamination. Remediation efforts required improved transport analysis, and the need for new measurements of physical and chemical phenomena such as dispersion, diffusion, and adsorption.

Many detailed studies of test sites were performed in Canada during these years: the measurement dimensions were in metres rather than kilometres. Studies of water supply were put on hold as the scientific emphasis shifted to studies on water quality driven by the need to predict movement of contaminants through the subsurface environment and by the importance of protecting groundwater aquifers. These studies were spurred by the introduction of contaminated sites legislation both in the US and in Canada, and by funding made available (e.g., by the US EPA) to drive this research work.

Numerical models became the essential tools for the assessment of regional-scale aquifers toward the end of the 1980s and during the 1990s. That time also saw an explosion in the development of conceptual and numerical models, in part due to extensive research investment in the field of radioactive waste disposal in Europe and North America. Two important themes were studied intensely: scale effects and uncertainty in model predictions. This work has been particularly beneficial to scientists working today to assess groundwater resources within regional-scale bedrock aquifers.

Fractured-rock hydrogeology might be said to have largely emerged from the radioactive waste industry. We have learned that scales of measurements and precision depend on the application. Accurate measurements of low-permeability media (done from millimetres to metres) are critical in the area of nuclear waste disposal, whereas characterization measurements of contaminated sites located in fractured rock environments are done from metres to hectometres, while those for water resources (supply) from regional fractured-bedrock aquifers range from deca-kilometres to hecto-kilometres. The smaller scale focus depends on the issue under consideration (e.g., well scale in relation to well performance and hundreds of metres to kilometers for well protection areas).

Hydrogeology is a relatively young science, but it is maturing rapidly as scientists understand

more about the physics and chemistry of groundwater flow.

The last attempt at a national assessment of Canada's groundwater resources was made over 45 years ago (Brown, 1967). Recent federal and provincial initiatives indicate a new momentum toward a comprehensive assessment and inventory of regional aquifers. The *Canadian Framework for Collaboration on Groundwater* (Rivera et al., 2003), produced by a national ad hoc committee, has become a catalyst to fill in our knowledge concerning Canada's groundwater resources. We need to map aquifers, to come to a better understanding of the amount of groundwater stored and used, and to improve our knowledge about renewal rates. We absolutely must improve our understanding of groundwater's role as it interacts with other components of the water cycle, including the many groundwater-dependent wetlands and other ecosystems across this country.

Groundwater is a science based on local conditions and there have not been sufficient studies of groundwater in specific Canadian localities.

Some of our current and future challenges include developing better-combined surface water–groundwater models, identifying regional key indicators of groundwater conditions, understanding aquifer storage evolution, evaluating groundwater flow and storage, assessing rates of withdrawals (pumping) at all levels (domestic, agriculture, and industry) on a more precise basis, translating scientific results into fact sheets for the general public, and increasing public understanding of groundwater.

Historically, Canadian scientists' research efforts have been dedicated to the cleanup and remediation of contaminated aquifers, coupled with experimental-scale studies. The need to create new programs focusing more on groundwater as a resource and on regional-scale aquifer assessments is clear, as is the need to prepare a new generation of groundwater scientists with this new focus. Our era's mindset combines science with other social, economic, and environmental factors, and the new generation of geoscientists should be linked more closely to looming issues. Good science is great, but great science should be translated into fact sheets, waterscape posters, reports for the public, and websites for outreach and factual scientific information.

Our emphasis should be on groundwater sustainability, vulnerability, and management along with societal, political, and environmental relationships. These are the very issues, perspectives, and focus that helped create this book.

The growth in Canadian groundwater use over the last 30 years (from 10% dependency in 1970, to 30% today; see Figure 16.2), coupled with current trends, strongly suggests that groundwater will become an increasingly more important water supply component in the future. We must identify the critical technical factors and underlying scientific, social, and environmental issues to be taken into consideration in order to quantify the amount of groundwater available for use in a sustainable manner.

1.2 GROUNDWATER RESOURCES IN THE WORLD AND CANADA

The world's water resources include all the fresh and brackish water in the atmosphere, streams, lakes, estuaries, the unsaturated zone, and groundwater. How much is in each of these compartments of the water cycle? And what is the average residence time in each compartment?

Estimates of the total volume of water on Earth are uncertain. The most "accurate" suggestions are attributed to Russian scientists (see for example Shiklomanov, 1999) who, for many decades, have made every effort to establish and refine the Earth's water budget. Table 1.1 shows estimates of the Earth's total water volume, including residence time. Average "residence time" indicated is an order of magnitude of the time during which a water molecule remains within a given compartment, before entering a different compartment or before it begins a new stage in the "water cycle" (see also Chapters 2, 4 and 5).

TABLE 1.1 ESTIMATES OF TOTAL WATER VOLUME ON EARTH (FROM THE WORLD RESOURCES INSTITUTE, 1990)

	VOLUME (KM^3)	% OF TOTAL	RESIDENCE TIME
Oceans	1,350,000,000	97.41	2,500 years
Glaciers	27,500,000	1.984	1,600 to 9,700 years
Groundwater	8,200,000	0.592	1,400 years
Inland Seas	105,000	0.00758	Unknown
Freshwater Lakes	100,000	0.00722	17 years
Humidity in soils	70,000	0.00505	1 year
Humidity on air	13,000	0.00094	8 days
Rivers	1,700	0.00012	16 days
Water in living cells	1,100	0.00008	A few hours

1.2.1 Groundwater in the hydrologic cycle

Groundwater is a vital and essential part of the hydrologic cycle; groundwater is water that infiltrates into the ground, filling the voids, pores, cracks, and fractures of soils and rocks.

Much of the precipitation that falls on the ground's surface is redirected back into the atmosphere as direct evaporation, or as transpiration from vegetation. The sum of both fluxes is called evapotranspiration and represents by far the most important flux of the cycle, some 63% of annual precipitation on average.

Another precipitation component infiltrates into the soils and rocks at ground surface. Some of this shallow infiltration is captured by vegetation to become transpiration. Deeper infiltration of water into the ground represents the recharge to the groundwater contained in those rocks which form aquifers. This deeper infiltration comprises, on average, 13% of precipitation.

Surface runoff is another important flux of the hydrologic cycle, representing, on average, 24% of precipitation. This overland flow eventually forms rivers, but how it does so varies considerably according to soil type and the rain intensity. A large part of groundwater also ends up in the rivers, forming what is known as their "baseflow," the natural flow in the absence of rain (explaining the flux difference between oceans and land in Figure 2.1, Chapter 2).

The sum of evapotranspiration, ~ 496,000 km^3/year from oceans and land, is equal to the sum of precipitation at the global scale (Figure. 2.1). As a general rule, rain on the continents exceeds water loss due to evaporation, whereas on the oceans, evaporation exceeds rainfall. At the global scale, this difference is 40,000 km^3/year. Because the water cycle exists in equilibrium, this means that, every year, the Earth's continents send 40,000 km^3 of water to the oceans (World Resources Institute, 1990). See also Tables 2.1 and 2.2 in Chapter 2.

1.2.2 Water quantities

Estimates of the volume of available surface fresh water on the planet vary, depending on the information source, although the order of magnitude is the same in all cases:

- 135,000 km^3 of fresh surface water ("total not frozen or underground"), including soil and atmospheric moisture, and water contained in biota (Gleick, 2000)
- 104,120 km^3, excluding soil, atmospheric, and biotic water (Gleick, 2000)
- 109,119 km^3, excluding soil, atmospheric, and biotic water (UNESCO WWAP, 2006; Shiklomanov and Rodda, 2003)

These numbers, however, represent only a tiny percentage of the world's total available fresh water (35 Mkm^3). Glaciers, permanent snow cover, ground ice, and permafrost account for 24.3 Mkm^3, but this quantity is not readily accessible. The remaining total fresh water in the world accounts for ca. 10.7 Mkm^3, of which 10.6 Mkm^3 is groundwater and the balance is surface water. Put in percentages, these numbers indicate:

• Glaciers	69.40% (*not readily accessible*)
• Groundwater	30.28%
• Surface water	0.31% *(lakes, rivers, and wetlands)*

Thus, all rivers and all lakes of the world account for less than 1% of total available fresh water. The volume of Earth's oceans has been well known for many years, whereas global estimates for groundwater storage vary by orders of magnitude. Table 1.2 charts estimates made between 1945 and 1997 of the volume of water in the oceans and of groundwater: this data has been compiled from different studies of the world's water balance as reported by Alley et al. (2005). Today, most scientists agree that the global pool of groundwater lies between 11 and 15 Mkm^3.

Such variability can be attributed to different considerations of depth and salinity when defining the global groundwater pool. Additionally,

TABLE 1.2 ESTIMATES OF VOLUMES OF WATER IN THE OCEANS AND GROUNDWATER

	CUBIC KILOMETRES OF WATER ($\times 10^3$)	
Date	**Oceans**	**Groundwater**
1945	1,372,000	250
1967	1,320,000	8,350
1978	1,338,000	10,530–23,400
1979	1,370,000	4,000–60,000
1997	1,350,000	15,300

this difference reflects a lack of knowledge about groundwater as compared to other global water pools. Early estimates of the global groundwater pool greatly underestimated its volume. It was not until the mid-20th century, after development began in earnest, that a universal appreciation of the large groundwater storage volume emerged (Alley, 2006).

Let's compare the groundwater volume in one major aquifer to one of the largest and most well-known surface water reservoirs of the world, the North American Great Lakes. South America's Guarani aquifer, shared by Brazil, Argentina, Paraguay, and Uruguay (Tujchneider et al., 2003; Vives et al., 2000) contains 40,000 km^3, compared to circa 23,000 km^3 contained in all five Great Lakes. This single aquifer contains nearly two times as much fresh water as the largest surface freshwater reservoir in the world!

Groundwater is not an isolated resource, it is linked to surface water bodies and to ecosystems; furthermore, it can affect, or be affected by land use, human activities, pollution, over-exploitation, and climate changes. Groundwater as a resource can be characterized by two main variables: rate of renewal, and storage volume. These two factors are difficult to compare quantitatively, but both must be known before any resource management plan is implemented.

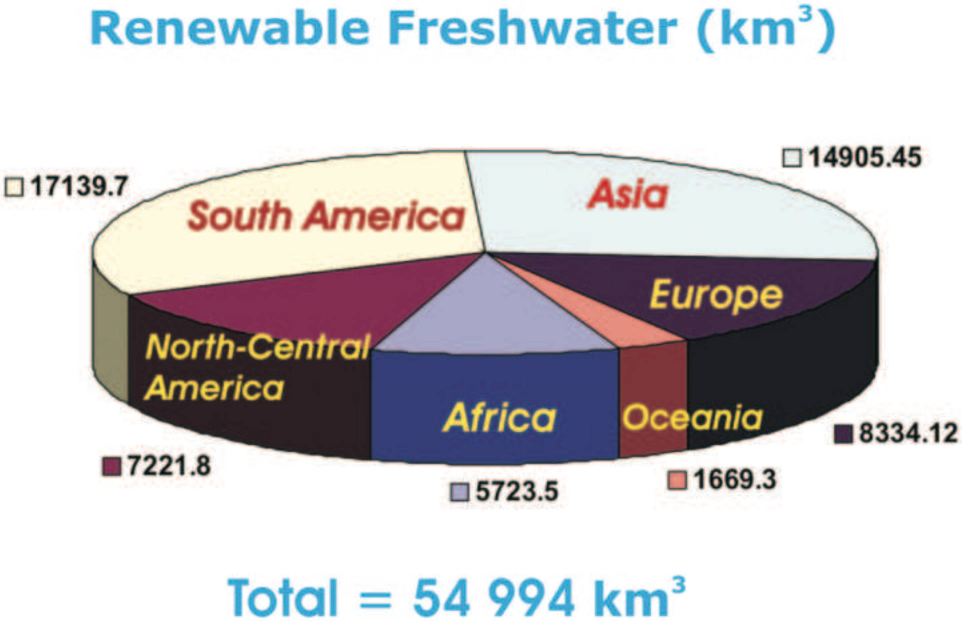

Figure 1.1 Total renewable freshwater supplies by continent, as reported by Gleick (2004).

1.2.3 Water availability

Although the quantities of water within a hydrologic system (see pools and/or fluxes in Chapter 2, Figure. 2.1) can be measured, computed, or estimated in a straightforward manner; water availability cannot. Like water sustainability, water availability is an elusive and multifaceted concept (Alley et al., 1999), and, as a result, the challenges of determining groundwater availability are numerous.

Groundwater availability is a function not only of the quantity and quality of the water within an aquifer system, but also of the physical structures, laws, regulations, and socioeconomic factors that control its demand and use. Physical and chemical characteristics of any given aquifer may be used as indicators of groundwater availability; however, at the local level, where most decisions are made, these characteristics must be considered in conjunction with those societal factors which determine actual groundwater availability, and society's tolerance of the consequences of its use. Societal perspectives and constraints change and evolve with time, just as the groundwater resource does (Alley and Leaky, 2004).

Within the context of this book, we will equate "water availability" with "renewable freshwater resources"; that is, yearly surface water runoff and groundwater recharge, excluding the volume in storage[2]. The world's yearly renewable freshwater resource is estimated to be between 43,000 km^3 and 55,000 km^3, depending on the source (e.g., Gleick, 2004; Shiklomanov, 1999; de Marsily, 1995).

The Pacific Institute for Studies in Development, Environment, and Society, based in Oakland, California (USA), publishes a biennial report on the world's freshwater resources by country. Figure 1.1 presents a graphical representation of the world's renewable fresh water in each continent, from the Institute's 2004 report (Gleick, 2004). The data contained within the graphic includes both renewable fresh surface water and groundwater, which, combined, are designated by the United Nations Food and Agriculture Organization as "total natural renewable water resources," and by the European Union as "total freshwater resources." The renewable fresh surface water and groundwater resources for the three NAFTA countries are featured in Table 1.3. For a deeper analysis on the availability of groundwater resources as a function of recharge, see Chapters 4 and 6.

TABLE 1.3 RENEWABLE FRESH SURFACE WATER AND GROUNDWATER RESOURCES IN THE NAFTA COUNTRIES. THE DATA REPRESENTS AVERAGE VALUES AS COMPILED BY GLEICK (2004) FOR DIFFERENT YEARS; ACTUAL ANNUAL RENEWABLE RESOURCE WILL VARY FROM YEAR TO YEAR

	SURFACE WATER (KM^3/YR)	GROUNDWATER (KM^3/YR)	TOTAL (KM^3/YR)
Canada	2,901	380	3,281
USA	2,662	1,300	3,992
Mexico	361	139	500

1.2.4 Water supply and use

Let us now analyze the world "supply," assuming that by supply we mean "withdrawal", or the actual use of fresh water—a widely accepted definition (UNESCO WWAP, 2006). As a whole, the world extracts between 3,500 km^3 and 5,500 km^3 of total fresh water per year (the sum of surface water and groundwater), depending on the year and on the source of information. Figure 1.2 shows a graphical representation of the world's total fresh water withdrawal for each continent, from the Institute's 2004

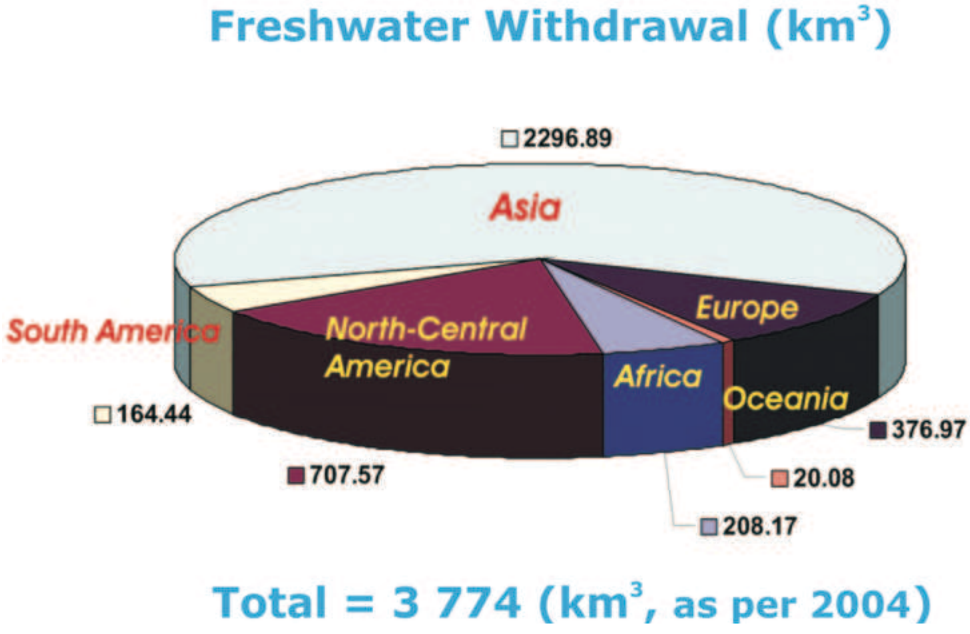

Figure 1.2 Total freshwater withdrawals by continent (Gleick, 2004).

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[2] In other parts of the world (arid and semi-arid regions) this exclusion may not apply.

TABLE 1.4 WATER CONSUMPTION IN THE WORLD DURING THE 20TH CENTURY, BY SECTORS IN KM^3/YR (DE MARSILY, 2000)

SECTOR	1900	1950	1990	2000	% (IN 2000)
Agriculture	525	1,130	2,680	3,250	63
Industry	37	178	973	1,280	25
Domestic	16	58	470	661	12
Totals	578	1,366	4,123	5,191	

report (Gleick, 2004). In that report, "withdrawal" refers to water taken from a water source for use. It does not refer to water "consumed" in that use. The report further classifies withdrawal based on end use—namely, in the domestic, industrial, and agricultural sectors.

The world's total withdrawal has varied substantially over the years and within individual continents. Table 1.4 illustrates total global water used during the 20th century in the three main sectors. We can see that, by the beginning of the 21st century, use of water had increased by factors of 6 to 50 over the preceding hundred-year period. This escalation can be explained by the rapidly growing population and its ever-burgeoning demand for water to sustain community growth.

When these numbers are compared with those of the global water cycle in Table 2.2 of Chapter 2, we find some 40,000 km^3 of "available" freshwater, of which 27,000 km^3 comes from river flow and 10,500 km^3 from groundwater baseflow. If the 27,000 km^3 cannot be contained by the current capacity of the world's dams (Canadian dams have a capacity of 846 km^3), then only 10,500 km^3 of baseflow is left. This means that the total fresh water withdrawn in the world in the year 2000 (5,191 km^3 in Table 1.4) was about half of the baseflow volume. Thus, the "problem" is not lack of water, but the disparity between population needs and water source location. The Earth's freshwater sources are not evenly distributed, so there are very water-rich regions and very water-poor regions.

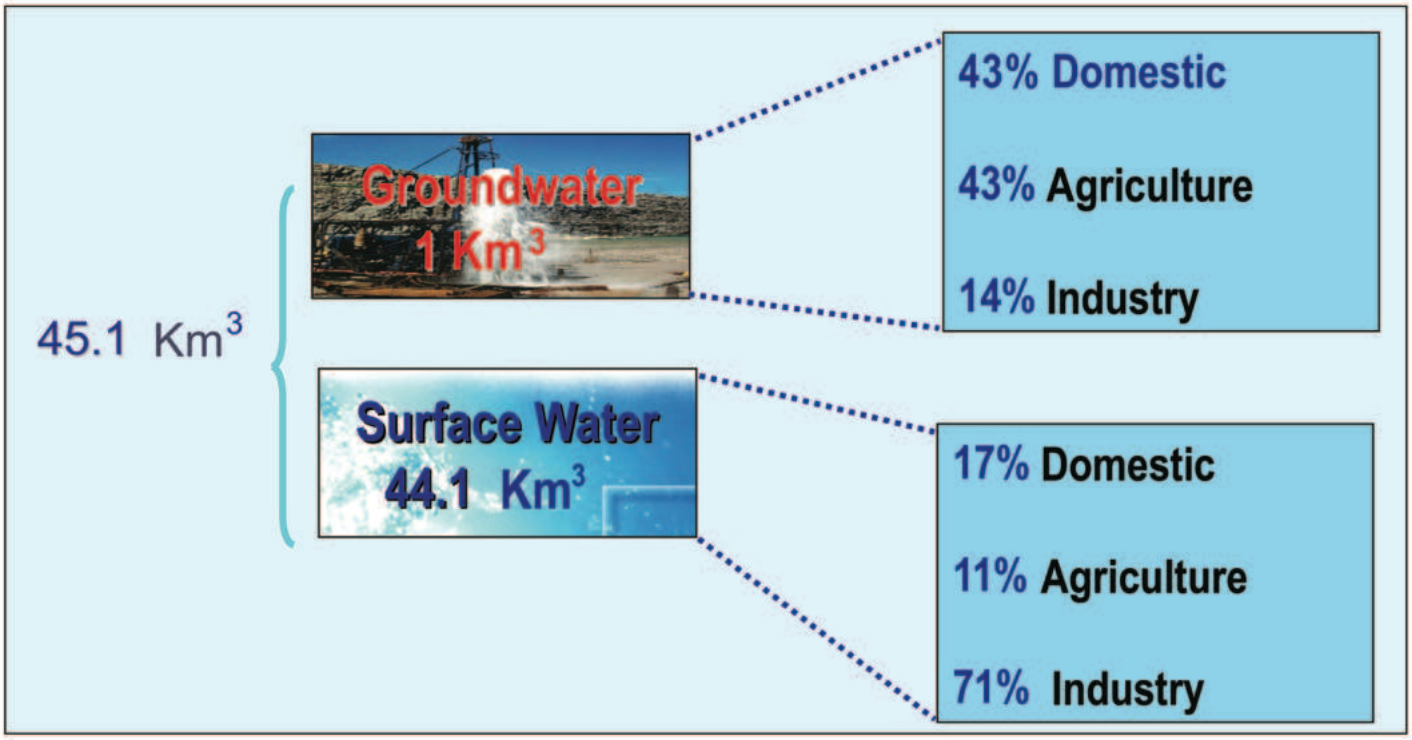


Figure 1.3 Freshwater withdrawals in Canada as per 1996 (Source data from Statistics Canada, 2003)

Location of the world's water demand centres relative to available sources is a key issue. The demand centres (e.g., urban areas) put major pressure on local water resources. This is especially true in Canada, where most of our water resources are located in more northerly locations, well away from most of Canada's population and its economic centres. Some areas of western Canada are already experiencing periodic water shortages.

It is true that, when compared to the rest of the world, Canada's use of fresh water seems negligible. We have charted total freshwater withdrawals in this country in Figure 1.3, broken down by source (surface water and groundwater) and by sector. The aggregate volume withdrawn by all sectors is roughly 45 km^3 per year, which is small compared to the total yearly "renewable" fresh water in Canada (3,281 km^3). Nevertheless, we should be careful when considering these numbers because of geography, population distribution, and other factors.

Most of the runoff from Canadian rivers (60%) drains north and is "lost" into oceans, while most of our population (85%) lives along the southern border with the United States. Furthermore, Canada does not have the installed capacity, with our present infrastructure, to capture runoff. That is one of the reasons why the use of groundwater for domestic purposes has increased so dramatically over the past three decades—from 10% in the late 1960s to 30% in the late 1990s (Figure 16.2).

Total groundwater use in Canada is ~1 km^3 per year (Statistics Canada 2003), mostly withdrawn for domestic and agricultural purposes, as illustrated in Figure 1.3. Nearly 30% of the Canadian population uses groundwater for domestic drinking water. And trends indicate that future groundwater use will continue to increase at a rate faster than that of surface water use. Possible explanations for such an increase are (a) abundant fresh water at shallow depths, (b) generally good water quality in aquifers, and (c) the fact that acquisition facilities for groundwater are fast and cheap to build and maintain.

The single largest disadvantage about groundwater, as compared to surface water, is that we simply do not know enough about it as a resource at the regional scale. We use it and develop it without assessing its dynamics, its recharge and discharge, its interactions with surface water and ecosystems, its volume in storage, vulnerability, and sustainable yields, although at the local level (well-scale), where groundwater is critical for economic development, the resource is studied in more detail and is better understood.

1.3 BOOK STRUCTURE AND OVERVIEW

The purpose of this book is to provide a science-based overview and a collective understanding of Canada's groundwater resources in order to support sustainable use and protection. We are writing for the interested public, decision makers, and science and professional communities. Our scope is to depict the state of knowledge on groundwater resources at the regional scale, as well as to identify knowledge gaps.

The book is organized into five parts: Part I provides a general introduction with background and historical perspectives. Part II is composed of two chapters providing the basics for understanding groundwater and the approaches to regional assessments of groundwater resources. Chapter 2 provides an overview of the basics of groundwater as a resource, and includes definitions and discussions of aquifers, mechanisms of groundwater flow, wells, natural quality of groundwater and interactions with the environment. Chapter 3 presents the basic steps and current practices of mapping and assessing regional-scale aquifers.

Part III consists of thematic overviews and is composed of four chapters: climate and recharge (Chapter 4), surface water/groundwater interactions (Chapter 5), sustainability and vulnerability of groundwater (Chapter 6), and groundwater as a source of energy (Chapter 7). These discussions present brief descriptions of some outstanding scientific and technical issues related to groundwater, focusing on how they apply in and for Canadian conditions. For a more comprehensive and universal description of these topics, the reader is referred to the many excellent textbooks on these topics where physical, mechanical, and chemical properties of groundwater and aquifers are described in more detail (Freeze and Cherry, 1979; Bear, 1972; de Marsily, 1986; Domenico and Schwartz, 1998).

Part IV provides overviews of Canada's main hydrogeological regions and is composed of nine chapters: an introductory chapter (Chapter 8) with vignettes and descriptions of the hydrogeological regions of Canada, the Cordillera region (Chapter 9), the Plains region (Chapter 10), the Precambrian Shield (Chapter 11), the Southern Ontario Lowlands (Chapter 12), the St. Lawrence Lowlands (Chapter 13), the Appalachians (Chapter 14), and the North (Chapter 15). In part V, Chapter 16 describes the current state of groundwater management and governance in Canada.

1.3.1 Objectives of major parts and chapters

Part II, "Understanding Groundwater," introduces the basic tenets of groundwater science by describing groundwater systems and approaches to groundwater assessments. The two chapters in this section present the steps of regional aquifer characterisation and groundwater resource assessments, leading to the integrated understanding of aquifer systems and the necessary science required for the sustainable management of groundwater resources.

Part III, "Thematic Overviews," represents the scientific part of the book. The four chapters in this section summarize modern scientific knowledge of groundwater in order to synthesize the contexts and conditions of groundwater resources as they apply in Canada. Most of the material in this segment has already been presented in other more universal publications; however, surface water/groundwater interactions, climate change and groundwater, sustainability, and energy sources are treated here with particular emphasis on Canadian context and conditions. We hope that the material presented in this part will be useful for universities training new scientists interested in the hydrogeological conditions of Canada, as well as for groundwater resource managers who may find it helpful in planning or making management decisions. We believe that part III will prove its worth to students, consultants, practitioners, managers and government officials alike.

Part IV, the "Overview of Hydrogeological regions," answers specific questions on a region-by-region basis, by synthesizing groundwater knowledge existing in Canada at the time of the preparation of this book. The reader looking for original material, data and information on aquifers and groundwater resources in Canada will find them in this part. It is expected that future editions of this book will concentrate on updating data and information presented in part IV of the book. Furthermore, it is also hoped that other efforts to provide information on the state of groundwater resources in Canada can make direct use of the data, information, tables, figures, maps, and statistics provided in this section.

Our authors, as they prepared this part of the book, were directed to present the data and information in a similar template for each chapter, in order to provide consistency and cross-comparisons between Canada's nine identified hydrogeological regions, although this was not possible for all locations due to the paucity of scientific information.

The principal parts of the template designed for each hydrogeological region contains a description of the region (physiography, groundwater use, population, climate, hydrography); detailed geological and hydrogeological contexts and aquifers; current knowledge of the region (recharge, groundwater quality, groundwater levels, groundwater fluxes, knowledge gaps, etc.); and specific examples with regional studies in separate boxes within the chapter to highlight a well-documented aquifer, or an outstanding of groundwater issue in each of the hydrogeological designations.

Questions and issues we address in this section of the book include

- What are the important aquifer systems within each region?
- How much groundwater does the region have (e.g., proven, potential, probable)?
  - What is the recharge of regional aquifer systems? (how, how much)
  - What are typical well yields?
  - What are the groundwater fluxes of regional aquifer systems? (rates, velocity, gradients)
  - What is the volume of groundwater stored?
  - What is the residence time of the groundwater?
- What is the groundwater quality of the region?
- Is groundwater vulnerable to contamination from the surface land use?
- What is the state of groundwater use?
- What are the groundwater issues for each region? (non-point source contamination, lack of regulations, management practices, management versus governance)

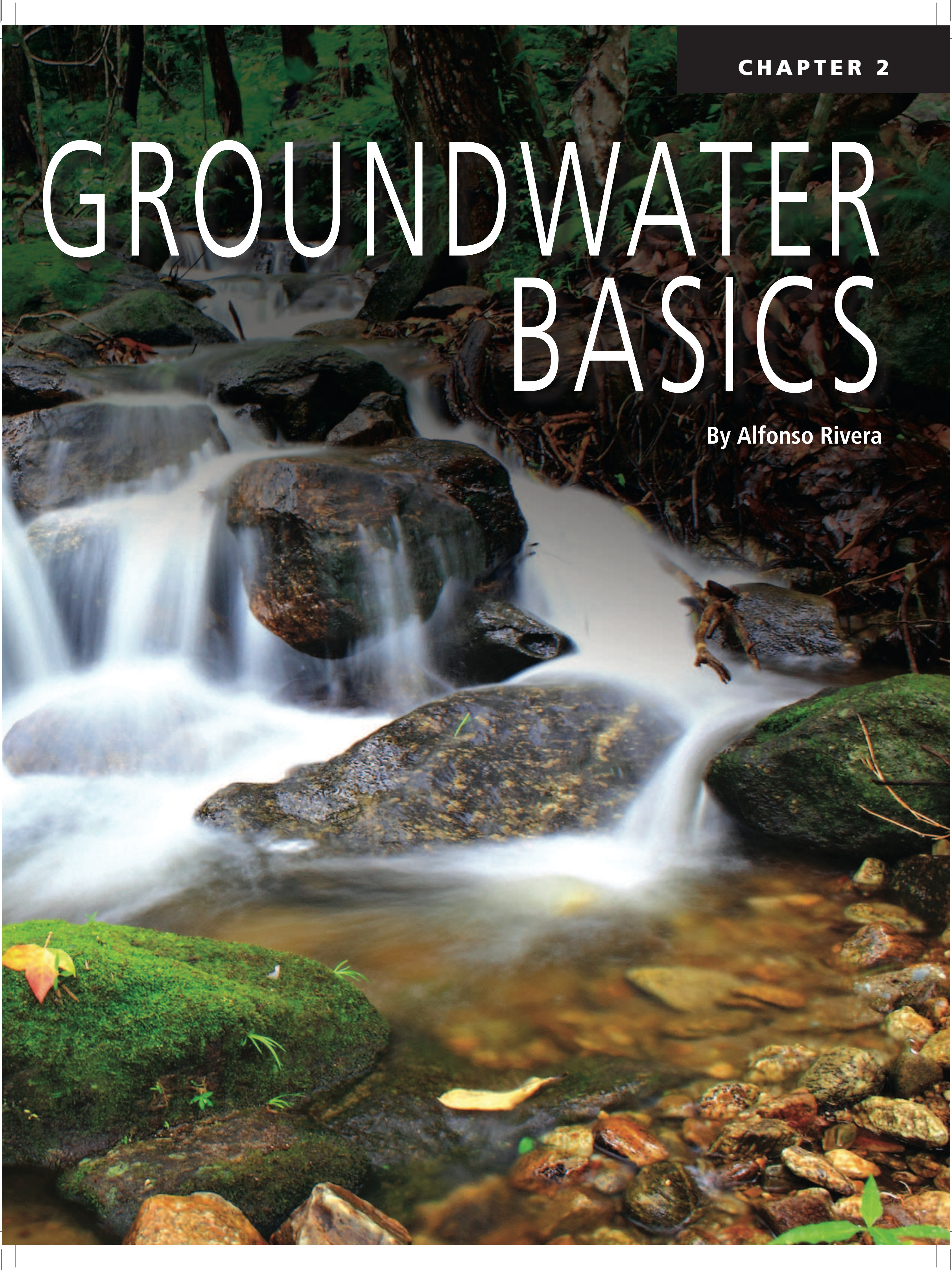
In brief, *Canada's Groundwater Resources* is designed to provide a contribution not only toward the development of an improved knowledge base in the field of hydrogeology across this country, but also, and perhaps more importantly, to provide decision makers with relevant scientific information on Canada's groundwater resources so that they can arrive at sensible decisions for future sustainable management of the resource.

PART II:
UNDERSTANDING GROUNDWATER

CHAPTER 2

GROUNDWATER BASICS

By Alfonso Rivera



2.1 INTRODUCTION

Groundwater accounts for nearly all of the potentially drinkable water on Earth, with the exception of water in polar caps. New exploration and production techniques and a better understanding of the dynamics of natural groundwater reservoirs are helping Earth scientists find new sources of this essential commodity.

Global changes, such as population growth, climate variability, expanding urbanization, often combined with pollution, severely affect water availability and are leading to chronic water shortages in a growing number of regions. The World Health Organization estimates that, within 12 years, two thirds of the world's inhabitants will live in countries with serious water problems. Inventive approaches and innovative technologies must be developed for every possible water resource.

Groundwater is one of the most important natural resources; it is the main source of water for irrigation worldwide (more than one-third of the arable landmass is irrigated with groundwater), and it is the main source of drinking water for a number of countries.

Within this chapter, we provide an overview of groundwater's basic characteristics as a resource by exploring aquifers, groundwater flow mechanisms, wells, the natural quality of groundwater and its interaction with the environment. Together with Chapter 3, this chapter expands on regional aquifer characterization and groundwater resource assessments for an integrated understanding of aquifer systems and the science required for sustainable management of groundwater resources.

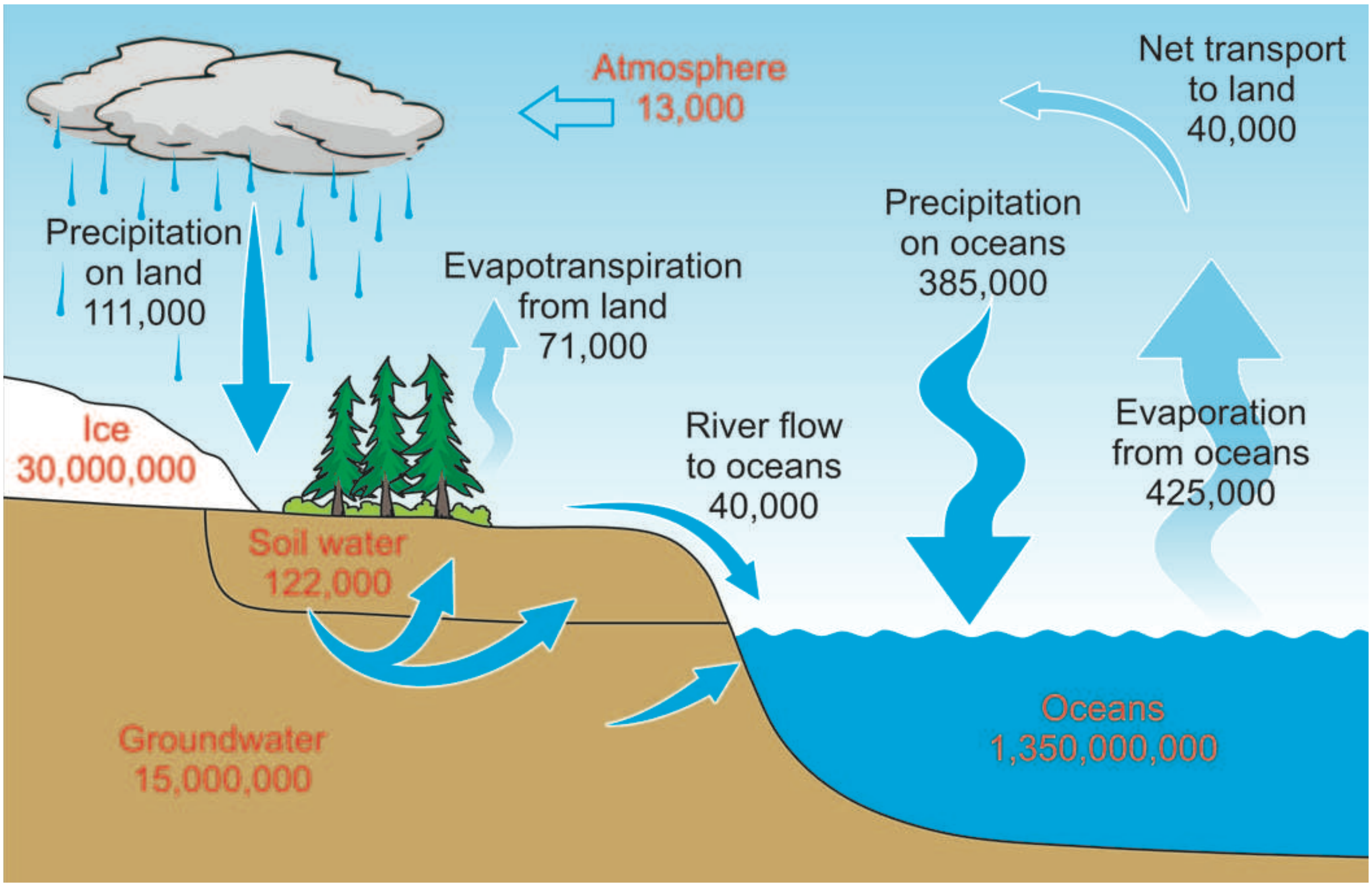


Figure 2.1 Global pools and fluxes of water on Earth, showing the magnitude of groundwater storage relative to other major water storage and fluxes (reproduced and modified from Schlesinger, 1997). Pools (in red text) are in cubic kilometres; fluxes are in cubic kilometres per year.

2.2 WHAT IS GROUNDWATER?

Groundwater is a vital and essential part of the water or hydrologic cycle; it is the water that seeps into the ground, filling voids, cracks and fractures in rocks. The water cycle (schematically represented in Figure 2.1 in the form of pools and fluxes) is driven by thermal energy provided by the Sun. Water evaporates from the surface of the oceans and continents and is transported through the atmosphere, where it remains no longer than eight days before it precipitates as rain on continents and oceans. Once on the ground, precipitation fluxes are redistributed. Direct evaporation returns one part of the flux to the atmosphere during and after rainfall. Transpiration from vegetation returns to the atmosphere as part of the water that has seeped into the ground during rainfall. The sum of both fluxes is called evapotranspiration and it is by far the most important flux of the cycle, representing, on average, 63% of annual precipitation.

During the summer, ground infiltration helps form the near-surface stock of water needed for evaporation and transpiration. In cooler seasons, however, water infiltrates deeper into the ground, recharging the groundwater contained in soils and rocks. This deeper infiltration represents, on average, 13% of annual precipitation.

Runoff, representing, on average, 24% of precipitation, is another important flux of the hydrologic cycle. Runoff occurs immediately after soil saturation, when the soil can no longer absorb more water. Runoff has high variability, depending on

the type of soil and rain intensity; it may, as surface water, eventually form rivers. A large part of groundwater also ends up in rivers, forming what is known as river "baseflow," or natural water flow in the absence of rain (these occurrences explain the differences between ocean fluxes and land fluxes in Figure 2.1).

The sum of evapotranspiration (ET), ~ 496,000 km^3/year from oceans and land, equals the sum of precipitation (P) at the global scale (Figure 2.1). Rainfall, on average, exceeds evaporation on the Earth's continents, whereas evaporation exceeds rainfall on the Earth's oceans. This difference is 40,000 km^3/year at the global scale. The equilibrium

TABLE 2.1 GLOBAL VALUES OF WATER FLUXES ON THE SCALE OF THE PLANET (IN VOLUME, KM³/YR, AND IN EQUIVALENT WATER BAND, MM/YR; WRI, 1990)

Evaporation on oceans	425,000 km^3/yr	(1,250 mm/yr)
Evaporation on continents	71,000 km^3/yr	(410 mm/yr)
Precipitation on oceans	385,000 km^3/yr	(1,120 mm/yr)
Precipitation on continents	111,000 km^3/yr	(720 mm/yr)

TABLE 2.2 WATER FLUXES FROM CONTINENTS TO OCEANS (IN KM³/YR)

Flow rate of rivers	27,000 km^3/yr
Base flow from aquifers to rivers and oceans	10,500 km3/yr
Input from glaciers to oceans	2,500 km^3/yr
Total	111,000 km^3/yr

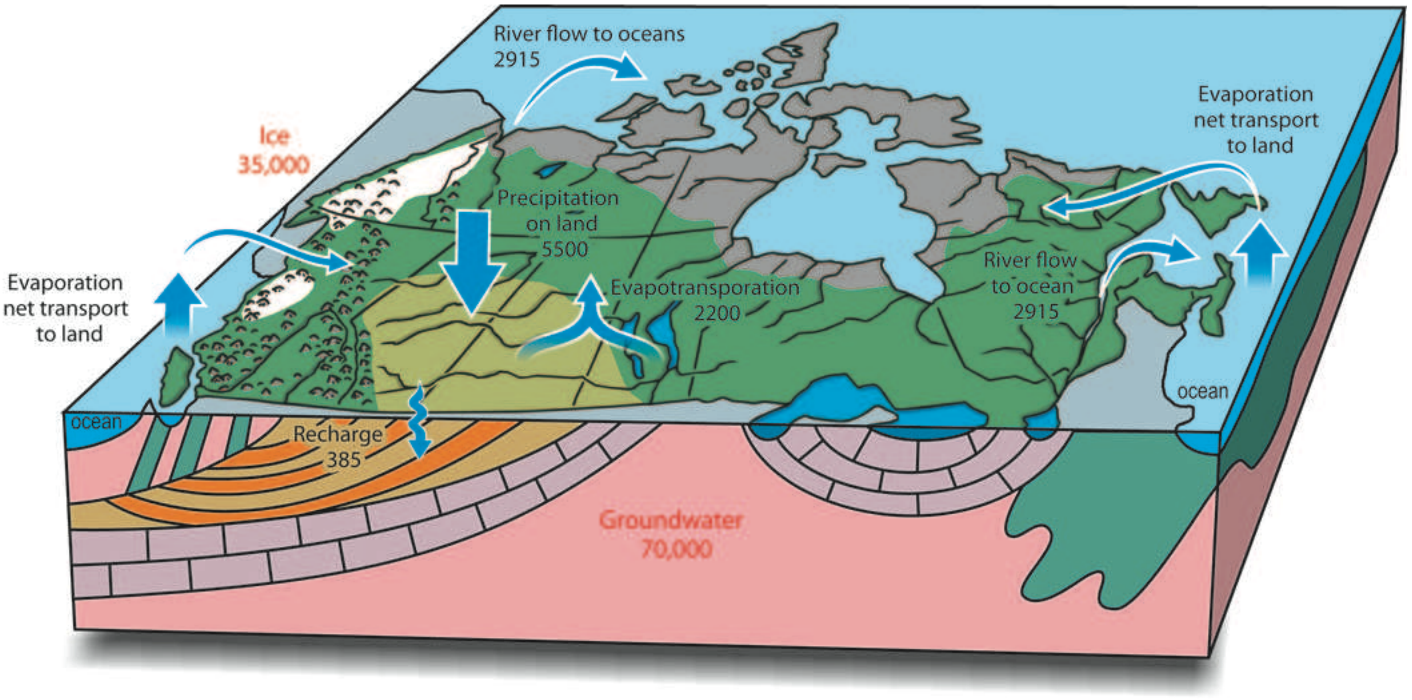


Figure 2.2 Pools and fluxes of water in Canada. Pools (in red text) are in cubic kilometres; fluxes are in cubic kilometres per year (Sources: P from Statistics Canada, 2003; ET from Liu et al., 2003; RF from WRI, 1990; ice from Demuth, 1997; I from WRI, 2007, and groundwater in storage [pool], Rivera, 2008; Rivera and Vigneault, 2010).

of the Earth's water cycle means that every year continents send 40,000 km^3 of water to the oceans (World Resources Institute [WRI], 1990) (Tables 2.1 and 2.2).

In temperate regions, like Canada, when rain arrives on the ground, one part infiltrates and is essentially used to recharge the "soil reservoir" from where evapotranspiration transports it back to the atmosphere. During the cooler seasons, when evaporation is lowest, water continues downward and reaches the water table. This process is complex and variable, depending on the region. Permafrost, for instance, has often been considered an impermeable barrier (or aquiclude) to groundwater movement because of the presence of ice-filled pores and fractures. Consequently, many people believe that northern Canada lacks active groundwater flow systems. Although permafrost does have a significant impact on groundwater flow regimes, especially the recharge component, active groundwater flow can be found to varying degrees throughout Canada's permafrost regions (see Chapter 15).

How does Canada fit into the global water-balance picture? Figure 2.2 summarizes Canada's pools and water fluxes. 5,500 km^3 of precipitation (P) falls on Canada every year, mainly in the form of rain and snow. Evapotranspiration (ET) accounts for 40% of P with 2,200 km^3. River flow (RF), fed by runoff and groundwater (baseflow), accounts for 53% of P with 2,915 km^3. The contribution of runoff to streamflow varies seasonally, depending on precipitation, snowmelt, and in some locations, the summer melting of glaciers. Lastly, groundwater recharge (I) accounts for 7% of P with 385 km^3 (estimated from the sum of all baseflow of the rivers in Canada for which data exist). The pools in the figure, ice and groundwater, are much larger than the yearly precipitation and all river flow combined (Figure 2.2). However, the ice pool cannot be used directly, although it does serve to maintain river flow and to recharge aquifers in some

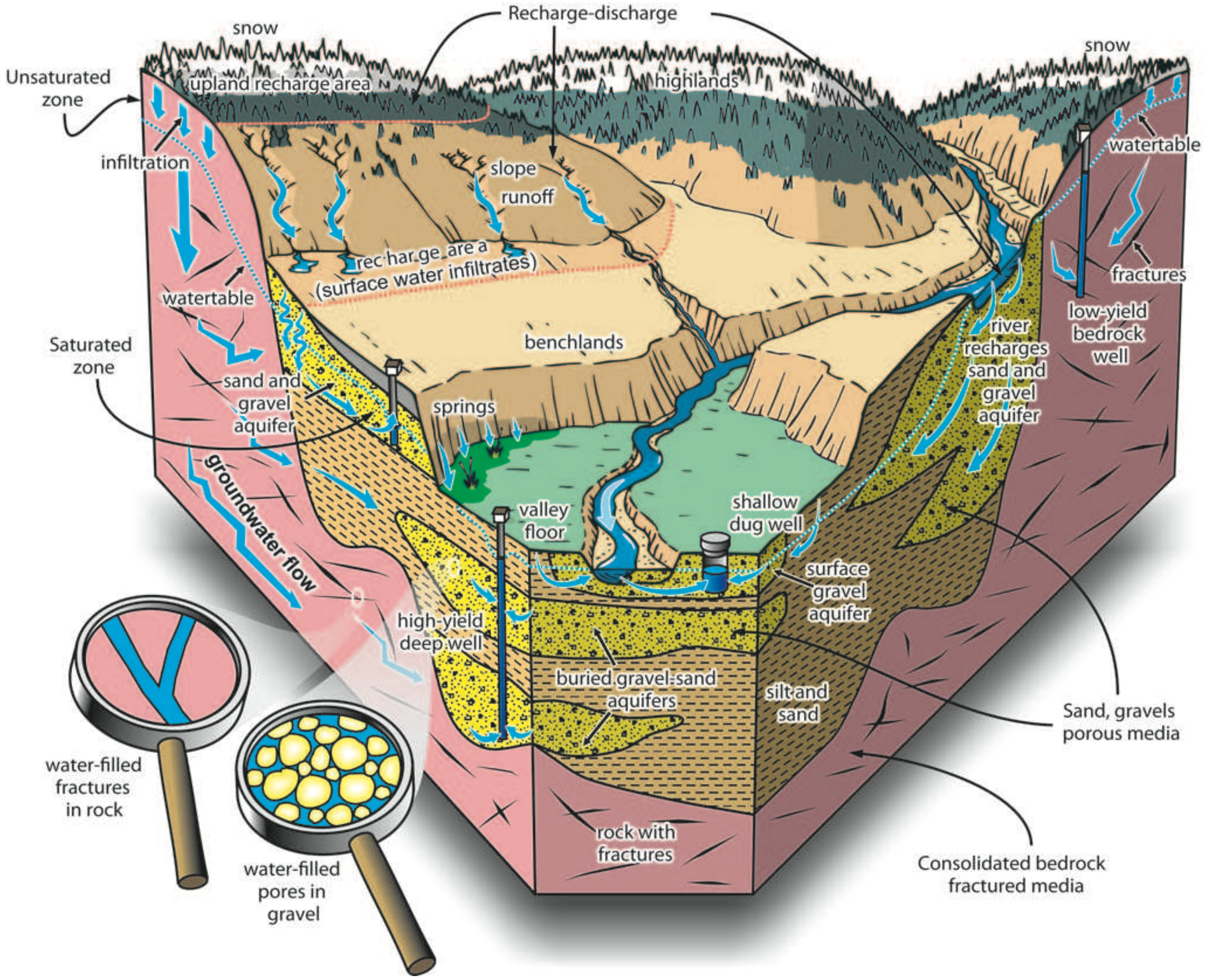


Figure 2.3 Groundwater flow and geological units forming aquifers.

locations (e.g., the foothills of Alberta).

Canada's large groundwater pool (estimated to be 70,000 km^3, Figure 2.2; Rivera and Vigneault, 2010) represents the storage volume of groundwater in aquifers, other than the yearly recharge. This storage volume is estimated to be an average of the upper 150 metres only; it is not all usable and might not be sustainable over the long term. Currently, there are no precise estimates available of the volume that would be sustainable on a national scale.

A comparison of Canada's average yearly water fluxes with global water fluxes on Earth (water cycle, Figure 2.1), reveals some particular differences. Evapotranspiration is much lower in Canada than the world average, while runoff is more than twice the world average. Recharge, on the other hand, is smaller than the world average (although there is much uncertainty about estimates of this flux). Canada's climatic, geographic and geological characteristics impact on the country's water cycles, making Canada quite different from many other countries.

2.2.1 Groundwater flow mechanisms

Groundwater refers to water that resides within the zone of saturation beneath the Earth's surface;

An aquifer is a permeable material that can transmit significant quantities of water to a well, springs or surface water bodies.

it is the liquid that completely fills pore and fracture spaces in the subsurface, as shown in Figure 2.3. Geological units can be defined on the basis of their ability to store and transmit water. An aquifer is a permeable material that can transmit significant quantities of water to a well, springs or surface water bodies. An aquifer is by no means equivalent to a single geologic, lithographic or stratigraphic unit; two contiguous layers of sand and limestone, for instance, may form a *single* aquifer. Conversely, a single regional stratigraphic unit may have more than one groundwater flow type, depending on the space and time scales considered. In some cases, we define *aquifer systems*, which include more than one type of groundwater flow. Aquifers may be composed of (a) unconsolidated sand and/or gravel; (b) permeable consolidated deposits, e.g., sandstone, limestone; or (c) consolidated less-permeable fractured rocks (granitic and metamorphic rocks).

Figure 2.3 shows unsaturated and saturated zones defined by water table or piezometric levels. In general, groundwater is gravity-driven: it moves from areas of high hydraulic head (pressure) to areas of lower hydraulic head (e.g., toward lowland areas in Figure 2.3). In some exceptional circumstances, groundwater can move against gravity, as in the case of density-driven flow (e.g., the occurrence of dense non-aqueous phase liquids, commonly known as DNAPLs, or interaction between fresh water and saltwater). However, on a regional scale, groundwater always moves from high to low topographic points.

Aquifers are recharged in many different ways. In addition to direct recharge from precipitation (Figure 2.3), surface water bodies can be both sources and sinks for groundwater. For example, the right-hand side of Figure 2.3 shows groundwater recharged by river water, which later discharges back to the river. Thus, surface water–groundwater interaction is highly dynamic. This interaction may not always take place, depending on the type of aquifer system, the permeability of rocks, and climate. In Canada, this interaction is extremely important because most of the currently exploited aquifers are shallow, and located in unconsolidated Quaternary sediments. Groundwater also maintains wetlands and aquatic health by buffering nutrients and temperature fluctuations, especially in riparian and hyporheic zones (Hayashi and Rosenberry, 2001).

2.2.2 How do groundwater aquifers differ from surface water watersheds?

Groundwater flow occurs in aquifers, while surface water flow occurs in watersheds. Watershed boundaries can be clearly defined by topography, whereas aquifer boundaries cannot. Aquifer boundaries and watershed boundaries may or may not coincide, but more often they overlap. In some cases, very deep aquifers may be recharged in remote mountain ranges. Water infiltrating into fractured rock within the mountains may flow downward and then move laterally into confined aquifers. In some regions, these aquifers extend for many hundreds of kilometres beneath the land surface, and sometimes crossing natural surface watershed boundaries or jurisdictional boundaries. Thus, groundwater in a confined aquifer may recharge in one watershed and discharge in another, or perhaps recharge in one province or nation and discharge in another; the latter

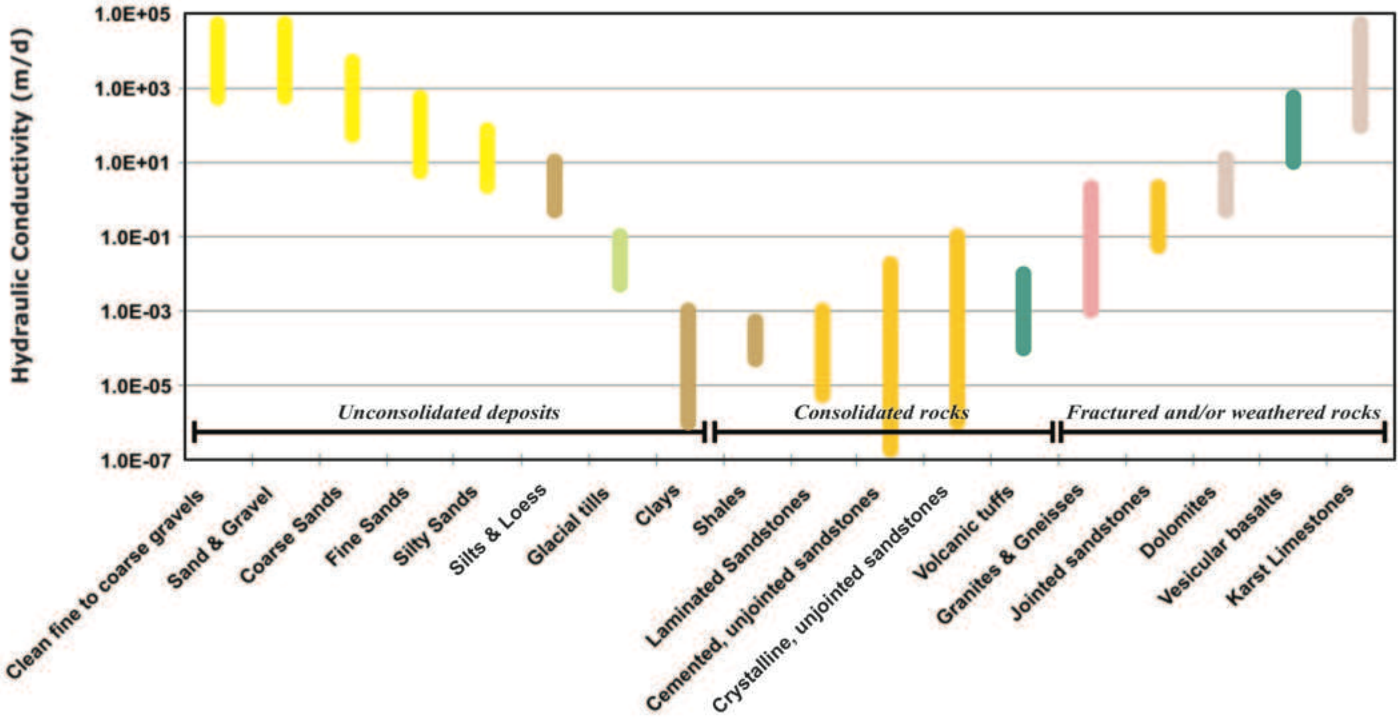


Figure 2.4 Range of hydraulic conductivity (K) values for geological materials (modified from Driscoll, 1986 and Todd, 1980).

phenomenon is classified as a "trans-boundary aquifer" (see section 2.6 and Chapter 16).

Watershed boundaries and aquifer boundaries may coincide when aquifers are located in unconsolidated shallow sediments, under unconfined conditions, such as valleys and deltas composed of glaciolacustrine or glaciofluvial sediments. In those cases, interaction between surface water flow and groundwater flow occurs as a result of hydraulic interconnections between surface water bodies and aquifers under phreatic conditions (at atmospheric pressure).

In cases where surface water and groundwater interact, seasonal water table fluctuations follow a pattern similar to those of river levels (more details in Chapter 4 and 5).

Materials through which groundwater can pass easily are said to be permeable and those that scarcely allow groundwater to pass or only with difficulty are described as impermeable.

2.3 NATURE OF PERMEABILITY

Permeability is an essential physical property of rock-forming aquifers. Scientists distinguish two permeability types: intrinsic, or specific, permeability (in m^2) and hydraulic conductivity (in m/s). The former relates to the porous medium regardless of the fluid characteristics (as used in soil/rock mechanics), while the latter is a vector as used in hydrogeology. The intrinsic permeability is only defined at the macroscopic scale with dimensions of a surface area. However, permeability is often expressed in darcys, which is a unit equal to 0.987 10^{-12} m^2. Intrinsic permeability and hydraulic conductivity are linked by the intrinsic properties of the medium and physical nature of the fluid, defined as:

$$K = k \rho g / \mu \tag{2.1}$$

where K is the hydraulic conductivity; k is the intrinsic permeability; ρ is the water density (kg/

m^3); g is the acceleration of gravity (m/s^2); and μ is the dynamic viscosity of the fluid (usually water) (kg/m s). Intrinsic permeability depends on the porous matrix properties exclusively. The medium is termed *homogeneous* if k does not vary in space. If k varies in different points in space, the medium is called *heterogeneous* and if k varies in different directions, the medium is called *anisotropic*, otherwise it is *isotropic*.

Other factors, which can affect the intrinsic permeability of a medium, include deformation of the porous matrix (e.g., consolidation leading to land subsidence), dissolution of solid particles, and chemical and biological processes.

The relationship between K and k in Eq. 2.1 is not very often used in studies of groundwater resources, but rather in studies of coupled phenomena such as hydraulic-mechanic (subsidence due to intense pumping), and hydraulic-transport (solute or heat transfer in groundwater pollution problems or in variable-density problems).

Groundwater resource studies most commonly use the hydraulic permeability, K (the permeability of hydrogeologists), generally without distinction with k. For most practical purposes, and under isothermal conditions, intrinsic permeability (k) can be related to hydraulic conductivity (K) as $k\ (m^2) = 10^{-7} \cdot K\ (m/s)$.

Hydraulic conductivity is a measure of the ease with which groundwater flows through the rock-forming aquifers. The ease with which groundwater flows through a rock mass in a porous aquifer, or the fractures in a fractured aquifer, depends on a combination of the size of the pores, or the fractures, and the degree to which they are interconnected. These features determine the overall permeability of the aquifers. For instance, in clean, granular materials, hydraulic conductivity increases with grain size. Typical ranges of hydraulic conductivity for the main types of aquifer materials are shown in Figure 2.4. The limit separating permeable from impermeable material is often (arbitrarily) set at 10^{-9} m/s, which is acceptable for most groundwater resources studies.

2.3.1 Darcy's Law

Darcy's Law (formulated by Henry Darcy in 1856) is an equation which describes groundwater flow. This law states that the volumetric flow rate through porous media is proportional to flow area A, the hydraulic conductivity K, and the hydraulic gradient i:

$$Q = A\,K\,i \qquad (2.2)$$

in which

$$i = (h_2 - h_1)/\Delta l \qquad (2.3)$$

where Q is the volumetric rate of flow through area A under a hydraulic gradient $\Delta h/\Delta l$ (the difference in hydraulic heads ($h_2 - h_1$) between two measuring points), divided by the distance between them.

Equations 2.2 and 2.3 can be combined to represent the volumetric flow per unit surface area q, as:

$$Q/A = q = -K\,(h_1 - h_2)/L = -K\,\Delta h/\Delta l \qquad (2.4)$$

The direction of groundwater flow in an isotropic aquifer is at right angles to lines of equal head. A simple experimental apparatus used to demonstrate Darcy's Law is shown in Figure 2.5, indicating also the elevation and pressure components of hydraulic head referred to above. The equation for Darcy's Law is conventionally written with a minus sign because flow is in the direction of decreasing hydraulic heads.

This representation is very convenient because it

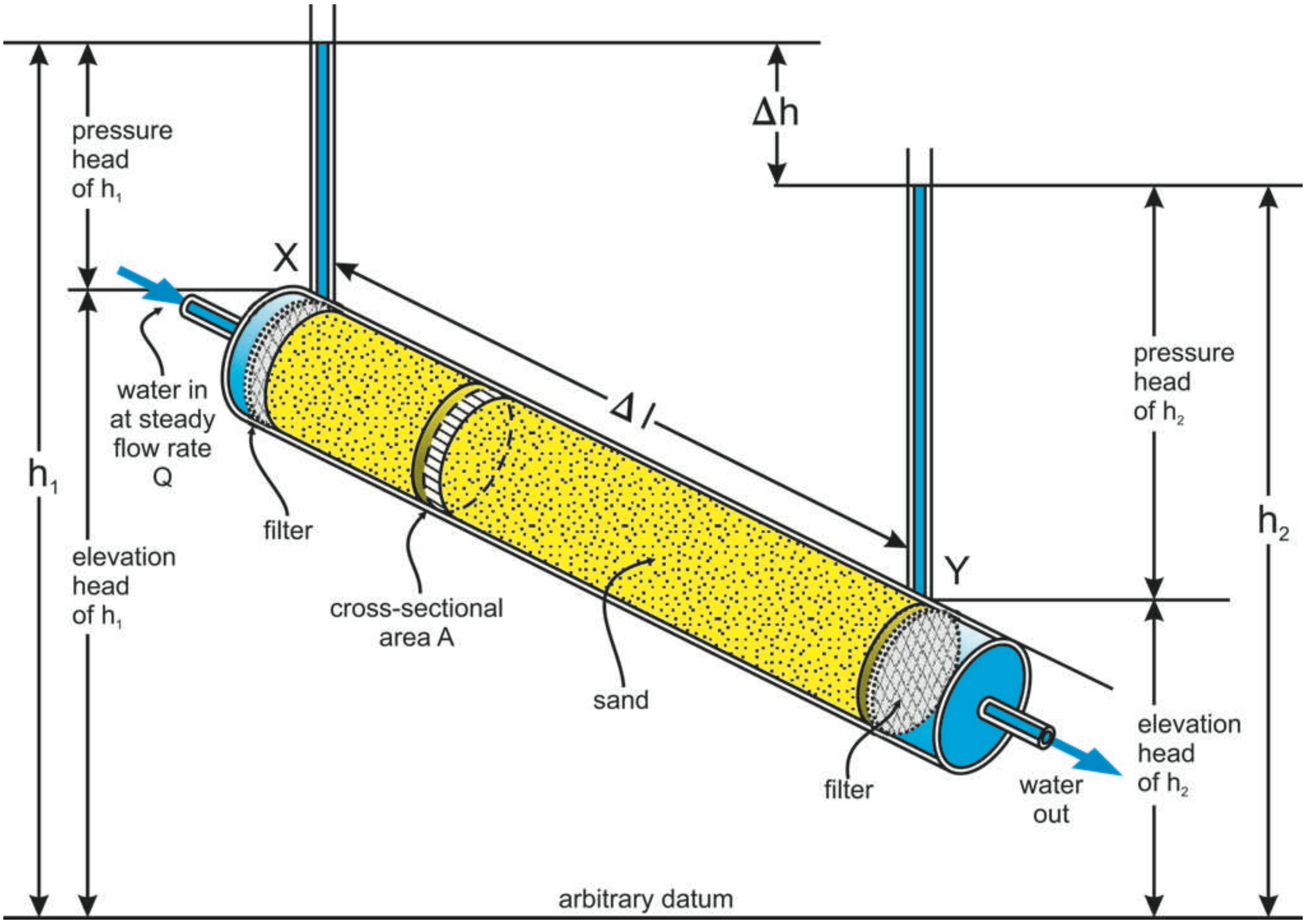


Figure 2.5 Darcy's experimental setup (modified from Price, 1996).

provides rapid and easy estimates of groundwater flow where values of groundwater elevations are known or available. A graphical illustration of the use of the steady-state groundwater flow equation (based on Darcy's Law and the conservation of mass) is in the construction of groundwater flow lines (or equipotentials), to quantify the amount of groundwater flowing under a dam or an aquifer. An example of this is given below (see Figure 2.6).

Darcy's Law is only valid for slow, viscous flow, but, fortunately, most groundwater flow cases fall in this category. Typically any flow with a Reynolds number[1] less than 1 is clearly laminar, and Darcy's Law would apply. Experimental tests have shown that flow regimes with Reynolds value numbers of up to 10 may still be Darcian.

A very simple and practical example of the usefulness of Darcy's Law is given below.

Consider the aquifer depicted on a 2D-horizontal dimension over a three-dimensional schematic aquifer in Figure 2.6; using Darcy's Law, calculate:

1) The time it takes to transport a drop of groundwater from point B to point A
2) The groundwater volumetric fluxes per streamline and per metre thickness of aquifer, in m^3/year
3) The water infiltrated over the whole area of the aquifer in an equivalent recharge, in mm/year

The aquifer is composed of a porous medium

---

[1] In fluid mechanics, the Reynolds number (Re) is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. Re is used to characterize different flow regimes, such as laminar or turbulent flow: laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion, that is generally the case for groundwater flow in porous medium.

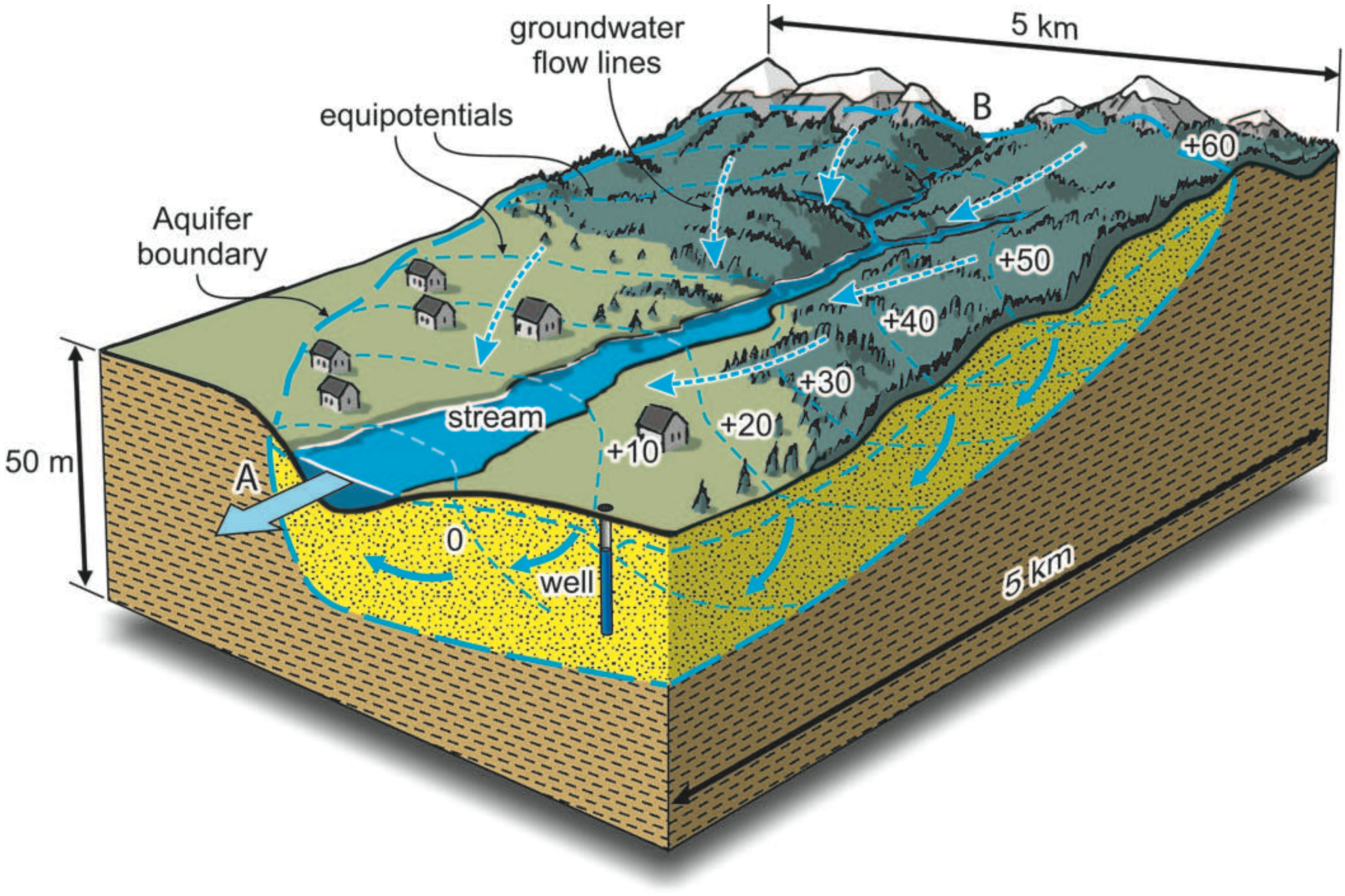


Figure 2.6 Example of application of groundwater flow lines and Darcy flow.

with sand and gravels. Let's take typical values from Figure 2.4 and Table 2.3: a hydraulic conductivity of $K=10^{-3}$ m/s and a specific yield (Sy) of 10%.

Using equations 2.2, 2.3 and 2.4 we have:

Darcy flux and groundwater velocity:

Using $q = -K\cdot i$; with i from Eq. 2.3:

$$i = (h_{60} - h_0)/L = 60/5000 = 1.2 \cdot 10^{-2}$$

$$q = 10^{-3}\ \text{m/s} \cdot 1.2 \cdot 10^{-2} = 1.2 \cdot 10^{-5}\ \text{m/s}$$

A linear pore velocity (average linear groundwater velocity), v, which is the volumetric flow rate per area of connected pore space can be calculated as $v=q/n$, if the porosity, n, is known (it is necessary to know the effective or dynamic porosity, ne, which represents the proportion of the total porosity involved in groundwater movement). This can often be difficult to measure, although, for unconfined aquifers, n is probably close to the specific yield values given in Table 2.3. Thus we can define:

$$V = q / S_y = 1.2 \cdot 10^{-4}\ \text{m/s}$$

and the travel time from B to A as: $L/v = 4.17 \cdot 10^7$ sec, or 1.32 years

Volumetric fluxes:

Using Eq. 2.4, we can calculate the groundwater flux across each unit surface area ($\Delta h = 10$ m):

$A = 5000\ \text{m} \times 10\ \text{m}$; and

$Q = q \cdot A = (1.2 \cdot 10^{-5})\ (5 \cdot 10^4) = 0.6\ \text{m}^3/\text{s}$

Or a total of 19 Mm^3/year, per flow line, per metre

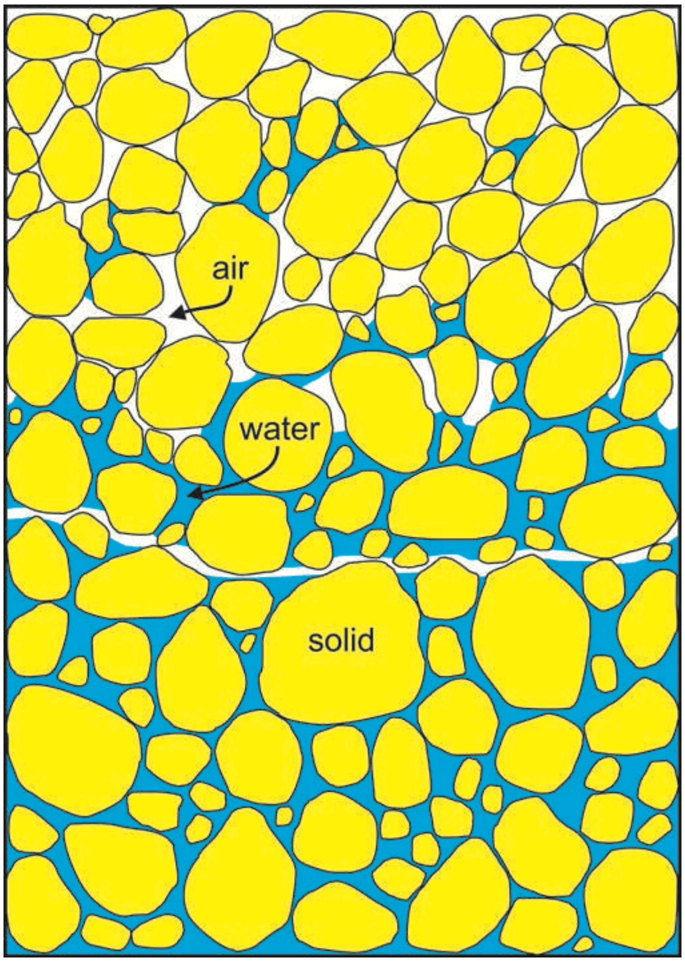


Figure 2.7 Water, solid and air phases in a porous media rock formation.

thickness of aquifer.

Infiltrated equivalent water band:

I = Volume/surface area (m^3/year/m^2)

I = 1.9 ·10^7 (m^3/year) / (Length ·Width) (m^2) = 760 mm/year

2.4 ROCK-FORMING AQUIFERS

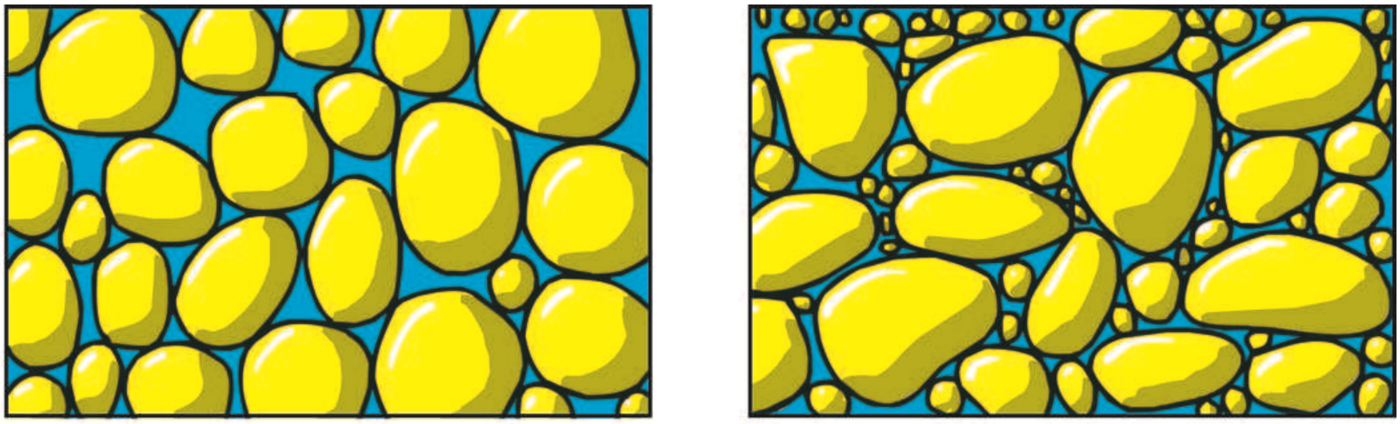
Groundwater occurs in most geological formations because nearly all rocks in the uppermost part of the Earth's crust possess openings called pores or voids. Figure 2.7 depicts schematically water situated in the voids or pores of a porous media rock formation. Geologists traditionally subdivide rock formations into three classes according to origin and creation: *Sedimentary rocks, Igneous rocks* and *Metamorphic rocks.*

Sedimentary rocks are formed by deposition of material, usually underwater, from lakes, rivers and the sea. Unconsolidated granular materials such as sand and gravels have voids, or spaces between the grains (Figure 2.8A). The material may become consolidated, through physical compaction and chemical cementation (Figure 2.8D), to form typical sedimentary rocks such as sandstone, limestone and shale, with the void space much reduced between grains, but with a porosity high enough to allow groundwater flow. These type of rocks form many important aquifers in Canada.

Igneous rocks are formed from molten geological material rising from great depths within the Earth, then cooling to form crystalline rocks either below ground or at the Earth's surface. These rocks include the granites and many volcanic types of lava such as basalts. Most igneous rocks are relatively dense and, being crystalline, usually have some voids between the grains, although these are not well-connected. Igneous rocks cover nearly one third of Canada's total land area (forming the Canadian Shield).

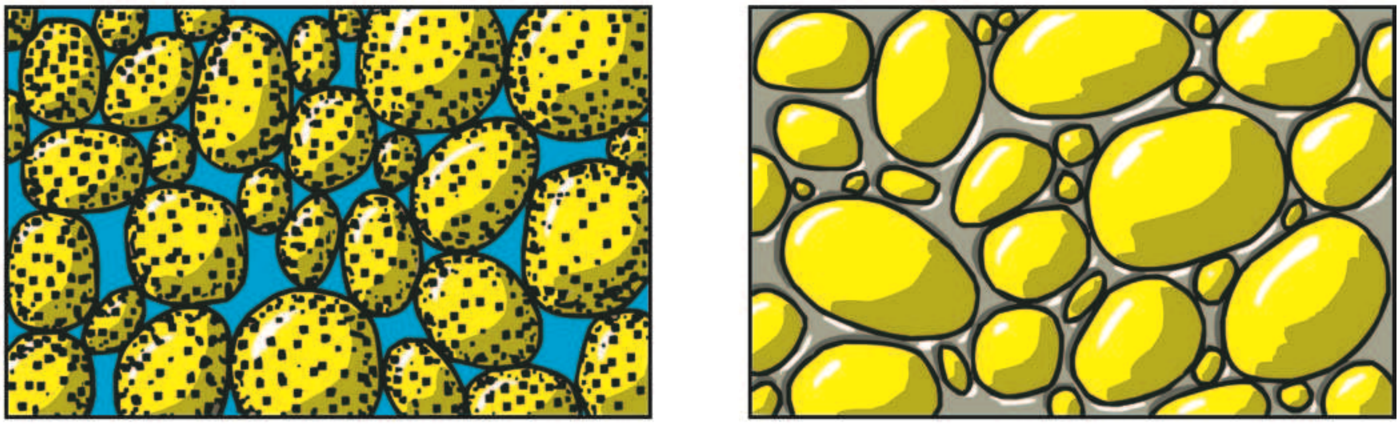
Metamorphic rocks are formed by deep burial, compaction, melting and alteration or re-crystallization of other rocks during periods of intense geological activity. These rocks include gneisses and slates. They are dense with few void spaces in the matrix between grains.

The only void spaces in some dense rocks, may be as a result of fractures caused by fold and fault stresses. These fractures may be completely closed or they may have small, not very extensive (or even poor) interconnected openings of relatively narrow aperture (Figure 2.8F). Weathering and decomposition of igneous and metamorphic rocks may significantly increase void spaces in both the rock matrix and in the fractures. Fractures may



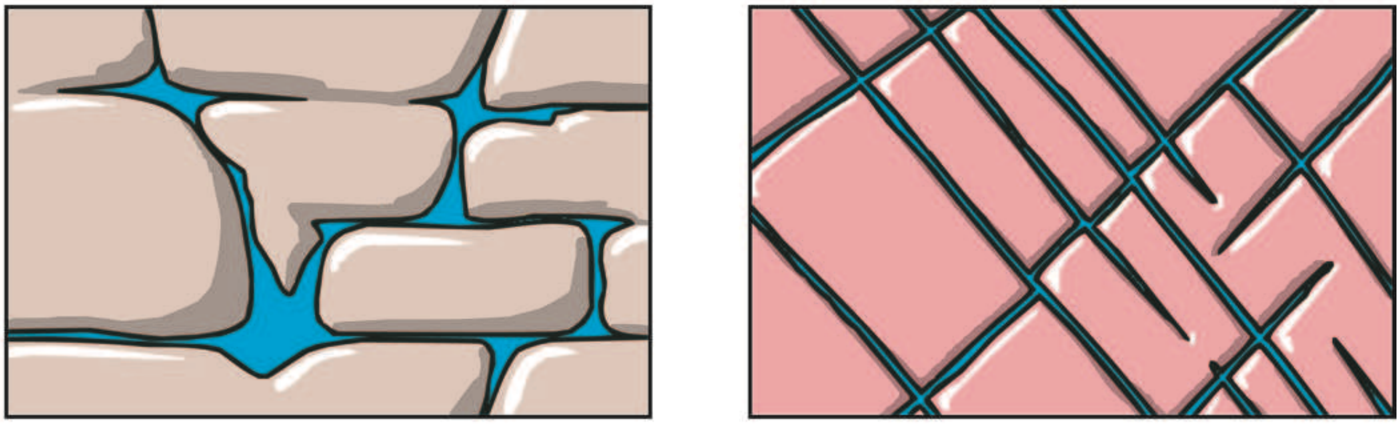
(A) Well-sorted, unconsolidated sedimentary deposit having high porosity

(B) Poorly-sorted, sedimentary deposit having low porosity



(C) Well-sorted, sedimentary deposit consisting of pebbles that are themselves porous, so the deposit as a whole has high porosity

(D) Sedimentary deposit whose porosity has been diminished by the deposition of mineral matter between the grains



(E) Rock with porosity increased by solution

(F) Rock with porosity increased by fracturing

Figure 2.8 Rock texture and porosity of typical aquifer materials (based on Todd, 1980).

also be enlarged into open fissures as a result of dissolution by flowing groundwater (Figure 2.8E). Limestone, largely composed of calcium carbonate, and evaporates composed of gypsum or other salts, are particularly susceptible to active dissolution, which often produces the caverns, sinkholes and other characteristic features of karstic aquifers.

The three basic rock formations described above

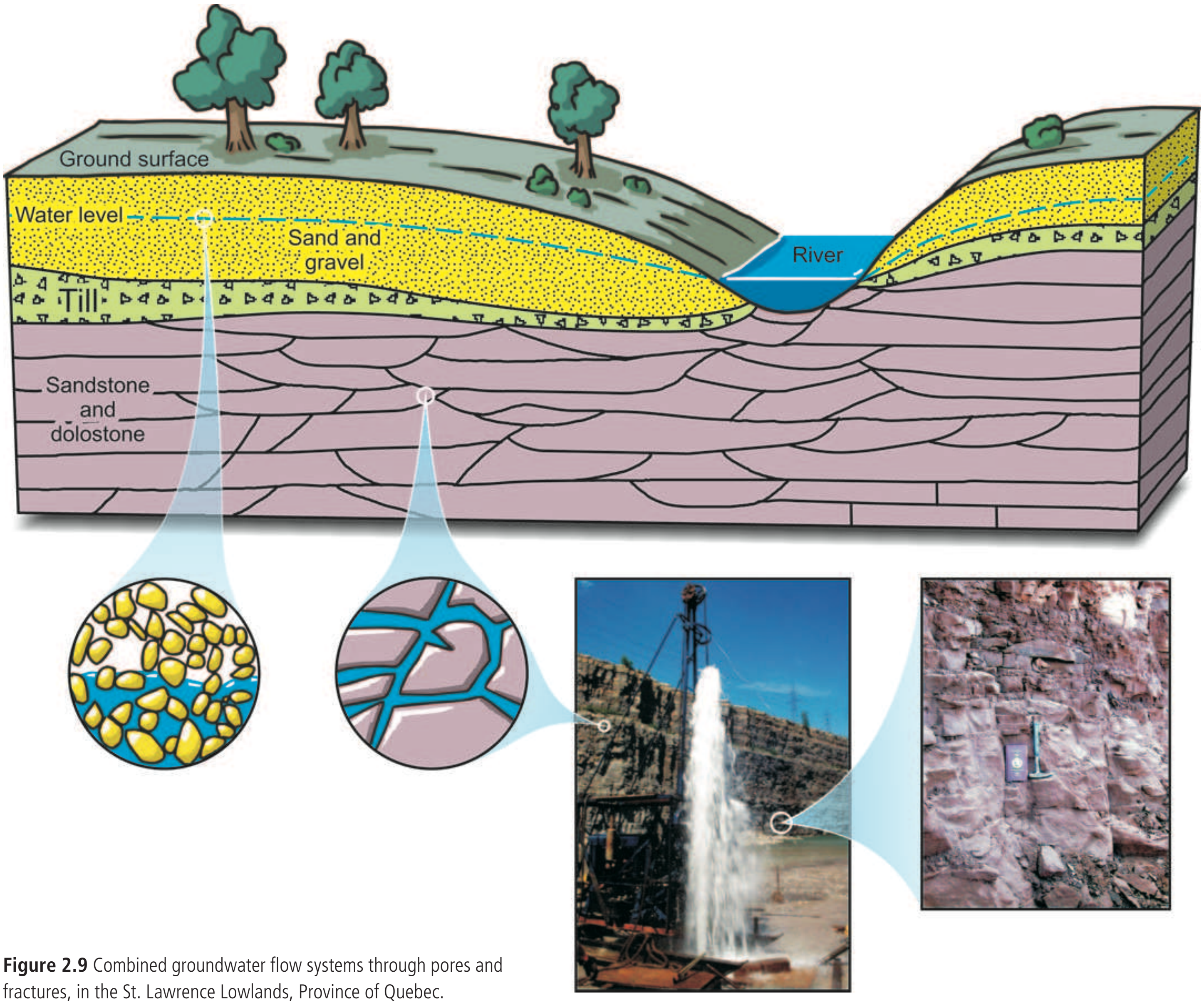


Figure 2.9 Combined groundwater flow systems through pores and fractures, in the St. Lawrence Lowlands, Province of Quebec.

are usually subdivided by geologists to study origins, structure and other natural processes. Hydrogeologists, on the other hand, tend to classify rock-forming aquifers as unconsolidated or consolidated, depending on whether water is stored and on how it moves between grains of the rock matrix, or through fractures. Because geological maps are one of the main sources of information required to characterize aquifers and to assess groundwater flow systems, it is worthwhile to understand the main geological terms geologists use (see also Chapter 3).

2.4.1 Porosity

Rock *porosity* depends on the volume of water that can be stored in the rock, which in turn, depends on the proportion of openings or pores in any given rock volume. Thus, the porosity of a geological material is the ratio of the rock volume to total volume, expressed as a decimal fraction or percentage.

Figure 2.9 shows a typical case in the St. Lawrence Lowlands, Province of Quebec (see the Central St. Lawrence Lowlands Hydrogeological Region in chapter 13), where groundwater flows through both the pores and fractures.

TABLE 2.3 POROSITY AND SPECIFIC YIELD OF GEOLOGICAL MATERIALS (FREEZE AND CHERRY, 1979; DOMENICO AND SCHWARTZ, 1998)

MATERIAL	POROSITY	SPECIFIC YIELD
Unconsolidated sediments		
Gravel	0.25-0.35	0.16-0.23
Coarse sand	0.30-0.45	0.1-0.22
Fine sand	0.26-0.5	0.1-0.25
Silt	0.35-0.5	0.05-0.1
Clay	0.45-0.55	0.01-0.03
Sand and gravel	0.2-0.3	0.1-0.2
Glacial till	0.2-0.3	0.05-0.15
Consolidated sediments		
Sandstone	0.05-0.3	0.03-0.15
Siltstone	0.2-0.4	0.05-0.1
Limestone and dolomite	0.01-0.25	0.005-0.1
Karstic limestone	0.05-0.35	0.02-0.15
Shale	0.01-0.1	0.005-0.05
Igneous and metamorphic rocks		
Vesicular basalt	0.1-0.4	0.05-0.15
Fractured basalt	0.05-0.3	0.02-0.1
Tuff	0.1-0.55	0.05-0.2
Fresh granite and gneiss	0.0001-0.03	<0.001
Weathered granite and gneiss	0.05-0.25	0.005-0.05

Although water is present in the unsaturated zone between the surface of the soil and the top of the saturated zone underneath, it cannot be considered as a resource because its residence time is short and transient: the water is not in hydrodynamic equilibrium. The deeper saturated zone of soil and rock, with its ensemble of voids, allows water to accumulate. It is in this area where groundwater is considered as a resource, and the soils and rocks containing the groundwater considered as aquifers.

In this book we consider groundwater as a resource only within the saturate zone.

Porosity is a very useful property in hydrogeology, as increasing pore space results in higher porosity and greater water storage potential. Typical porosity ranges for common geological materials are shown in Table 2.3, with emphasis on the hydrogeologists' division of unconsolidated and consolidated aquifer types referred to above.

2.5 GROUNDWATER SYSTEMS

One common belief about groundwater is that it

A sinkhole in a karstic aquifer

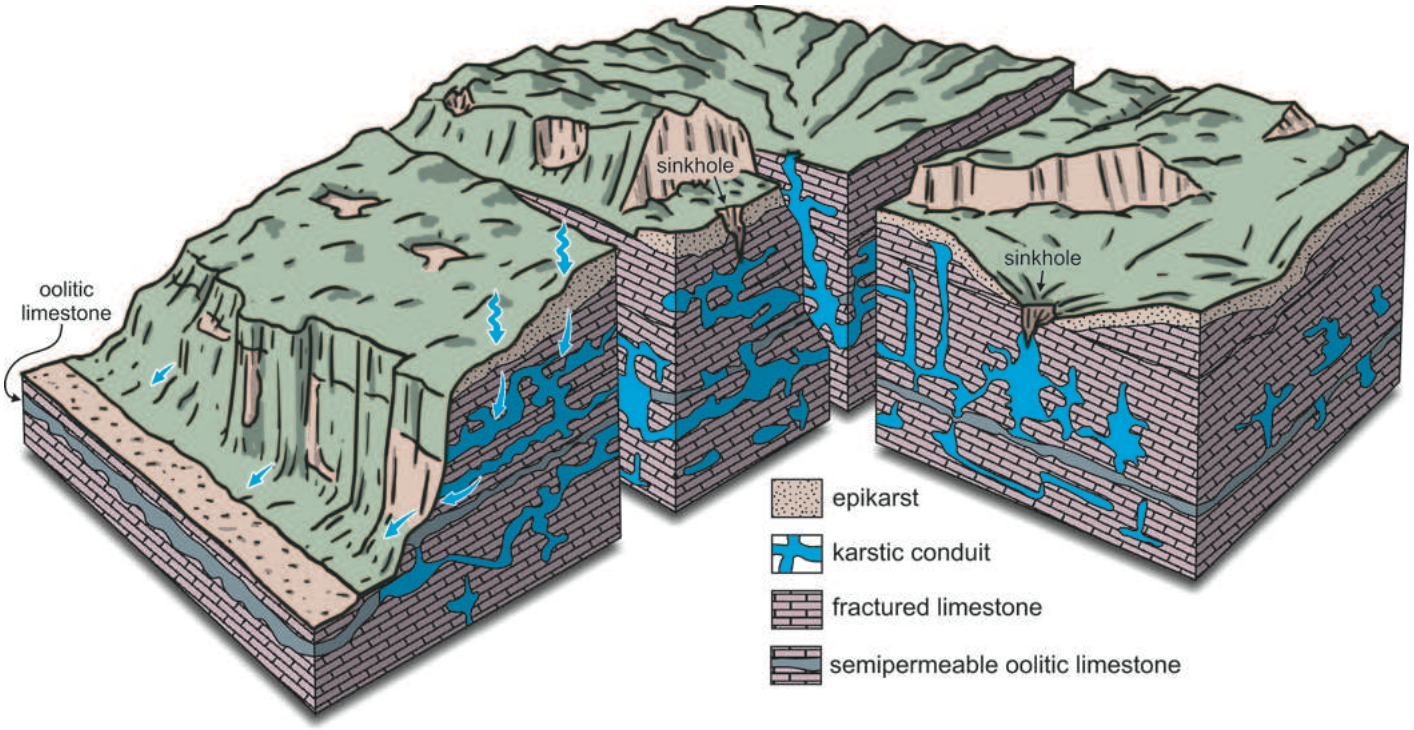


Figure 2.10 Karstic aquifer systems (modified from Bakalowicz, 2005).

flows through underground rivers or collects in underground lakes. Groundwater is not confined to only a few channels or depressions in the same way that surface water is concentrated in streams and lakes. Rather, it exists almost everywhere underground, in the spaces between particles of rock and soil, or in crevices, fractures and cracks in rock.

The water filling these openings is usually within 100 metres of the Earth's surface, although it can also be found hundreds of metres lower, in deeper formations, depending on rock conditions (much of the Earth's fresh water is found in these voids). These openings are much smaller at greater depths because of the weight of overlying rock. They hold considerably smaller quantities of water, which may be of significantly poorer quality.

Very often these saturate zone voids are small, even sub-millimetric, sometimes existing as spaces between the grains of sedimentary rock, or as small holes visible only under the magnifying glass in rocks like chalk or sandstone. These voids can also exist as very fine fissures (a fraction of a millimetre aperture) formed over time in hard rocks like granites, some lavas and certain hard carbonate rocks. In very special cases, these apertures may be centimetres or even metres wide; forming what are known as karstic systems.

Dolostone and carbonate rocks of the Chateauguay aquifer south of Montreal.

Sandstone outcropping on a cliff in Prince Edward Island

2.5.1 Aquifers

An aquifer can be defined as a single geologic unit, or as a set of interconnect hydrostratigraphic units which can yield significant quantities of water to wells. Aquifers are classified as unconsolidated or consolidated, and, in the latter case, reclassified as to whether water is stored and moves mainly between the grains of the rock matrix, or through fractures. In Canada, aquifers formed of unconsolidated granular material, such as sand and gravels, abound in deltas and buried valleys, and are typically formed by deposition of material usually underwater from lakes, rivers and the sea, or as remnants of past glaciations. Sedimentary rocks, on the other hand, turn into consolidated aquifers through physical compaction and chemical cementation, as the voids between the grains in sandstone, limestone, and shale are much reduced. In these types of consolidated aquifers, water is stored and transmitted through fractures, rather than through pores.

Other types of consolidated aquifers include igneous and metamorphic rocks of differing origins and types (granites, lavas, basalts, gneisses). These rock formation specimens have very few void spaces in the matrix between grains. Indeed, the only void spaces may be fractures resulting from fold and fault stresses; these fractures may be completely closed or have very small, and not extensive, or poorly interconnected openings of relatively narrow aperture. Fractures may be enlarged into open fissures as result of dissolution

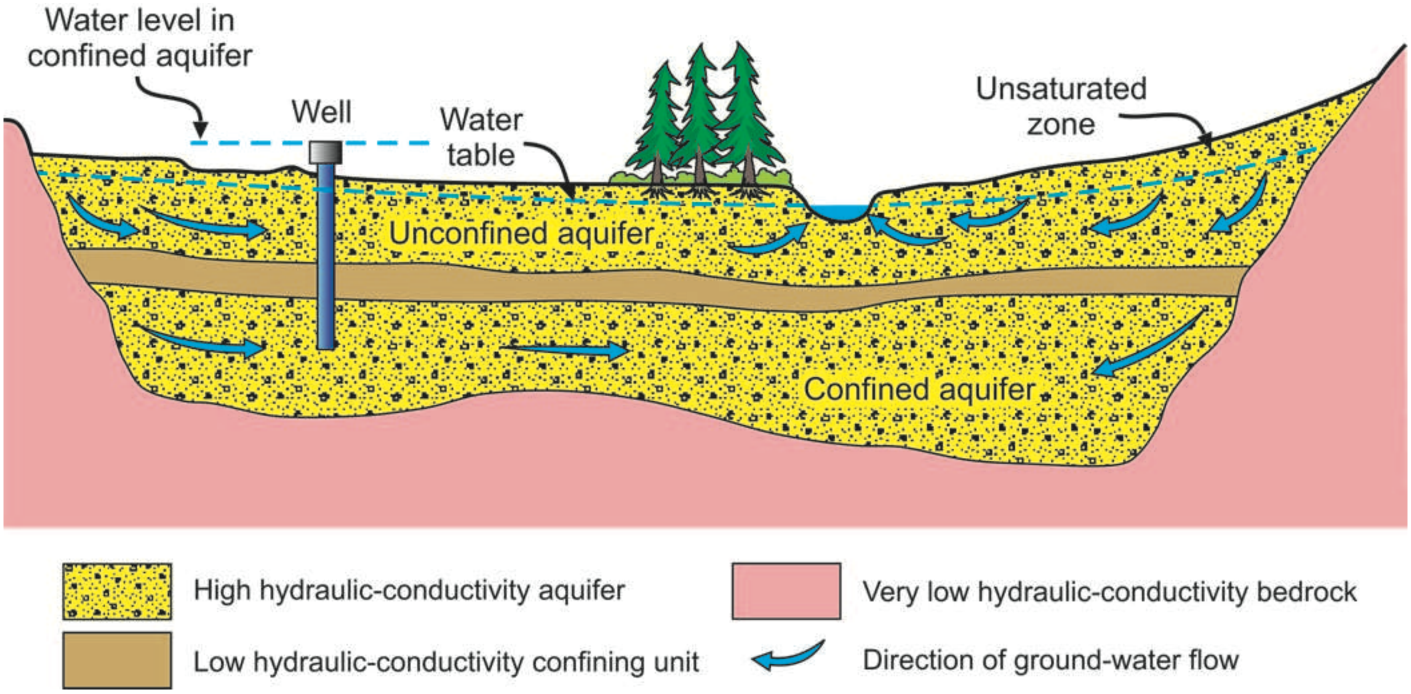


Figure 2.11 Unconfined and confined aquifers.

An artesian well north of Montreal

by flowing groundwater. One particular case of rock susceptible to active dissolution is limestone, which is largely made up of calcium carbonate, and evaporates of gypsum or other salts. This limestone dissolution can produce the caverns, sinkholes and other characteristic features of karstic aquifers (see Figure 2.10).

Many Canadian aquifers are in unconsolidated deposits of sand and gravel formed by rivers or lakes created from melting glaciers during the last ice age; some regional examples of these granular aquifers include

- Waterloo Moraine, Ontario
- Fredericton area, New Brunswick
- Carberry aquifer, Manitoba
- Fraser Valley aquifer, British Columbia

Many other regional aquifers are in fractured-rock formations; regional examples of these include

- The entire province of Prince Edward Island (sandstone)
- Winnipeg region (carbonate, shale), Manitoba
- Montreal region (carbonate, dolostone, dolomite),

Quebec

- Moncton area (carboniferous), New Brunswick

Aquifers can be further differentiated under *confined* and *unconfined* conditions (Figure 2.11). This distinction has important implications for groundwater development and protection.

An unconfined aquifer is one in which the upper limit of the zone wherein all pore spaces are fully saturated (i.e., the water table) is at atmospheric pressure (see Figure 2.11). When the aquifer extends to greater depths, less permeable layers are found. These diminish the aquifer's effective thickness, but may induce water pressures much greater than atmospheric. When the overlying layer of an aquifer has such low permeability (as in clay) that it prevents water movement through it, the aquifer is defined as fully confined. Water pressure at any point in a confined aquifer is greater than atmospheric. When a well is drilled down through the confined layer into the aquifer, groundwater will rise up the borehole to a level that balances the aquifer pressure. An imaginary surface joining well water levels in wells and drilled boreholes in a confined aquifer is called the piezometric (or equipotential) surface, which can be above or below the ground surface. An example of this surface is illustrated in Figure 2.11 (for more detailed examples of these hydrogeological conditions see also Figures 2.12 and 2.13). If the pressure in the confined aquifer is such that the piezometric surface is above ground level, then a well drilled through the aquifer will overflow. These types of overflowing wells are called artesian wells.

A large percentage of Canadian wells can be found in unconfined aquifers. These aquifers are favoured, from a groundwater development perspective, because their storage properties make them more efficient, and they are also likely to be shallower and therefore cheaper to drill into and pump from. A confined aquifer, on the other hand, even with a modest overlying less permeable layer, is likely to be much less vulnerable to pollution.

Development of groundwater resources in unconfined, shallow Canadian aquifers may have important consequences in terms of groundwater sustainability and vulnerability. Shallow, unconfined aquifers are generally hydraulically connected to surface water bodies and, thus, more likely to affect or be affected by these water bodies (in terms of baseflow or surface water pollution); alternatively, many of these shallow aquifers provide essential water needs for ecosystems (wetlands, riparian zones, fish, etc.; see Chapter 5). Development and effective management of shallow unconfined aquifers must consider long-term implications of water availability and water quality for all users.

2.5.1.1 Aquifer systems

Any "aquifer system," from the hydrogeological viewpoint, is a set of spatially and hydraulically interconnected stratigraphic units of different origins having the ability to store and transmit water. One excellent example of such a system is Alberta's Paskapoo aquifer system (Figure 10.20).

Figure 2.12 illustrates the effects of groundwater pumping in aquifers. Without pumping (Figure 2.12a), water recharge from the sandy area flows toward the deepest part of the aquifer, then rises locally to discharge close to a surface water body, or to the sea. When this state is disturbed by groundwater pumping (Figure 2.12b), both the piezometric level of deeper beds and the water table in upper sands descend; the hydraulic gradient between them increases and most flowpaths

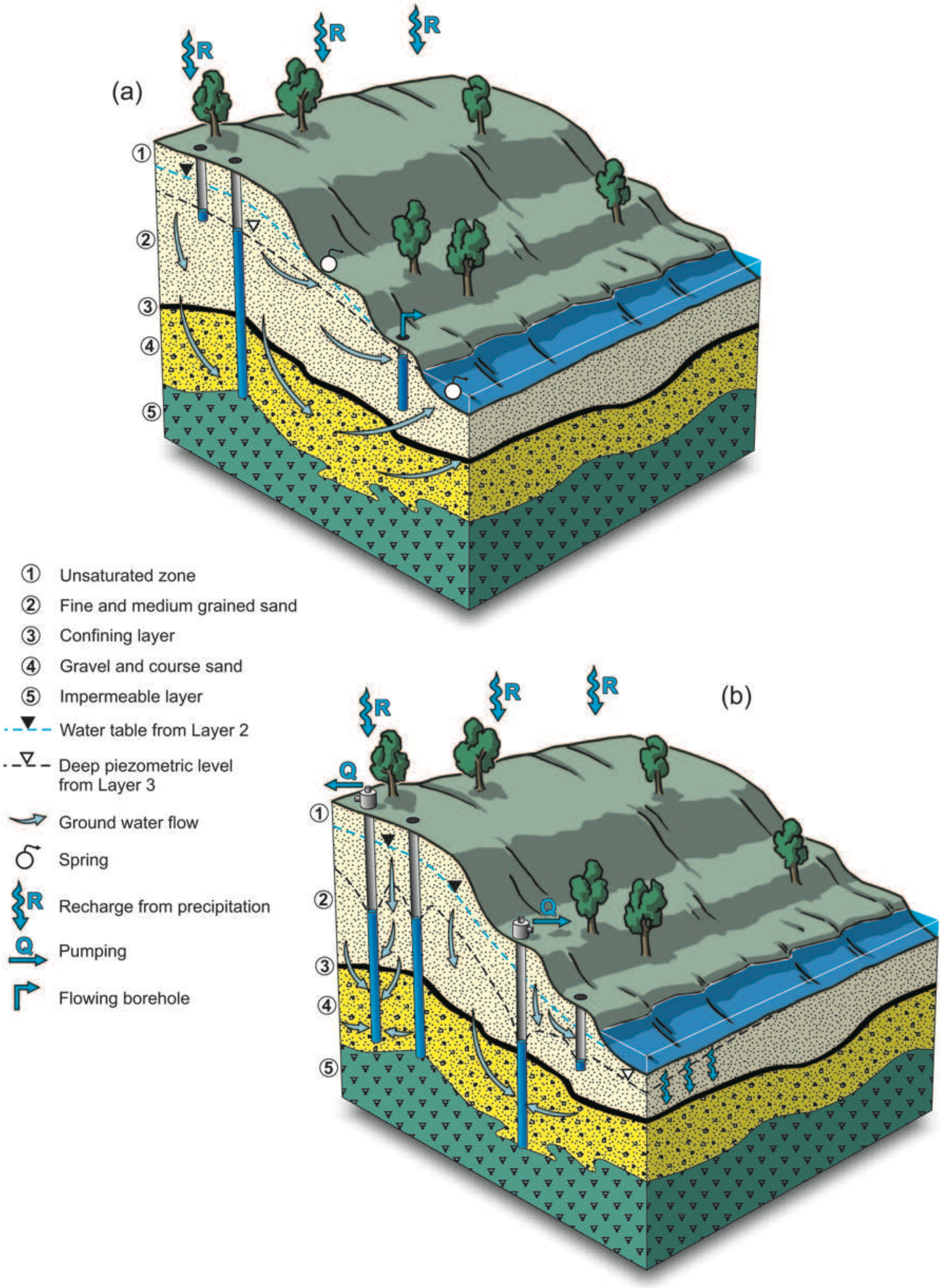


Figure 2.12 Simplified sketch, showing groundwater pumping effects: **(a)** without groundwater pumping; and **(b)** with groundwater pumping.

turn downward, decreasing natural discharge to surface water bodies.

Developed aquifers are defined as those aquifers within which wells have been constructed to utilize groundwater.

2.5.2 Aquitard characteristics

An aquitard is a zone within the earth that restricts the flow of groundwater from one aquifer to another. An aquitard, when completely impermeable, can sometimes be called an *aquiclude* or *aquifuge*. Aquitards comprise layers of either clay or non-porous rock with low hydraulic conductivity. Northern Canada's permafrost layers can also be considered as a type of aquitard.

An aquitard may behave as an impermeable layer relative to the much more permeable aquifer layers above or below it. An aquitard is impermeable and it will remain impermeable, although an aquitard layer may eventually contribute to groundwater flow through layers in the vertical direction. This process can be artificially induced through heavy pumping into an aquifer underlying an aquitard (causing aquitard leakage). Such activity can lead to consolidation, or to subsidence, a phenomenon which occurs in many parts of the world (e.g., Mexico City, Venice, Houston, California, etc.).

2.5.3 Groundwater storage in aquifers

What is groundwater storage? How is water put into and taken out of storage?

The storativity of a saturated confined aquifer can be defined as "the volume of water that an aquifer releases or takes into storage per unit surface area of aquifer per unit change in the component of hydraulic head normal to the surface". The specific storage coefficient for a saturated porous media was originally derived from purely hydraulic principles in soil mechanics (Jacob, 1950; Cooper, 1966; Lohman et al., 1972), and defined as:

$$S_s = \rho \, g \, n \, (\beta_l + \alpha/n) \qquad (2.5)$$

where S_s is the specific storage coefficient (1/m), n is the porosity, β_l is the coefficient of compressibility of the fluid (water, in Pa^{-1} or kg/m s^2), and α is the coefficient of compressibility of the porous matrix (Pa^{-1}). It is convenient to think of the specific storage coefficient in terms of the storage related to the elasticity of the water, as well as storage related to the elasticity of the porous medium.

The coefficient defined by Eq. 2.5 is not often used by hydrogeologists studying groundwater resources. Instead, these scientists more often employ the storage coefficient S, which is related to S_s by:

$$S = S_s \cdot b \qquad (2.6)$$

where b is the thickness of the aquifer and S is dimensionless. S can be estimated with long-term pumping tests using observation wells or boreholes. However, in the absence of pumping tests, which in most cases are very expensive to carry out, S_s can be easily calculated if the compressibility and the porosity of the material are known. Indeed, as β_l is very small ($5 \cdot 10^{-10}$ Pa^{-1}), it can be neglected with respect to the value of α (except in low-porosity hard rocks).

Typical values of compressibility for some common materials are given below:

Clays	10^{-6} to 10^{-8} Pa^{-1}
Sand	10^{-7} to 10^{-9} Pa^{-1}
Gravel	10^{-8} to 10^{-10} Pa^{-1}
Sandstone	10^{-9} to 10^{-11} Pa^{-1}

TABLE 2.4 SELECTED VALUES OF STORAGE AND SPECIFIC STORAGE COEFFICIENTS

AQUIFERS/ROCK TYPES/REFERENCE	SPECIFIC STORAGE COEFFICIENT (S_S) [1/M]	STORAGE COEFFICIENT (S)
Mirabel aquifer St. Lawrence Lowlands; fractured/porous aquifer (Nastev et al., 2005)	Not available	Bedrock = 5×10^{-5} to 4×10^{-3}
Chateauguay aquifer; fractured/porous aquifer (Lavigne et al., 2010)	Not available	5×10^{-5}
Bedrock aquifers in the Appalachians; fractured rock aquifer (Rivard et al., see Chapter 14)	Not available	Bedrock = 10^{-4} (averaged) Sediments= 1×10^{-2} (averaged); 10^{-4} and 0.5 (range)
Oak Ridges Moraine porous medium aquifer, sand, gravel, till	5×10^{-3} to 5×10^{-4}	~0.3
Assiniboine aquifer Manitoba porous medium aquifer, sand and gravel	Not available	6×10^{-4} to 1×10^{-3}
Alluvial gravels of old river channels in Old Crow, Yukon; located on an old floodplain of the Porcupine River (see Chapter 15 and Trimble et al., 1983)	Not available	1.52×10^{-3} to 3.62×10^{-3}

Some selected values of specific storage coefficients (Ss) and of storage coefficients (S) in Canada are provided in Table 2.4, although, these values are approximate numbers obtained, for the most part, from consultants' reports or from pumping tests performed by the Geological Survey of Canada; their interpretation is often difficult and their values questionable. The lack of accurate storage coefficients is an important data gap throughout Canada, and one that hinders estimates and simulation of transient conditions in most aquifers.

2.6 PRINCIPLES OF REGIONAL GROUNDWATER FLOW

A groundwater flow system is a three-dimensional entity having the following components:

- a recharge area where water enters the flow system
- a discharge area where water exits the flow system
- hydraulic boundary conditions and physical dimensions

In addition to these features, groundwater flow is highly dependent on temporal and spatial scales.

2.6.1 Recharge

Recharge refers to water entering a groundwater system regardless of scale. Areas where recharge occurs are designated as *recharge areas* or *recharge zones*. There are several mechanisms through which recharge enters a flow system: these can include direct infiltration of precipitation, or by infiltration through streambeds or reservoirs (see Chapters 4 and 5). In some parts of the world, especially arid regions, infiltration of storm runoff through intermittent stream beds is the dominant recharge form. Water can also enter a groundwater flow system through inter-layered flow, or interformational flow, usually in the form of flow through leaky confining layers (see aquitards) where water is drawn in by drawdowns at wells, or where underlying aquifers have significant overpressure and water is forced upward.

Most research studies and numerical models

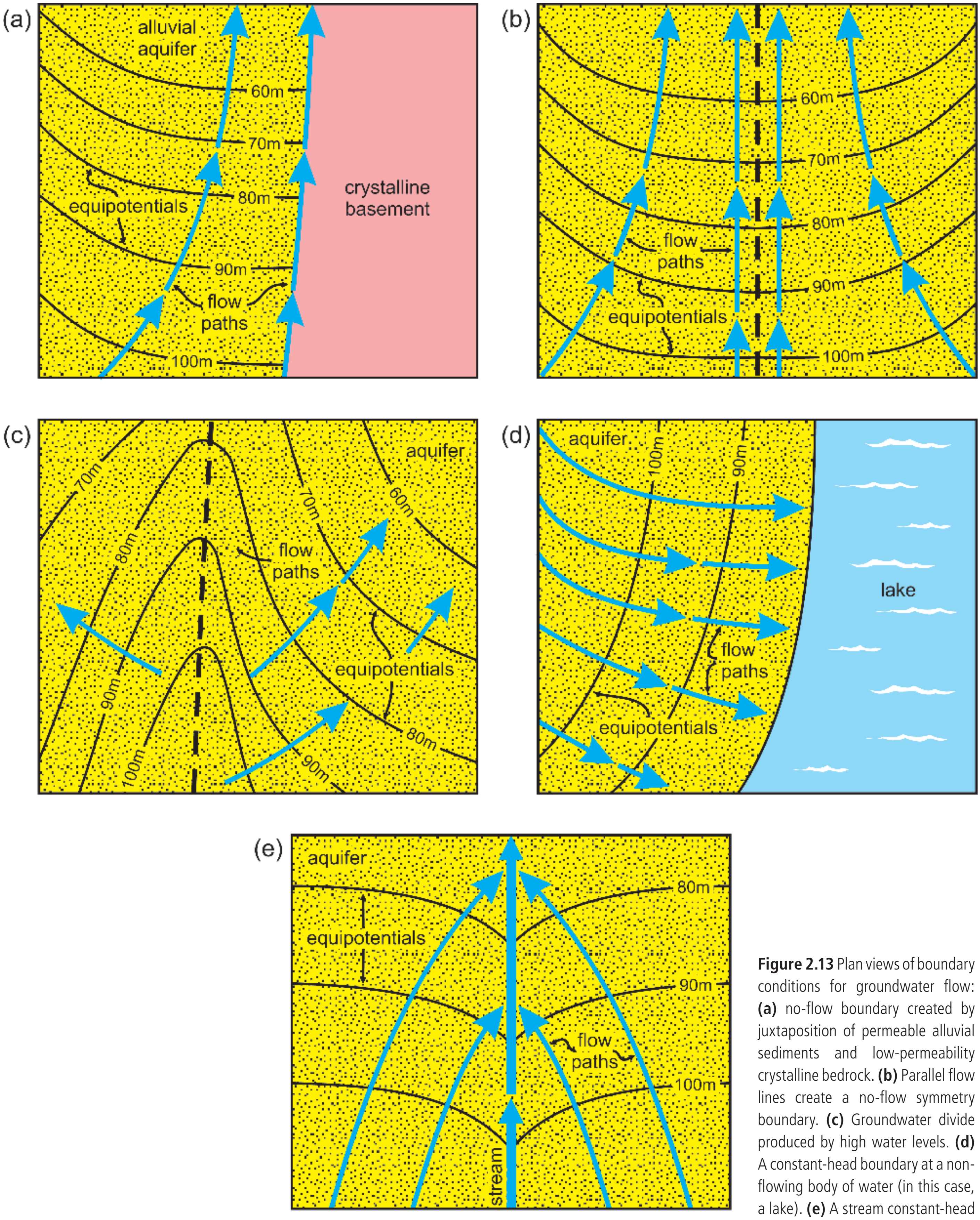


Figure 2.13 Plan views of boundary conditions for groundwater flow: **(a)** no-flow boundary created by juxtaposition of permeable alluvial sediments and low-permeability crystalline bedrock. **(b)** Parallel flow lines create a no-flow symmetry boundary. **(c)** Groundwater divide produced by high water levels. **(d)** A constant-head boundary at a non-flowing body of water (in this case, a lake). **(e)** A stream constant-head boundary.

Rates of groundwater turnover vary from years to millennia, depending on aquifer location, type, depth, properties, and connectivity.

consider recharge as some percentage of precipitation. These percentages have a wide range depending on the climate of the region and the geological and hydraulic characteristics of the aquifer. Chapter 4 provides a very detailed analysis of these. In Canada, recharge rates have a very large geographical distribution, varying from 7% of annual precipitation rates up to 65% in some specific locations (BC) (see Figures 4.3 and 4.5, and Table 4.2).

Recharge rates are difficult to quantify; many methods involve measuring precipitation and performing a water balance by quantifying all the other surface water fluxes (surface runoff, evaporation, transpiration).

2.6.2 Discharge

There are several mechanisms through which water discharges from a groundwater flow system. These include discrete discharge to a spring or seep, discharge into a gaining stream or lake, flow through formations, or pumping from a well. In some arid and semiarid regions (the Canadian Prairies, for example), direct evaporation and/or evapotranspiration from the shallow water table is the primary discharge mechanism.

Discharge can also be hard to quantify, especially in areas dominated by well pumping or evaporation. Discharge flow through formations (multilayered systems) is usually much less than that of other mechanisms. Flow through springs and gaining streams can be measured, and changes in flow across a certain areas attributed to either recharge or discharge. Chapter 4 provides detailed explanations of these mechanisms. Chapter 5 describes discharge mechanisms through riverbeds and other surface water bodies.

2.6.3 Boundary conditions

Groundwater flow systems are three-dimensional bodies with boundaries. There are two types of basic boundaries, or *boundary conditions*, which characterize the limits of groundwater flow systems at any scale: *no-flow boundaries* and *constant-head boundaries*.

A *no-flow* boundary has a hydraulic gradient of zero, expressed as $dh/dxi=0$ (where h is the hydraulic head and xi the flow directions), therefore no flow occurs across boundaries. No-flow boundaries can be physical when permeable aquifer units are in contact with low-permeability bedrock (Figure 2.13a). A no-flow boundary can also exist when flow lines are parallel, creating a *symmetry boundary* (Figure 2.13b). Modellers often use symmetry boundaries to constrain numerical groundwater models of aquifers. On a smaller scale, high water levels can create a type of no-flow boundary known as a **groundwater divide** (Figure 2.13c) wherein water flows away from the partition on either side (similar to surface runoff at a drainage divide).

A **constant-head boundary** is characterized by hydraulic heads that do not change. Non-flowing bodies of water, such as lakes, ponds, or oceans, can create a constant-head boundary (Figure 2.13d) as, in each case, the shore of the body represents a single equipotential line (or line of constant head) in the aquifer: water flow is perpendicular to the shoreline (either into the aquifer from the surface body or vice versa). A stream can also act as a constant-head boundary (Figure 2.13e); although the actual heads will vary along the stream gradient, each point is considered constant and represents a point on an equipotential.

2.6.4 Issues of scale: Time and space

Groundwater is often misinterpreted because of the lack of knowledge of time and space scales associated with the response of groundwater flow to natural and anthropogenic stresses.

Groundwater flow systems occur at different scales both in space and in time. Hydrogeologists distinguish three spatial scales and two temporal scales (Rivera, 2008).

Spatial scales are identified as: (a) regional (greater than 1,000 km^2; found usually under steady-state conditions), (b) local (typically hundreds of square kilometres; found both in steady-state and transient conditions), and (c) site (generally less than 100 km^2; typically found under transient conditions).

Temporal scales refer to (a) steady-state conditions of hydrodynamic equilibrium, and (b) transient conditions in which the system is under stress (by pumping).

Although absolute areas for each spatial scale are somewhat arbitrary, they do indicate important differences in Canadian aquifers (Rivera, 2005). Figure 2.14 is a schematic representation of these scales. In general, aquifers are heterogeneous in nature, and their hydraulic/hydrogeological behaviour (flow rates, flow volumes, mass and heat transport) is partially dictated by this heterogeneity. Site-scale shallow aquifers demonstrate a relatively rapid response to applied stresses; the effect of these stresses is limited in time and in space, from hundreds of metres to a few kilometres, and from tens of days to hundreds of days. Aquifers at local to regional scales have a much broader and longer-term response; the effects are spread out over tens of kilometres, and tens to hundreds of years. These space and time effects are even more striking when aquifer systems contain aquitards (relatively impermeable layers) (Figure 2.14), a situation not uncommon in Canada, as has been observed in the Prairies

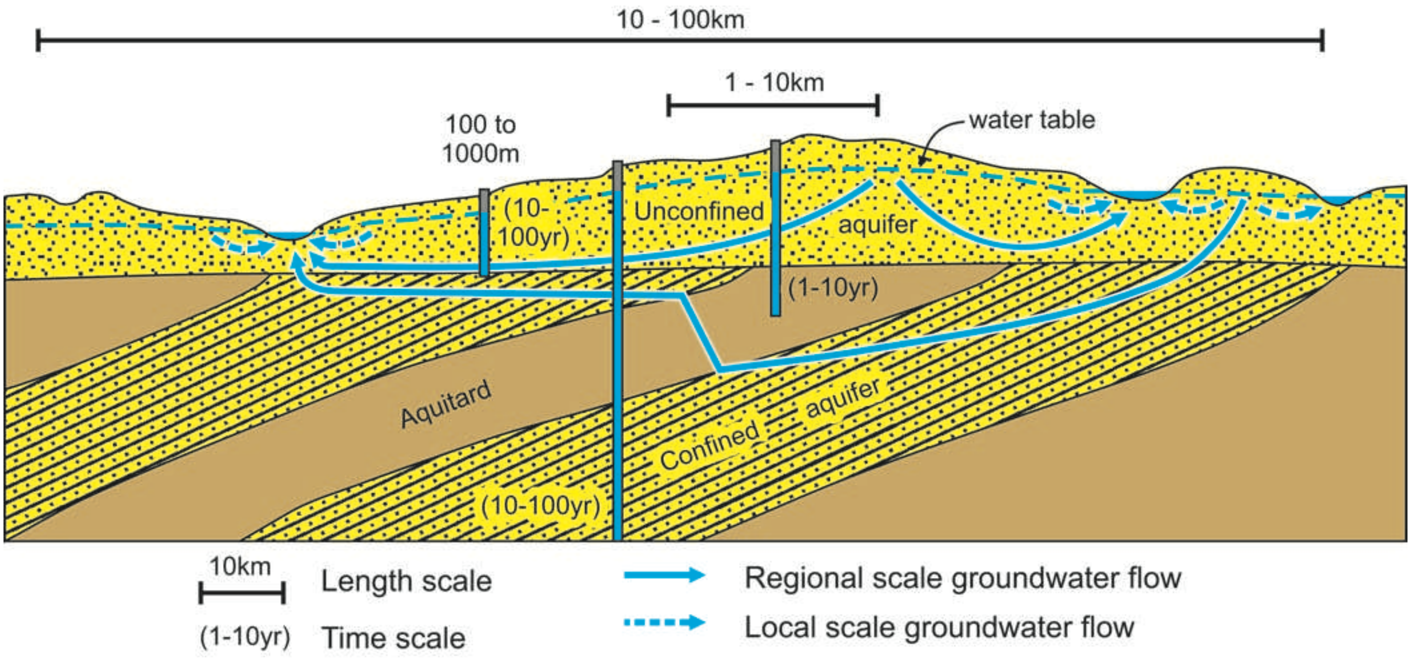


Figure 2.14 Schematic representation of space and time scales for groundwater (modified from Johnston, 1999).

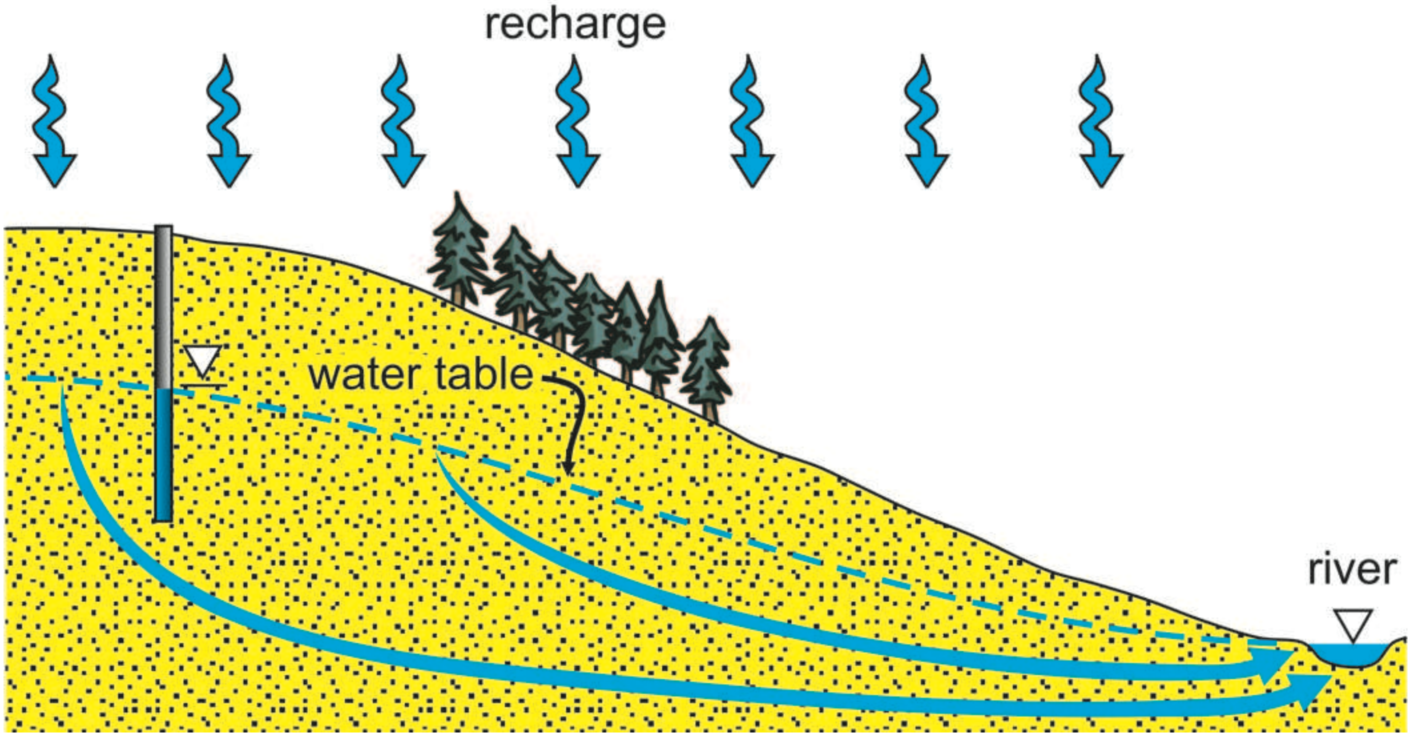


Figure 2.15 Cross section of a water-table aquifer showing the relationship between topography and the orientation of the water table.

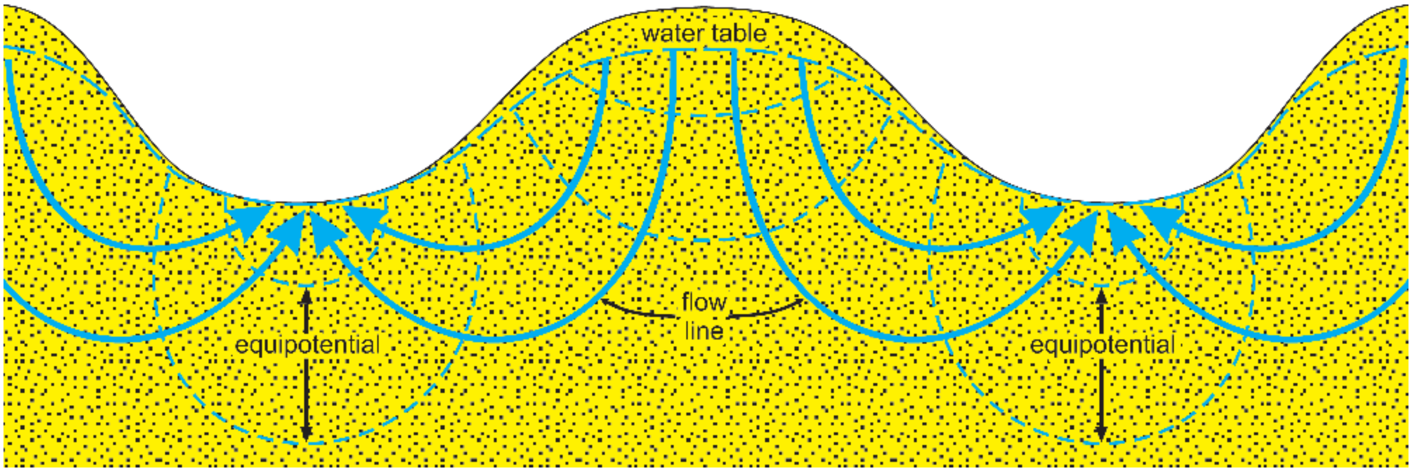


Figure 2.16 Flow patterns control by topography (after Hubbert, 1940).

(Maathuis and Thorleifson, 2000).

The scale issue is not trivial and cannot be ignored. One question a water resource manager or a community might ask is: "How quickly can we expect to detect a change in groundwater level during a drought?" or "Should nutrient source controls be implemented, how fast would we see a change in nitrate concentration of the aquifer?"

How rapidly an aquifer responds to change in hydraulic stress (increase or decrease in the amount of water input or increase in well pumping), or chemical stress (decrease in nitrogen loading) can be estimated by calculating an aquifer's *hydraulic* or *chemical response time*.

Hydrogeologists are able to calculate hydraulic response time once they know the key aquifer parameters and the relative permeability of adjacent rocks. If chemical reactions and transport parameters are known, the chemical response time can also be calculated.

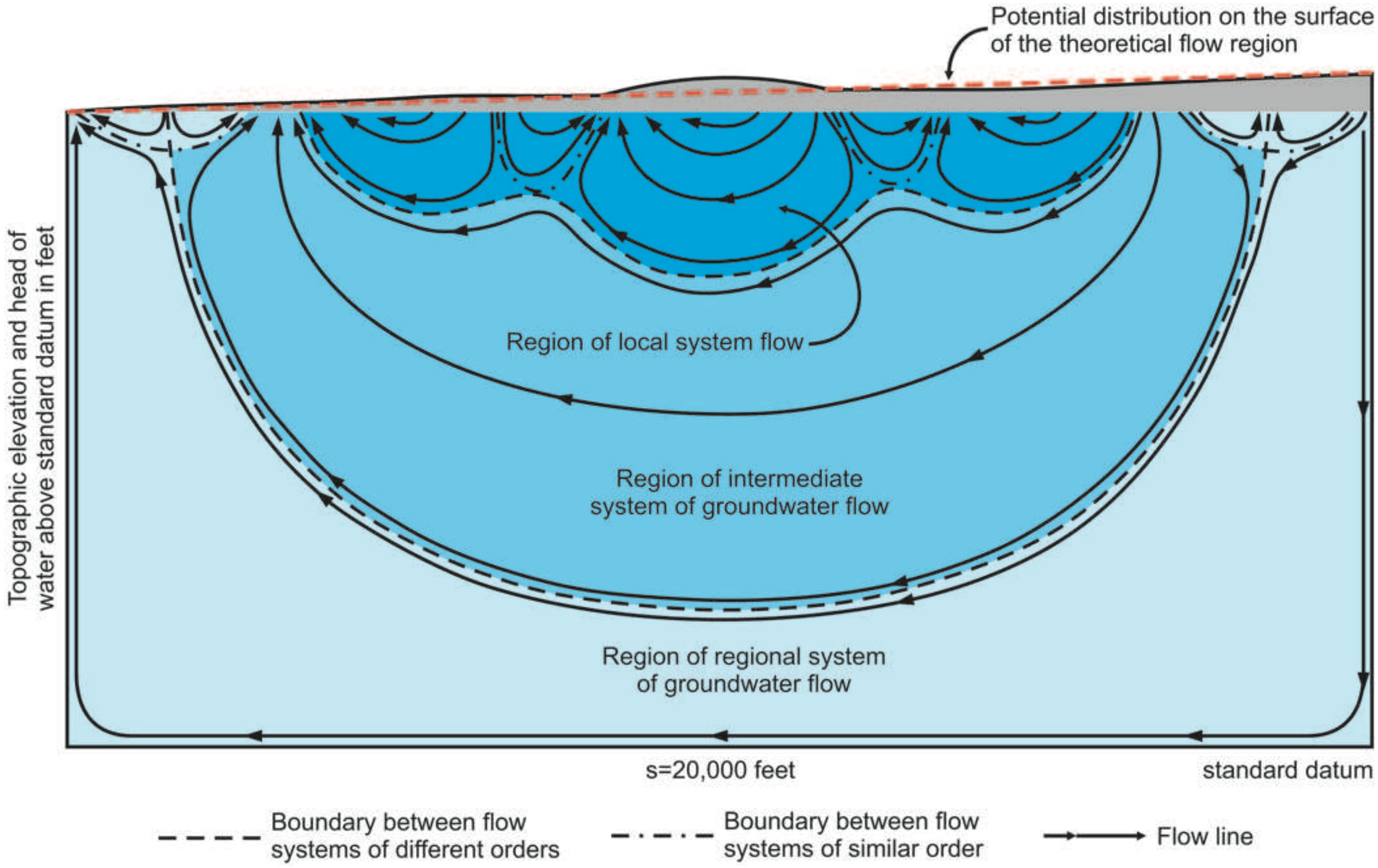


Figure 2.17 Hierarchically nested gravity-flow systems of groundwater in drainage basin with complex topography (after Tóth, 1962).

2.6.5 Gravity-driven groundwater flow

Scientists were aware of the relationship between topography and groundwater flow patterns in unconfined aquifers as early as the end of the 19th century. King (1899) and Hubbert (1940) noticed that any water table tends to become a subdued replica of its topography (Figure 2.15), while Hubbert (1940) suggested that topography can control groundwater flow patterns so that high elevations become recharge areas and low elevations discharge areas (Figure 2.16). Tóth (1962) and Freeze and Witherspoon (1967), working in the 20th century, developed computer models that simulated the effects of topography on groundwater flow systems: both of these simulations supported King's and Hubbert's conclusions. The models also illustrated the fact that sinusoidal topography can result in the formation of smaller local flow systems, with local recharge and discharge areas, within larger regional systems (Figure 2.17, after Tóth, 1962).

2.7 GROUNDWATER EXTRACTION AND WELLS

Developed aquifers are those aquifers wherein wells have been installed to utilize groundwater. Over the long term, a developed aquifer may function by inducing recharge from surface water sources and/or by decreasing discharge to streams and springs. The sum of these two flow components is sometimes termed as the "capture" (Bredehoeft et al., 1982); capture is dynamic, highly dependent on aquifer properties, space and time scales, and aquifer geometry. Any increase in aquifer inflow usually originates from three primary sources: 1) a rise in percolation due to irrigation surplus,

changed soil characteristics and decreased evapotranspiration; 2) induced recharge from surface water bodies; and 3) induced recharge from neighbouring aquifers or groundwater basins. A combination of conditions 2 and 3 may also happen at regional scales.

The initial lowering of the water table, or piezometric surface, sparked by pumping, ceases when capture and pumping stresses reach a new equilibrium. An extraction which may have initially appeared as "excessive" overdraft can later reveal itself to be sustainable, albeit with some loss of local surface water or aquifer discharge. Should groundwater pumping exceed available capture, therefore preventing an equilibrium, the difference will be drawn from storage, and groundwater levels will decrease (see more in Chapters 6 and 10).

In the preceding sections of this chapter, we have described the regional approach, or aquifer scale. Hydrogeologists and planning engineers must also consider the scale of pumping wells—what happens in the vicinity of an individual well and how to determine the **drawdown** produced in the well itself and in its vicinity?

A pumped aquifer may reach a new equilibrium within the expected time frame and hydraulic conditions described above, or it may not.

Consider the case of Saskatchewan's Estevan aquifer, a preglacial, buried-valley formation described in Box 10-2. In 2011, 17 years after pumping ceased, residual drawdown in the aquifer was still far from equilibrium, as shown by Maathuis and van der Kamp (2011). Thus, the

In this book, we examine wells only as input or output sources which affect the overall groundwater flow pattern of any aquifer. Actual well structure, drilling, completion techniques and sealing are not elements we have considered. Instead, we refer readers to specialized texts on these subjects (e.g., Johnson Inc., 1966; Campbell and Lehr, 1973)

combination of conditions 2 and 3, as described above, does not seem to include all equilibrium factors. In the case of the Estevan aquifer, the most likely explanation is that excessive groundwater continued to be removed from storage, dictating a much longer recovery time frame than would have been the case if conditions 2 and 3 (outlined above) had been rigorously applied.

Long-term analysis of well data indicates that sustainable yield for this type of aquifer can often be significantly less than originally expected (Maathuis and van der Kamp, 2011).

Hydrogeologists evaluating groundwater resources use terms like groundwater yield, well yield, aquifer yield, and more recently, sustainable yields. These concepts are important and applicable at several scales, and they are clear indicators of the main question hydrogeologists seek to discover: what are the maximum possible pumping rates compatible with the hydrogeological environment from which aquifer water will be taken? As scientists search for answers, they need to find a compatible compromise between the environment and groundwater availability; they must evaluate those groundwater yields in terms of balance between the benefits of pumpage and the undesirable changes such pumpage induces. The most common change pumping produces is a lowering of groundwater levels. Thus yield can be defined, in the simplest cases and at more local scales, as the maximum rate of allowable pumpage to ensure that water-level declines are kept within acceptable limits.

Chapter 6 provides a more detailed analysis of aquifer scale sustainability.

The hydraulics of pumping wells is in itself a vast domain, developed mostly from well pumping tests drilled in confined, leaky, and phreatic aquifers, under a myriad of conditions. The resulting literature is comprehensive, consisting of a large number of analytical equations designed to solve for groundwater flow to a well and to provide boundary values, which define aquifer parameters. Some of the most complete handbooks on this topic include Kruseman and de Ridder (1970), Ferris et al. (1962) and Walton (1970). Bear (1979) also provides an exhaustive summary of the mathematical treatment of pumping hydraulics and recharging wells.

What is the response of an aquifer to pumping, as measured by *aquifer yield*? This yield depends both on the manner in which the effects of withdrawal (pumping) are transmitted through the aquifer and on changes in groundwater recharge rates and discharge induced by withdrawals. Note that aquifer withdrawal is not only the result of pumping (anthropogenic conditions); it can also occur as a result of natural climate changes, for example, increase in evapotranspiration or decrease in river flow.

In its simplest, the transient hydrologic projection for any saturated portion of an aquifer can be described as

$$Q(t) = R(t) - D(t) + dS/dt \qquad (2.7)$$

where:

Q(t) = total rate of groundwater withdrawal

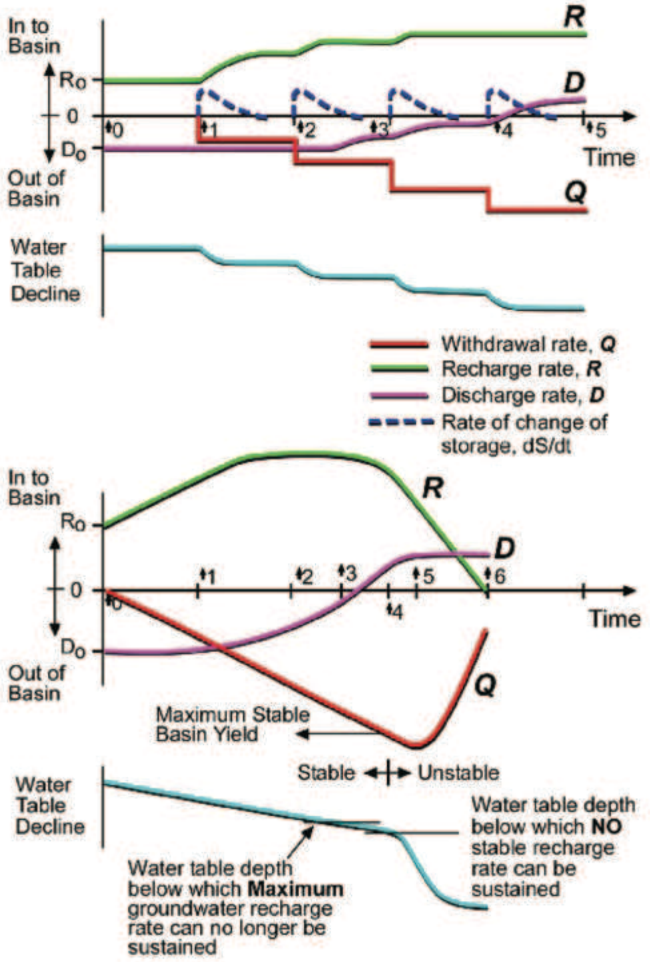


Figure 2.18 Relationship between pumping (Q), recharge (R), and discharge (D) in a basin (reproduced from Freeze, 1971).

R(t)= total rate of groundwater recharge to aquifer

D(t)= total rate of groundwater discharge from aquifer

dS/dt= rate of change in storage in the saturated zone of the aquifer

Freeze (1971) examined the response of R(t) and D(t) to an increase in Q(t), applying Eq. 2.7 to a hypothetical aquifer in a humid climate where the water table is located near the Earth's surface. He simulated the response using a three-dimensional transient analysis of a complete saturated-unsaturated system equipped with a pumping well.

Figure 2.18 (reproduced from Freeze, 1971), illustrates the hydraulic behaviour of an aquifer as a function of time as groundwater is pumped. These diagrams depict time-dependent changes, which might be expected as a result of Eq. 2.7 variables under increased pumpage. Groundwater pumping increase in a step-wise manner causes recharge increase in a subtly similar stepwise manner because the resultant signal impacts are spread over a large area, causing a stepwise discharge decrease.

The upper portion of Figure 2.18 initially depicts a steady-state condition at to wherein recharge Ro equals discharge Do. New wells begin to tap the system and the pumping rate Q undergoes a set of stepped increases. Each increase in an unconfined aquifer is initially balanced by a change in storage (dS/dt). Increases in Q translate to immediate water-table declines in this case (see also Figure 2.12). Forces within the aquifer move to find a new hydraulic equilibrium under conditions of increased recharge, R. After a certain pumping time (t5), Q is fed entirely by recharge and induced discharge, D, resulting in a significant water table decline. Steady-state equilibrium conditions are reached prior to each new increase in withdrawal rate (Q).

The lower portion of Figure 2.18 shows the same sequence of events under conditions of continuously increasing groundwater development (pumping) over several years. This schematic clearly illustrates that, when pumping rates increase indefinitely, an unstable situation may arise. The declining water table will reach a depth below which the maximum rate of groundwater recharge R can no longer be sustained. It is impossible for an aquifer to supply increased rates of withdrawals once the maximum available rate of induced discharge is attained. The only remaining groundwater source lies in an increased rate of storage withdrawal (dS/dt), which manifests itself in a rapidly decreasing water table, among other consequences.

One of the most well-known consequences of groundwater overexploitation is land subsidence. Many areas around the world are coping with problems of regional subsidence on a regional scale: some of the better-known examples have been documented in California's San Joaquin Valley, the Houston-Galveston area, Bangkok, Venice and Ravenna, and Mexico City (Rivera et al., 1991).

Groundwater pumping may, and often does, have an important impact on our environment, specifically in the form of water level reduction, baseflow decline, subsidence and saltwater intrusion. These issues, and other environmental concerns are described in more detail in Chapters 5 and 6.

2.8 INTERACTIONS WITH SURFACE WATER

The scientific community has long recognized that, within the water cycle, there are continuous dynamic interactions between surface water bodies (e.g., rivers, lakes, wetlands) and groundwater (aquifers). These occur at various spatial and temporal scales.

Clearly, surface water and groundwater should be considered and treated in an integrated way, despite their very different nature and scales. Very few scientists, however, let alone water resource managers, take this holistic approach; surface water resources are usually studied, and managed, without consideration of groundwater. Most water investment research funding in Canada is used to assess and develop surface water resources; much less is allocated to groundwater study.

Much of this funding discrepancy can be attributed to persistent knowledge gaps about the interaction between surface water and groundwater, although the physical processes and mathematics needed to assess surface water/groundwater interactions (SW-GW) are known and relatively well established. Scientists today couple basic hydraulics principles, hydrological processes and geology with equations describing groundwater flow (i.e., Darcy's Law) to assess these interactions. However, the application of theory is not straightforward, even when basic theoretical knowledge exists, due to complex interactions between groundwater and surface water.

> Shallow groundwater flow systems should be distinguished from deep groundwater flow systems; the former interact with surface water, the latter do not.

A sound hydrogeological framework is needed to understand these interactions in relation to climate, landforms, geology, hydrology and biotic factors. It is the lack of such a framework that represents the main knowledge gap in Canada.

Studies of SW-GW interactions have expanded in recent years (Sophocleous, 2002) to include studies of headwater streams, lakes, wetlands, and estuaries. Those countries with limited water resources have widened their SW-GW research scope to include conjunctive use of surface water and groundwater in water management practices. A major factor in modern-day SW-GW research is the introduction of comprehensive conceptualizations of SW-GW interactions involving teams of geologists, hydrogeologists, hydrologists and ecologists.

Research needs and challenges facing this evolving field are linked components of a hydrological continuum leading to related water sustainability issues:

- Current frontiers in SW-GW interactions seem to be near-channel and in-channel exchange of water solutes and energy. Understanding these processes is key to evaluating the ecological structure of stream systems and their management (Sophocleous, 2002)

- Analysis over time of sediment and reach scales within the hyporheic zone (that thin layer beneath the river bed) remains unclear at present, and can be neglected when dealing with regional-scale integrated water resources (water quantity). For detailed biochemical analysis and transport, however, this layer is very significant and must be considered in any detailed biochemical and transport investigation
- SW-GW should not be estimated but measured
- The use of heat, chemical tracers, and age dating should be studied, and the results integrated into numerical models
- Groundwater-level measurements should continue and be increased. When and where possible, these measurements should be taken in real-time, especially in shallow, sensitive aquifers. The resultant figures should be analyzed at the basin-scale and in association with river hydrographs

Chapter 5 presents a more comprehensive analysis of surface water and groundwater interactions and related issues pertaining to Canadian conditions of use, dynamics and occurrence.

2.8.1 Differences in flows between surface water and groundwater

When we consider groundwater in terms of flowpaths and fate, there are two classifications: shallow groundwater flow and deep groundwater flow. Shallow groundwater flow, termed as groundwater *runoff* by some scientists, intercepts the land surface, feeding springs which seep back to surface waters as the perennial flow (or baseflow) of streams/rivers and other freshwater bodies (swamps, wetlands and lakes, for example). Deep groundwater flow, or groundwater *runout*, on the other hand, does not intercept the land surface; instead, it flows directly, albeit very slowly, into the Earth's oceans. The source of shallow groundwater flow is shallow percolation (or shallow groundwater infiltration). On a global basis, deeper groundwater infiltration accounts for an average of 13% of the Earth's precipitation, while the amount of shallow percolation is equal to the annual amount of baseflow discharging into the world's streams and rivers. Since baseflow constitutes about 30% of streamflow (or runoff) and streamflow is on average about 24% of precipitation, it follows that baseflow or shallow percolation constitutes $(0.30 \times 0.24) \times 100 = 7.2\%$ of precipitation.

Chapter 5 describes groundwater extraction and its influence on surface water bodies (rivers, lakes, wetlands) in greater detail.

2.9 GROUNDWATER QUALITY (NATURAL AND CONTAMINATED)

2.9.1 Natural quality

Water, in nature, is never "pure". It picks up small amounts of everything with which it comes into contact, including minerals, silt, vegetation, fertilizers, and agricultural runoff. Canada's diverse physical geography (from coastal regions to mountains from prairies, to northern tundra and the Canadian Shield) means that the characteristics of its natural water will vary greatly across the country, and, even in relatively pristine areas, will usually requires some type of treatment before it is safe to drink.

Canada's drinking water comes either from groundwater (wells in aquifers), or from surface waters (lakes and rivers). Most Canadians get their drinking water from public water systems which must meet quality requirements set by provincial and territorial governments. People living in rural and remote areas may get their drinking water from wells, or from surface water sources located on private property. These consumers are individually responsible for the safety of their drinking water.

68.7% of all of the Earth's fresh water is permanently stored in icecaps and glaciers, 30.1% is groundwater, 0.3% is surface water, and 0.9% is other minor storage (soil water, plants) (Figure 2.1). Further, an analysis of available fresh water on the planet shows that groundwater is about one hundred times more plentiful than surface water, although surface water is typically low in salt ions. Groundwater, however, particularly that lying at great depth, may contain high concentrations of salt ions, significantly limiting its use as natural drinking water.

The natural quality of groundwater has important implications for its use and sustainable development.

Water quality is assessed by measuring the amounts of its various constituents; these are often expressed as milligrams of substance per litre of water (mg/L) (which is equivalent to the number of grams of a substance per million grams of water).

The natural quality of groundwater differs from that of surface water because (a) groundwater quality, temperature and other parameters, for any given source, are less variable over the course of time; and (b) the range of groundwater parameters encountered is much greater than that for surface water. TDS (total dissolved solids[2]) in groundwater can range from 25 mg/L within some areas within the Canadian Shield to 300,000 mg/L in the deep saline waters of the Interior Plains.

Deep groundwater infiltration, by definition, does not belong to the surface water catchment area and, therefore, it cannot affect its quantity.

Groundwater tends to be harder and more saline than surface water, when the two are compared, at any given location, although this is by no means a universal rule. Another generality is the fact that groundwater becomes more saline with increasing depth, although, again, there are many exceptions to this rule.

The salinity of fresh water is less than 500 mg/L, while the salinity of ocean water is about 35,000 mg/L. Definitions of water salinity vary within the literature. For example,

- Brackish water is defined as having a TDS concentration ranging from 1,000 to 10,000 mg/L; saline water from 10,000 mg/L to 100,000 mg/L, and brine as >100,000 mg/L (Freeze and Cherry, 1979; Fetter, 1993).
- Hem (1970) defines moderately saline water as ranging from 3,000 mg/L to 10,000 mg/L.

Slightly saline water, an example of which might be irrigation water, has concentrations from 500 to 1,500 mg/L. Moderately saline water, such as drainage water, ranges from 1,500 to 5,000 mg/L, while highly saline groundwater may have salinity concentrations in excess of 10,000 mg/L. Groundwater is considered "saline" with concentrations in excess of 10,000 parts per million (mg/L).

Saline groundwater depth in the United States varies from less than 150 metres to more than 300 metres (Alley, 2003). Saline groundwater in Canada may be found at various depths depending on the "saline" definition. In Alberta, for example, saline groundwater is defined as water with a TDS concentration exceeding 4,000 mg/L (this

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[2] Total Dissolved Solids (TDS) concentrations are comprised of dissolved inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonate, chloride and sulphate) and small amounts of organic matter.

TABLE 2.5 MAXIMUM ACCEPTABLE CONCENTRATIONS (MAC) IN GROUNDWATER IN CANADA (HEALTH CANADA, 2010)

PARAMETER	MAXIMUM ACCEPTABLE CONCENTRATION (MAC)
BACTERIOLOGICAL	
Escherichia Coli	0 per 100 mL
Total coliforms	0 per 100 mL
Heterotrophic plate count	No numerical guideline required
Emerging pathogens	No numerical guideline required
Protozoa	No numerical guideline required
Enteric viruses	No numerical guideline required
Turbidity	0.3/1.0/0.1 NTU
CHEMICAL AND PHYSICAL PARAMETERS	
Aluminum	0.1/0.2 (mg/L)
Ammonia	No numerical guideline required
Antimony	0.006 (mg/L)
Arsenic	0.010 (mg/L)
Asbestos	No numerical guideline required
Benzene	0.005 (mg/L)
Bromate	0.01 (mg/L)
Chlorate	1.0 (mg/L)
Chlorine	No numerical guideline required
Chloride	≤250 (mg/L)
Chlorite	1.0 (mg/L)
Cyanobacterial toxins--microcystin-LR	0.0015 (mg/L)
Fluoride	1.5 (mg/L)
Formaldehyde	No numerical guideline required
Haloacetic Acids--Total (HAAs)	0.080 (mg/L)
Hardness	No numerical guideline required
Iron	≤0.03 (mg/L)
Lead	0.01 (mg/L)
Magnesium	No numerical guideline required
Manganese	≤0.05 (mg/L)
Mercury	0.001 (mg/L)
2-Methyl-4-chlorophenoxyacetic acid (MCPA)	0.1 (mg/L)
Methyl *tertiary*-butyl ether (MTBE)	0.015 (mg/L)
Nitrate	45 (mg/L)
pH	6.5-8.5
Silver	No numerical guideline required
Sodium	≤200 (mg/L)
Sulphate	≤500 (mg/L)
Sulphide (as H_2S)	≤0.05 (mg/L)
Trichloroethylene (TCE)	0.005 (mg/L)
Trihalomethanes--Total (THMs)	0.100 (mg/L)
Uranium	0.02 (mg/L)
RADIOLOGICAL PARAMETERS	
Cesium-137 (^{137}Cs)	10 Bq/L
Iodine-131 (^{131}I)	6 Bq/L
Lead-210 (^{210}Pb)	0.2 Bq/L
Radium-226 (^{226}Ra)	0.5 Bq/L
Strontium-90 (^{90}Sr)	5 Bq/L
Tritium (^{3}H)	7,000 Bq/L

definition was developed to distinguish between saline and non-saline water use, largely as it related to agricultural purposes and crop tolerances, e. g., irrigation). Saline groundwater depth varies from 300 metres to 500 metres. Saline waters in other Prairie Provinces (Saskatchewan, for example) can contain over 300,000 mg/L at a depth of 600 metres (Grasby and Chen, 2005).

Water suitability for specific uses also depends on a variety of other factors including hardness, pH, and naturally occurring chemical elements or compounds found within the water (e.g. sodium, sulphate, etc.). Acceptable values for each of these parameters depend on the end water use, not on the source; thus those considerations important for surface water are equally applicable to groundwater.

The chemical nature of water continually evolves as it moves through the hydrologic cycle. Chemical constituents found in any groundwater sample depend, in part, on the chemistry of the related precipitation and recharge water. Precipitation near coastlines contains higher concentrations of sodium chloride, while airborne sulphur and nitrogen compounds, downwind of industrial areas, make precipitation in those areas acidic.

One of the most important natural changes in groundwater chemistry occurs in the soil, which contains high concentrations of carbon dioxide readily dissolvable in groundwater, creating a weak acid capable, in turn, of dissolving many silicate minerals. As groundwater passes from recharge to discharge area, it may absorb and dissolve those substances it encounters, or it may deposit some of those constituents along the way. The eventual groundwater quality depends on temperature and pressure conditions, on the kinds of rock and soil formations through which the water flows, and possibly on the residence time. In general, faster flowing water dissolves less material although groundwater carries with it any soluble contaminants with which it comes in contact.

2.9.2 Quality standards

In general we evaluate groundwater quality in relation to its end use.

Most of us think of water quality as a matter of taste, clarity and odour, and those additional terms which determine whether water is potable or not. Different properties, however, may be important when water is used for other purposes, and most of these properties depend on the types of substances dissolved or suspended in the water. Water for many industrial purposes need not be as pure as water used for drinking, but it must not

Arsenic (As) occurs naturally in Canada, although its concentration is generally below the recommended standard for drinking water (0.01 mg/L), and, in most cases below detection limits. Environment Canada has reported arsenic values less than 6 µg/L, and there are cases where As concentration is above the drinking standards (in Nova Scotia, for example, due to weathering of mining waste piles containing arsenopyrite). These instances are not of "natural occurrence," rather, they represent anthropogenic (human activity related) sources. This type of dissolved metal (As) contamination exists across Canada, sometimes in high concentrations (considered as point-source contaminates, because they travel via groundwater flow only tens and in some case hundreds of metres, but not kilometres, from mine waste sites; should these contaminates reach rivers or streams, however, they can easily travel hundreds of kilometres and more).

Health Canada reports of the highest concentrations of arsenic (and its inorganic compounds) within the Canadian environment occur near active and abandoned gold- and base-metal mining and/or ore processing facilities, as well as in those areas affected by the use of arsenical pesticides. Mean arsenic concentrations of up to 45 µg/L in surface waters, 100 to 5,000 mg/kg in sediments and 50 to 110 mg/kg in soils have been found near such sources in many areas throughout the country.

be corrosive and must not contain dissolved solids that might precipitate on the surfaces of machinery and equipment.

In Canada, all levels of government play a role making sure our water supplies are safe. Although provincial and territorial governments are generally in charge of protecting our water supply, the federal government also has a number of responsibilities in this area.

Groundwater quality is managed in part by the provinces and territories through

- Regulation of waste discharges to the ground
- Remediation of contaminated sites
- Regulation of drinking water sources
- Watershed planning and source protection measures
- Wellhead protection initiatives
- Application of best management practices
- Water quality standards and guidelines

The Federal Department of Health Canada works with the provincial and territorial governments to develop guidelines that set up the maximum acceptable concentrations of various substances in drinking water. The guidelines set out the basic parameters that every water system should strive to achieve in order to provide the cleanest, safest and most reliable drinking water possible.

Guidelines for Canadian Drinking Water Quality, published by Health Canada on behalf of the Federal-Provincial-Territorial Committee on Drinking Water (CDW), examines microbiological, chemical and radiological water contaminants, in addition to addressing concerns with physical characteristics, such as taste and odour.

These guidelines are updated regularly and published on Health Canada's website (www.healthcanada.gc.ca/waterquality). Table 2.5 provides a summary list of current numerical guidelines for microbiological, chemical and physical parameters.

According to Health Canada, quality standards specify (a) maximum acceptable concentration (MAC) of pollutants in groundwater which can be tolerated without creating a threat to human health, (b) aesthetic objectives (AO), an excess of which renders groundwater unsuitable for use as a drinking water source, and (c) operational considerations, listed as Operational Guidance Values (OG).

Trace metals (Ag, Cd, Cr, Cu, Hg, Fe, Mn, Zn) found in natural flowing groundwater rarely occur at concentrations high enough to comprise a significant percentage of the TDS; however, depending on the source and hydrochemical environment, some of the elements in this group (referred to as *heavy metals)* may have concentration above the limits specified in drinking water standards. Nevertheless, with the exception of iron, trace metals in natural groundwater almost invariably occur at concentration well below 1 mg/L.

Some elements, on the other hand, those known as *trace nonmetals* (including, for example, dissolved forms of chlorine and sulphur), occur in abundance in most natural and contaminated groundwater.

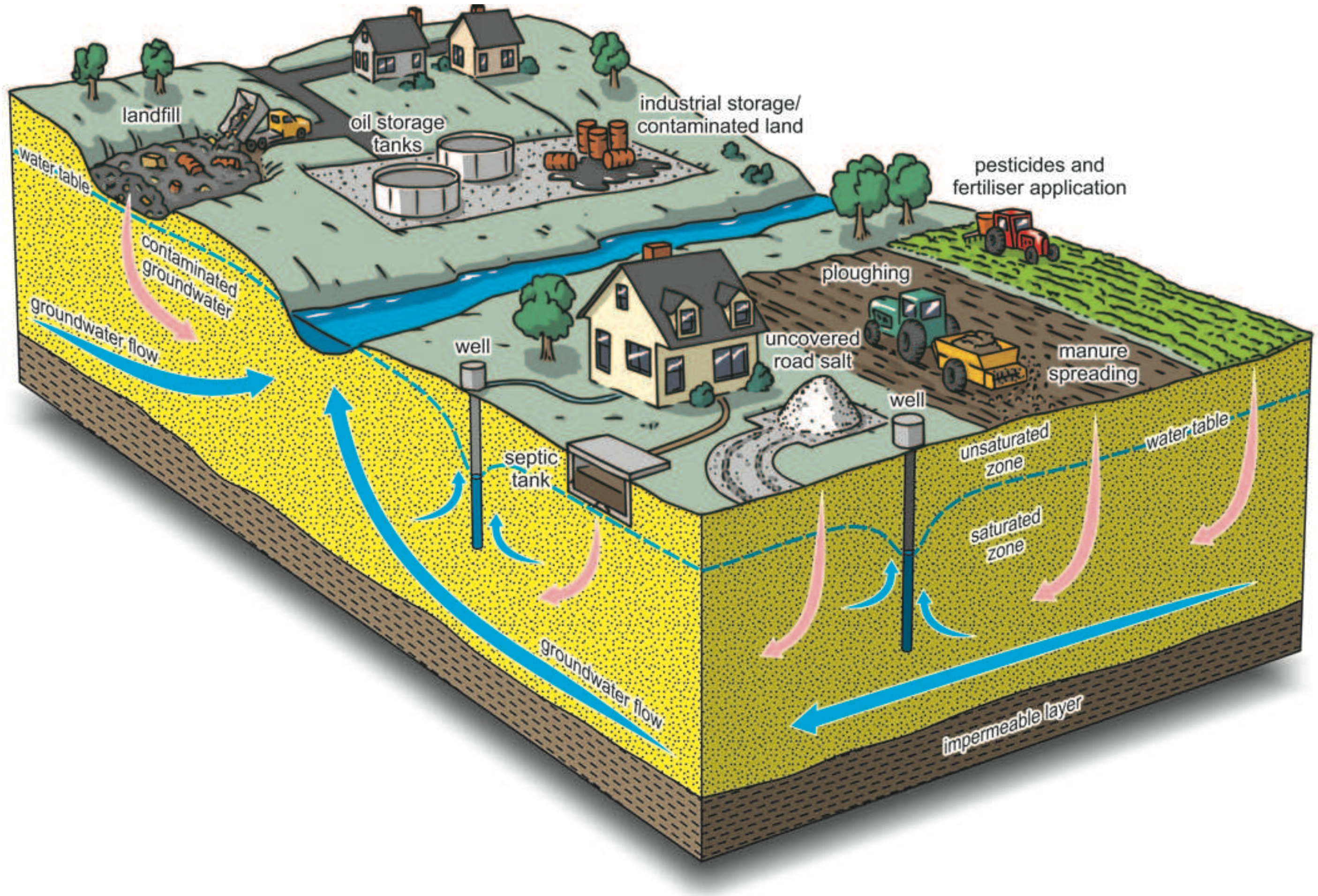


Figure 2.19 Groundwater contaminations from waste disposal sites.

2.9.3 Contaminated groundwater

Any human-activity-caused addition of undesirable substances to groundwater is considered contamination, and, although many people throughout history have assumed that contaminants left on or under the ground will remain there, this premise has proved a prime example of wishful thinking. Groundwater frequently spreads the effects of dumps and spills far beyond the original contamination sites; the resultant damage is extremely difficult, very costly, and sometimes impossible, to clean up.

Groundwater contaminants originate from two source categories: point sources and distributed, or non-point, sources.

Landfills, leaking gasoline storage tanks, leaking septic tanks, and other accidental spills are point source examples. Other point sources are individually less significant, but occur in large numbers all across the country. Examples of these dangerous and widespread contamination sources are septic tanks, cesspool leaks and spills of petroleum products and of dense industrial organic liquids.

Infiltration from farm land treated with pesticides and fertilizers is one example of a non-point source; others include municipal landfills and industrial waste disposal sites. When any of these occurs in or near a sand and/or gravel aquifer, the potential for widespread contamination is enormous (see Figure 2.19).

Septic systems are designed to degrade (or break down) a certain percentage of waste sewage within the septic tank proper, while dispersing the remaining sewage for absorption and breakdown into the surrounding sand and subsoil. Contaminants known to enter groundwater from septic and cesspool systems include bacteria, viruses, nitrates, detergents, and household cleaners. These can all create serious contamination problems, and, despite the fact that septic tanks are known contaminant sources, they usually are poorly monitored and very little studied.

Contamination often renders groundwater unsuitable for use, although the overall extent of the problem across the country is unknown. There are, however, many individually documented high profile contamination in Canada, including Ville Mercier (Quebec, see Box 13-3, chapter 13), Nova Scotia's highway deicing salt problem, the industrial effluents runoff in Elmira (Ontario), various pesticide infiltrations in the Prairie provinces, and industrial contamination in Vancouver, to name a few. In most of these, the contamination was identified only after groundwater users had been exposed to potential health risks.

Canada's groundwater contamination problems are increasing because of the large number of toxic compounds used in our industry and agriculture. This usage is increasing rapidly. Scientists suspect that many rural Canadian household wells are contaminated by substances from such common sources as septic systems, underground tanks, used motor oil, road salt, fertilizer, pesticides, and livestock wastes. Scientists also predict that, within the next few decades, more contaminated aquifers will be discovered, new contaminants will be identified, and more contaminated groundwater will be discharged into wetlands, streams and lakes.

Once an aquifer is contaminated, it is often unusable for decades. The response time, as noted in Section 2.6, can be anywhere from two weeks to hundreds or even thousands of years.

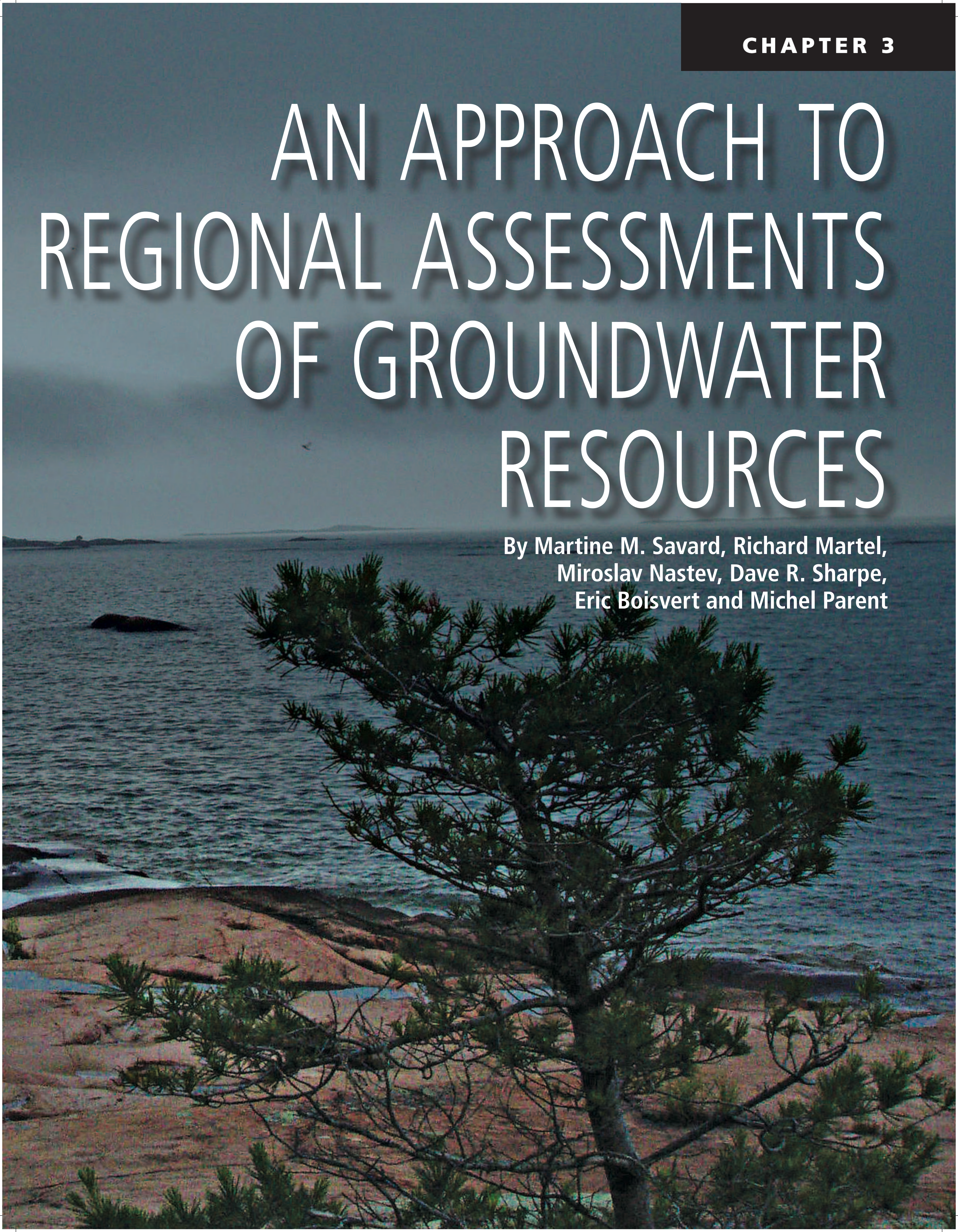
The effects of groundwater contamination do not end with the loss of well-water supply. Several studies have documented the migration of contaminants from disposal or spill sites to nearby lakes and rivers as the tainted groundwater passes through the hydrologic cycle; scientific opinion remains inconclusive at this time because these processes are not yet well understood.

Pollution of surface water by groundwater in Canada is probably at least as serious as contamination of the groundwater supply. The most practical solution to this problem is the prevention of contamination in the first place, which can be implemented through the adoption of effective groundwater management practices by all levels of government, by industry and by all Canadians. Current progress in this direction is hampered by a serious shortage of groundwater experts and a general lack of public knowledge about how groundwater behaves.

Some provinces have begun adopting a multi-barrier approach to safe drinking water; and understanding and meeting the guidelines described above is a very important component of this approach.

The most effective way to ensure our drinking water supply is clean, safe and reliable is to take a preventive risk management approach, herein we understand each water supply from its natural beginning to its final destination, the consumer. This approach presupposes knowledge of the water's characteristics, potential methods of contamination, and the type of treatment the water may require to become suitable for public use. Answers to all of these issues can be determined, and corrective procedures implemented through the collection and study of the drinking water supply and its three components: source water, the drinking water treatment system, and the water distribution system (which carries treated water to homes— the treated water inside every residence is an extension of this system—businesses, schools, and others).

As drinking water travels on its journey to the users, it can become contaminated in many ways. Thus, the multi-barrier approach to manage drinking water supplies is a preventive risk management approach that identifies all known and potential hazards and makes sure barriers are in place to reduce or eliminate the risk of contamination.



AN APPROACH TO REGIONAL ASSESSMENTS OF GROUNDWATER RESOURCES

By Martine M. Savard, Richard Martel,
Miroslav Nastev, Dave R. Sharpe,
Eric Boisvert and Michel Parent

3.1 REGIONAL AQUIFER SYSTEMS: HIDDEN AND SIZEABLE! HOW DO WE ASSESS THEM?

Canada's groundwater is an important water supply source for many urban areas and industries, in addition to being a vital supply for rural areas across the country.

The extent of Canadian groundwater reserves, however, is only partially understood, even as we do know that groundwater is a basic component of the hydrological cycle, forming the base flow to rivers and streams and sustaining water levels of lakes and wetlands (those shallow aquifer systems—less than 100 m—which represent reservoirs of easily extractable water, with much of excellent quality for potable use).

To date, there has been only limited mapping and quantification of our regional groundwater resources. The Canadian population continues to grow, requiring more and more fresh water. Surface water allocation limits have already been reached in parts of the country and future water demand will place a greater reliance on groundwater. Today's water requirements call for increasing abstraction of brackish to saline water in some areas, as climate change is modifying the hydrological cycle all over North America (IPCC, 2007). These facts raise several serious questions regarding the future of Canada's groundwater reserves. How much groundwater do we actually have? How much groundwater can be extracted annually in a sustainable manner? How will groundwater reserves be affected by stresses on the system (changing land use and climate change?)

Answers can only be drawn from quantitative assessments of Canada's aquifer systems. Generating of these assessments at local and regional scales, provide key information to create methodologies which will support sustainable groundwater use and groundwater resource protection.

This chapter presents an overview of these issues based on proven practices and techniques for systematic regional groundwater assessment.

Although groundwater is out of sight, properly conducted engineering and geoscientific investigations can identify and delineate it, characterize water quality and estimate groundwater availability. A multidisciplinary approach, one which combines geophysics, geology, hydrogeology, and information technology is recommended to produce new interpretations and understanding (Figure 3.1).

Such methodology has already been used in assessing fourteen regional aquifer systems within the provincial-federal coordinated Canadian framework (Rivera et al., 2003). Such investigations usually cover large areas ranging from tens

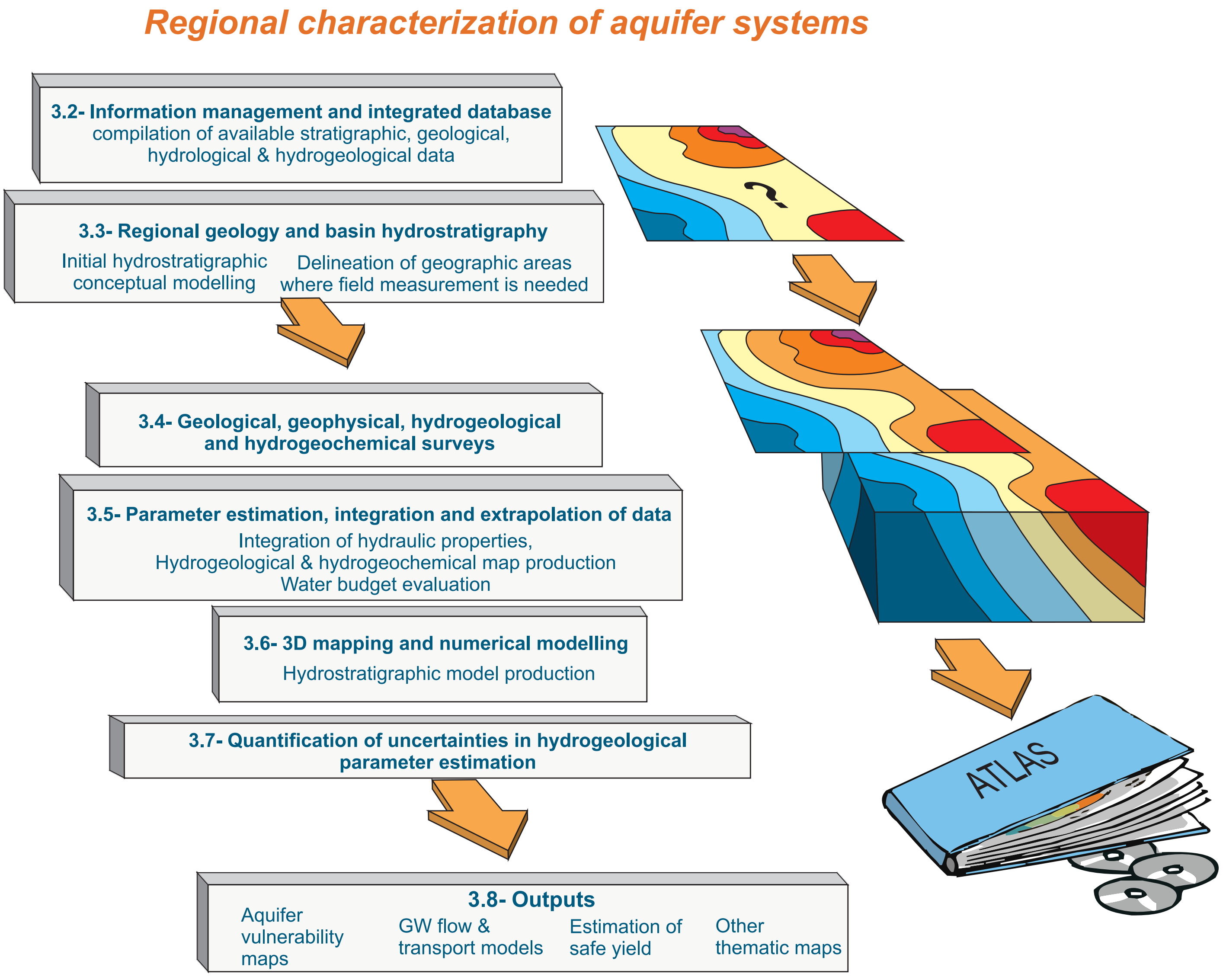


Figure 3.1 Suggested steps for regional characterization of aquifer systems.

TABLE 3.1 PRINCIPAL PARAMETERS REQUIRED FOR SYSTEMATIC REGIONAL SURVEYS OF AQUIFER SYSTEMS

(MODIFIED FROM SAVARD ET AL., 2008)

GEOLOGICAL PARAMETERS

Sedimentary Quaternary units

- Lithology
- Stratigraphy (age)
- Porosity
- Regional distribution
- Origin
- Facies types
- Landforms
- Orientation
- Sedimentary structures
- Paleoflow direction

Rock formations

- Lithology
- Nature of porosity
- Porosity volume
- Stratigraphy (age)
- Regional structures (folds, faults, fractures) and distribution

HYDROLOGICAL PARAMETERS

Climate

- Precipitation
- Temperature
- Solar radiation
- Wind

Surface waters

- Location
- Flow rate
- Hydrographs (water levels)
- Hydraulic link to aquifers

HYDROGEOLOGICAL PARAMETERS

Physical

- Water levels (depth to groundwater)
- Well hydrographs
- Groundwater flow directions
- Hydraulic gradient
- Hydraulic links between aquifer formations
- Recharge zones
- Discharge zones
- Estimation of recharge
- Estimation of discharge
- Hydraulic conductivity, transmissivity and storativity*
- Intrinsic vulnerability

Anthropogenic

- Wellhead protection areas
- Estimation of groundwater extraction
- Well yield

Hydrogeochemical

- Concentration of major and trace ions
- Concentration of total dissolved solids
- Electrical conductivity, temperature, pH, Eh
- Dissolved oxygen
- Water quality (e.g., relative to drinking criteria)
- Water type distribution
- Water age
- Source of contaminants

*Consider also specific storage or specific yield.

to thousands of square kilometres. The main challenges to regional characterization include selecting the proper amount of reliable coverage data to allow finding, at reasonable cost, the right quantity of groundwater to extract while protecting the aquifer's groundwater quality. Regional studies also need to overcome the problem of aquifer variability, and produce methodologies that allow extrapolation or "scale-up" parameters measured at local scales (tens of metres) to watershed scales (tens of kilometres).

Studies of Canadian groundwater began during the 1870s. Historical information about these research projects, and details on provincial and federal contributions to the first aquifer inventories may be found in Brown, 1967. More recent developments are covered in Chapter 16 of this book.

The assessment approach presented in this chapter was developed by the Geological Survey of Canada and, as mentioned above, its partners, and has been applied to a number of studies over the past 15 years. Variations of this approach are also being used by other agencies.

Within this chapter, we will describe state-of-the-art methodologies used to characterize regional aquifer systems through multidisciplinary assessments coupled with federal and provincial collaborative projects. These procedures provide the input required to properly characterize aquifers and understand groundwater flow systems described in Part IV of this book. This approach integrates field geophysical, geological, geochemical and hydrogeological surveys to produce a 3D hydrostratigraphic model within a linked database management system. Importantly, an estimate of regional hydraulic parameters as well as an estimation of the uncertainty of acquired information is crucial to reliable groundwater assessment (Figure 3.1; Table 3.1).

Regional aquifer systems should also be described in terms of hydrostratigraphy (rock reservoirs and layers of low permeability), hydrogeology (aquifer characteristics, hydraulic conductivity, recharge, etc.) and numerical modelling (potential drawdown). Quantitative assessment (water availability) and hydrogeochemistry (water quality; e.g., Cloutier, 2004) are two other vital elements of regional surveys, because reliable yield and water quality data are always included in any aquifer system assessment (Table 3.1). Chapters 4 through 7 address these elements in greater detail. The goal is to produce regional assessments that contribute to a national inventory

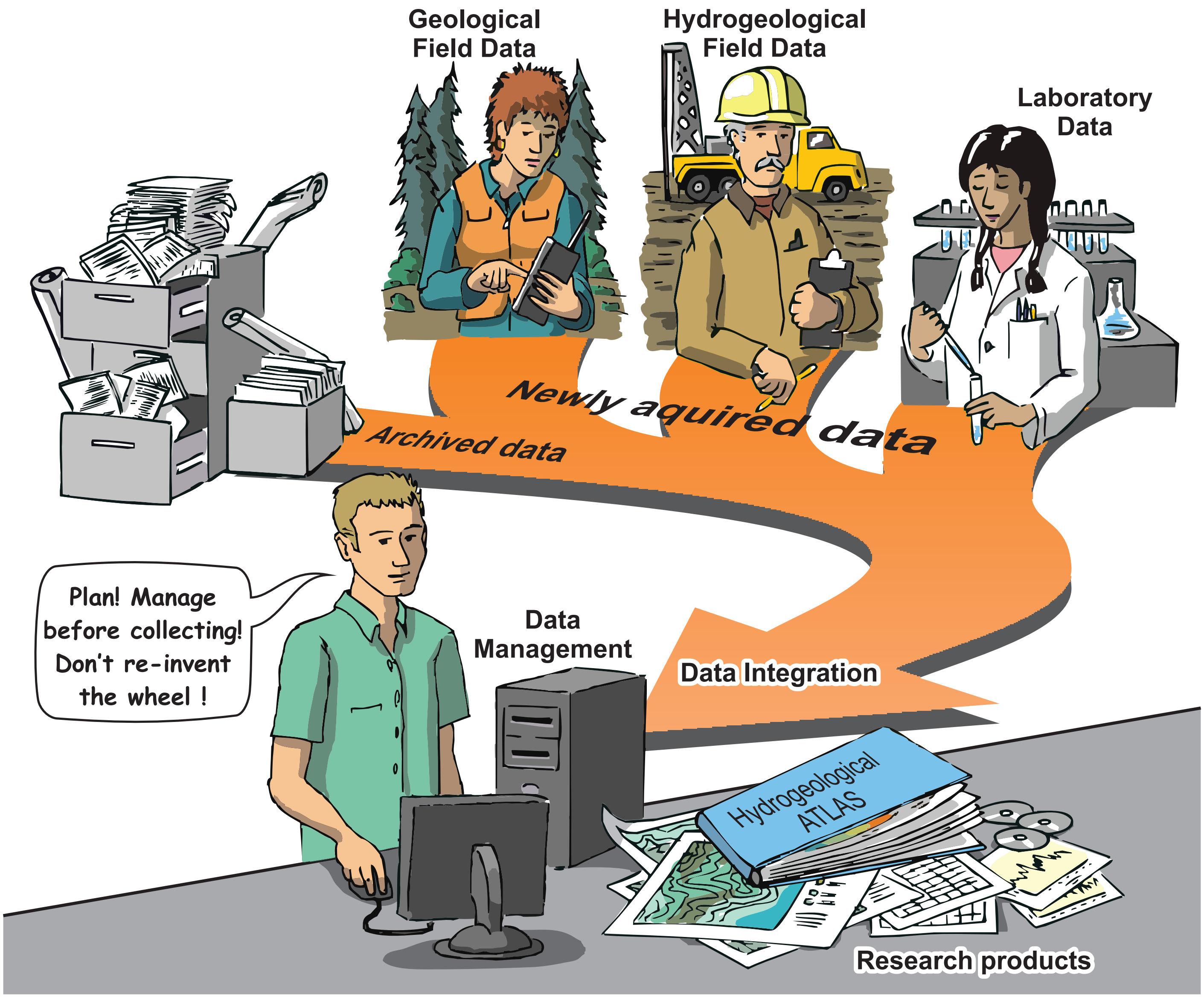


Figure 3.2 Importance of database organization and management for regional aquifer-system assessments.

used for sustainable development and protection of Canadian groundwater resources.

3.2 INFORMATION MANAGEMENT — INTEGRATED DATABASES

Once an area is selected for regional hydrogeological assessment, the first step of the process is to develop a regional database, compiled from reports, studies and data sets held by various agencies. Regional assessments inevitably generate large data sets which must be integrated and manipulated to be easily accessible for interpretation and hydrogeological modelling. Traditional sources of groundwater data, such as provincial water well records and geological maps are useful, particularly when combined with other data collections. Federal departments such as Environment Canada, Agriculture Canada and Statistics Canada hold a wealth of information, as do provincial agencies like Geological Surveys. Large information banks are held locally by municipalities, industries, consultants and community groups. All data collected should be stored in a properly structured relational database.

Given the abundance of sources, types and entries of information, establishment of a sound metadata strategy is important before the situation becomes unmanageable (Figure 3.2). Metadata records increase efficiency, and help the end user understand the assessment limits.

A sound analysis of user requirements, wherein the real assessment needs are known and weighed, must be done before studies start. The project needst must not overshadow responsibilities for post-project data management by other groups. When all requirements are understood, a scan of available datasets should be initiated to identify relevant material and potential gaps. This analysis will be used to construct a data acquisition plan where major gaps (according to project requirement) are addressed and prioritized. Computer systems owned by government departments, and staff resources already assigned to these systems should be considered as part of new regional projects.

A sound data model can guide the construction of a relational database for all geological, hydrogeological and geotechnical data. Do not forget that verification is a key step when populating databases. Location and elevation of all data should be checked before applying a standard elevation from a digital elevation model. It is helpful to use a standardization technique like a rock/sediment coding protocol based on unit descriptions from geological maps. A geologist with field experience in the study area must recode lithological descriptions of all input

data to new standardized classes.

Large regional assessments are generally conducted through partnerships involving scientists from multiple organizations; this leads to questions of data ownership, database management and database format (i.e., software), legal constraints, and accessibility, issues which may lead to the possibility of using several systems in a network. The standard procedures then shift from common database software to common data exchange protocols.

The Open Geospatial Consortium proposes a series of standards (http://www.opengeospatial.org) which can be used to exchange data over distributed systems. These standards are being implemented by software editors (such as ArcInfo or MapInfo). Governments, as well, are active participants in developing these standards and using them (GeoConnections, 2005). Several database management projects such as the National Groundwater Database of Natural Resources Canada (http://ess.nrcan.gc.ca/2002_2006/gwp/p2/index_e.php) take advantage of such standards to manage their data. Recently, the Groundwater Information Network (GIN, http://gw-info.net) began using a groundwater data encoding standard named GWML (Groundwater Markup Language) based on GML (Geographic Markup Language) to access a network of heterogeneous data stores (http://ngwd-bdnes.cits.nrcan.gc.ca/service/apingwds/en/gwml.html). GIN allows access to all data stores using a common interface and a common data format as if it was a seamless database. The data can be downloaded in a variety of popular formats (ESRI SHP file, Geodatabase, Microsoft Excel, Google Earth KML, etc.), although users should be aware that the quality of the dataset is quite variable (with, for instance, outdated stratigraphic units or erroneous lithological descriptions). As GIN is being implemented in Canada, other countries have also embarked in developing similar infrastructure, most notably the United States, with U.S. GIN (http://usgin.org/, which has an unfortunate identical acronym), Morocco HydrIS (http://www.springerlink.com/content/a646n54t002552m5/) and IUGS (International Union of Geological Science) One Geology (http://www.onegeology.org/).

A complete database system not only comprises software and hardware, it also includes database management procedures and experts who maintain, feed and use it. Database design and implementation requires qualified information technology professionals such as data modellers, database managers and programmers.

3.3 REGIONAL GEOLOGY AND BASIN HYDROSTRATIGRAPHY

3.3.1 Basin study

Developing a comprehensive model and understanding the geological setting of a region is a critical first step towards understanding its groundwater systems. Scientists undertaking regional studies of sedimentary rock or multi-layered unconsolidated aquifer systems often use basin analysis to delineate depositional environment and basin evolution, which, in turn, can be employed to develop geological and hydrostratigraphic conceptual models. Basin analysis reveals its history by analyzing of lithology, composition, structure and architecture of its sediment fill. Basin analysis specifically characterizes textural, stratigraphic and structural controls on groundwater flow systems at regional scales, including a characterization of fluids in the basin.

Consider surface water drainage in two drainage

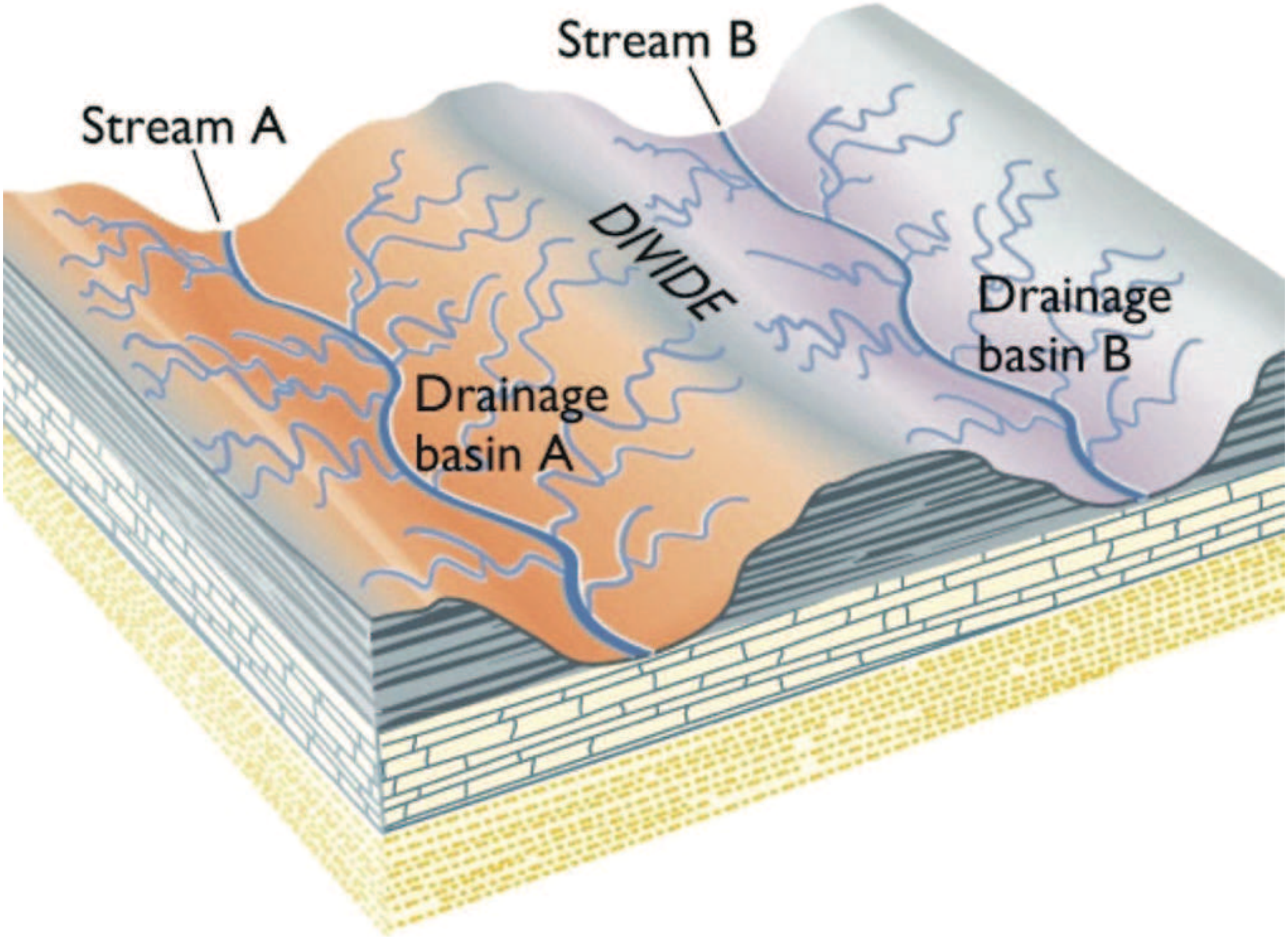


Figure 3.3 How a surface basin serves to define overland and stream flow based on topography (meandering light blue tributary lines). Regional groundwater flow provides a different conceptual model as infiltration at a topographic high may take a short flow path to the stream within the basin (light blue arrows). In areas where basins are tilted, some groundwater flow will take a longer path and flow, for example, from the basin A divide to discharge in the stream located in basin B (Czech Geological Survey, 2011).

basins. If the study region is characterized by surface flow which operates independently in the upper part of each basin (A, B in Figure 3.3), groundwater flow in layer-cake subsurface strata allows for inter-watershed flow in the underlying sedimentary basin strata (Figure 3.3). Variations on the simple surface and groundwater flow pattern may occur if the basin is folded, tilted, fractured or covered by glacial deposits.

Basin analysis in a more complex aquifer system can be illustrated with bowl-shaped sedimentary strata, like the Michigan Basin in Ontario and mid-western United States (Figure 3.4). The underground reservoir systems available for groundwater recharge, storage and flow can be thousands of kilometres across. Geological mapping and conceptual hydrogeological modelling of the bowl-shaped basins allows reservoir pathways (aquifers) and low-permeability layers (aquitards) to be portrayed with relatively sparse data, and derived, perhaps, from just a few wells and subsurface information from geophysical transects. Developing conceptual models, even for models of simple basins however (Figure 3.4), requires an organized set of steps.

3.3.2 Conceptual geological models

Conceptual geological models serve as schematic explanations of specific scientific principles and/

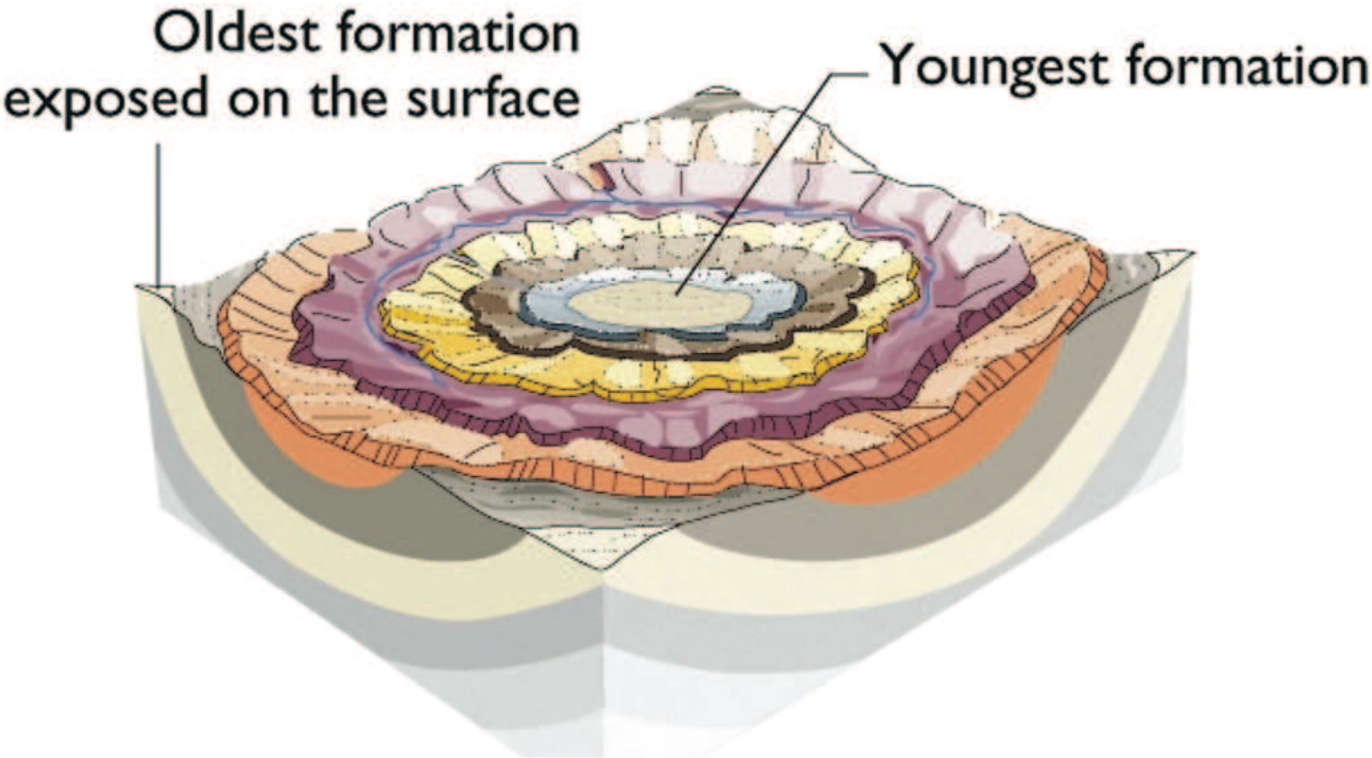


Figure 3.4 An illustration of how basin architecture (saucer shape) controls regional aquifer-system flow. Aquifers are depicted in light tones while aquitards (there is always flow in aquitards) are shown in darker tones. Bold blue arrows identify points of recharge (modified from Grotzinger et al., 2007).

or understandings. Canadian researchers need to refine the understanding of subsurface flow systems and to integrate more geological data at regional scales for groundwater flow modelling (Sharpe et al., 2002; Russell et al., 2006). It is crucial to extend our understanding beyond scarce data points, and to develop sound and physically credible conceptual models.

Conceptual geological modelling begins with a review of the geological and geotechnical literature reports, maps, sections, high-quality boreholes and other subsurface data. The resulting conceptual models should describe all relevant strata and their relative 3D geometries. These models are built from first principles in a four-step process (see also Figure 3.1): (1) development of conceptual understanding, (2) model preparation, (3) model construction, and (4) model testing and documentation. Systematics for conceptual modelling involves assignment of stratigraphic codes (organized rock sequence) based on the stratigraphic framework, and applying these codes to primary data within the stratigraphic framework. It is practical to use the stratigraphic framework and its geological rules to guide and constrain interpretation and coding of secondary data (e.g., water well data) and, where needed, to develop interpretive elements to infer plausible geometries. The stratigraphic framework of a region or basin is linked to its geometry, or the architectural relationships of its structural/stratigraphic units. A robust geological model incorporates current understanding of geological processes related to the basin under study. A basin subject to marine processes, for example, may be affected by poor water quality and other attributes of its environmental setting. Thus understanding earth processes allows researchers using the conceptual model to make informed predictions about areas where data is not currently available. The conceptual model can be portrayed in a schematic drawing which elucidates salient details of the basin's geological system. Examples of conceptual models representing regional geology are presented in section 3.6 (Russell et al., 2006).

3.3.3 Model testing and documentation

Geological models must be tested and documented, usingvery reliable data (e.g., geophysical profiles with core) for model refinement as time and data quality allow. The modeller must document all procedures in an accessible format with pertinent examples, along with identifying and explaining protocols used. Our experience in developing conceptual geological understanding and 3D modelling suggests that it may be appropriate to form 3D model peer review teams.

Chapter 8 provides conceptual models of Canada's hydrogeological regions. Each regional hydrogeological model has been developed on the basis of the physical properties of unconsolidated sediments, and their corresponding thickness over rock. The spatial extent of an aquifer is delineated by the presence of impervious physical boundaries, i.e., a low-permeability geological unit (a formation which is at least two orders of magnitude less permeable than the aquifer). No significant groundwater flows to the aquifer from such units. Note, however, that highly confined aquifers

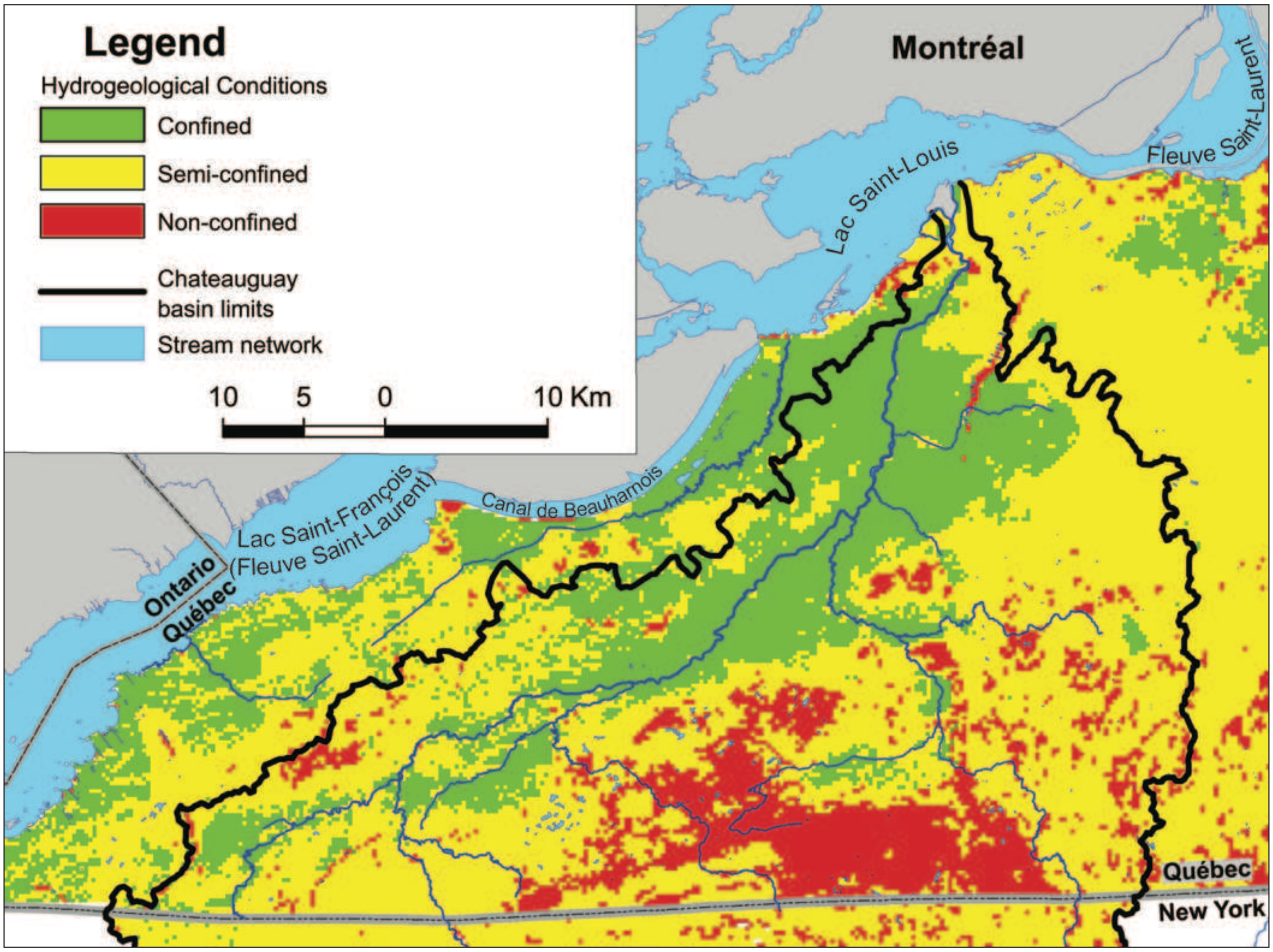
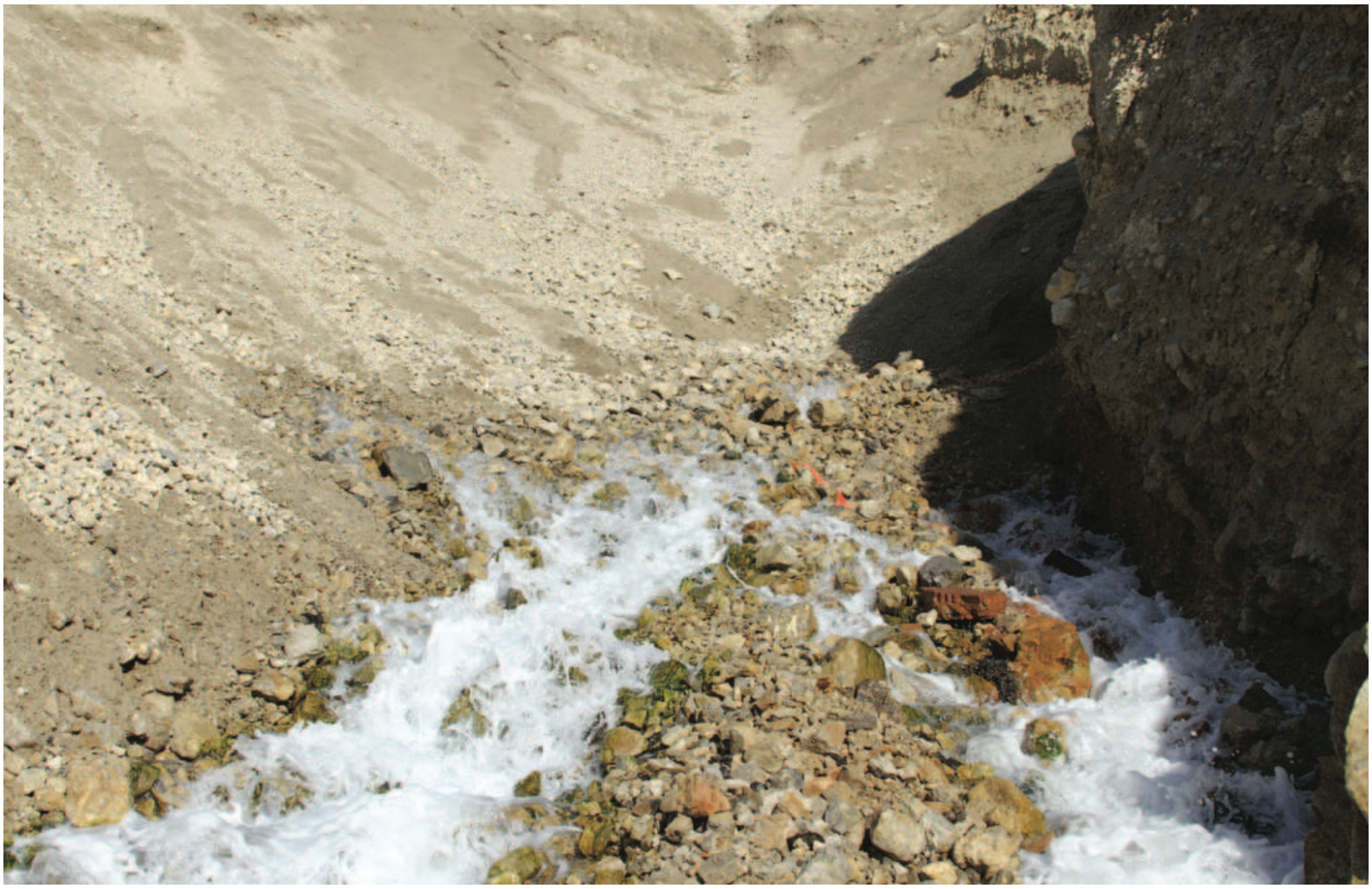


Figure 3.5 Hydrogeological conditions of the Chateauguay regional rock aquifer system defined on the basis of mapped unconsolidated sediment cover (after Croteau, 2007).



receive recharge only by slow seepage through surrounding low-permeability materials. A more detailed delineation of the aquifer systems, such as separation into sub-aquifers, can be defined through the use of hydraulic boundaries such as water divides located on topographic heights or rivers, or a line parallel to the flow (flow line). When the Chateauguay regional hydrogeological assessment was made, scientists defined confined flow conditions in areas covered with more than 5 m of marine mud characterized by low hydraulic conductivity (Croteau, 2007). Semi-confined flow was inferred for areas with marine mud less than 5 m and areas with more than 3 m of glacial sediments (till) above the aquifer. Rock outcrops or areas covered with thin till layers (<3 m), and/or by coarse, high-permeability sediments regardless of their thickness, were designated as non-confined, water-table aquifers. Based on this classification, the recharge rate was calculated to be lowest for the confined flow conditions, higher in semi-confined flow setting and highest under non-confined aquifer conditions (Figure 3.5).

Compilation of geological information through basin study and integration of the resultant data into a geological model concept constitute key steps of regional groundwater assessment. We believe that the generation of new geological information (see section 3.4) will motivate readjustment and refinement of this model, which provides the fundamental basis for planning and conducting the water quantity and quality assessments.

3.4 GEOLOGICAL, GEOPHYSICAL, HYDROGEOLOGICAL AND HYDROGEOCHEMICAL SURVEYS

Investigating the physical characteristics and properties of aquifers and groundwater is an important aspect of the regional groundwater assessment process. Field measurements are critical to verifying the assumptions inherent in conceptual and numerical models. Once the preliminary conceptual models have been determined, geological, geophysical, hydrogeological and hydrogeochemical surveys can be used to quantify the properties of the aquifer systems and groundwater, and to fill in data gaps wherever possible.

3.4.1 Geological surveys

The first steps in geological surveys include (1) interpretation of air photos to identify rock outcrops or thinly covered rock areas, in addition to the different regional settings of Quaternary sediments; (2) examination of existing geological maps; and (3) interpretation and consolidation of well logs (lithological descriptions of the material that wells intersect). Although individual Quaternary aquifers may be quite localized, they are important, and available data from geological maps or water well logs is often unable to identify the boundaries of specific sand/gravel aquifers or even indicate whether individual aquifers are present.

Most of Canada's basic geological framework has been well established by federal and provincial geological surveys and published as maps and reports commonly focusing on shallow aquifer systems (100 m deep or less) which generally contain important hydrogeological mapping information (Logan et al., 2005). Examination of existing rock and surficial-sediment geology maps provides a preliminary evaluation of the regional hydrogeological contexts, because valuable groundwater resources may be present in both lithified and unconsolidated units. Field verification of identified knowledge gaps is required prior to hydrogeological characterization of rock or surficial-sediment aquifer systems (Figure 3.1). Data gaps may occur in those areas where map units lack well support, and in such cases, it is wise to re-evaluate and update the conceptual geologic model based on assessment of new and archival data. When regional aquifers are located in sediments, however, a compilation of existing rock maps may provide sufficient characterization of the rock geology. We recommend compiling and integrating existing large scale reports and maps (e.g., 1: 20,000) to produce an intermediate scale map (e.g., 1: 100,000).

The rock characteristics which have the potential to control groundwater quality, quantity and movement are: porosity, mineralogical composition, textures and regional structures such as folds (bedding direction and dip), faults, fractures and joints (Table 3.1). The dissolution processes in carbonate rocks may result in significant alteration of primary structures such as fractures or bedding planes and produce an interconnecting network of permeable conduits which exert a major control on groundwater movement. Major structural features can be identified and located at the regional scale by using air photos and satellite images (Drury, 2001). Detailed information on characterization of rock aquifers information can be obtained from outcrops compiled, generalized and plotted on a geological map. Directional measurements of discontinuities such as strike and dip can be analyzed through a Schmidt diagram to identify families of structural features that may control groundwater flow (Ragan, 1968; Seyfert, 1987). Although usable groundwater in rock units usually resides in bedding planes and fractures, it may be necessary to estimate porosity of the bulk rock matrix (see Choquette and Pray, 1970; Friedman et al., 1992). The porosity estimation of the matrix in sedimentary rocks can be carried out in the laboratory (e.g., Hellmuth et al., 1999; Dubois et al., 1998). An analysis of rock core may be required to compile structural information, identify the lithological units in the third dimension and help develop the hydrostratigraphic conceptual model (see sections 3.3 and 3.5).

Quaternary and recent sediments commonly form a continuous to discontinuous cover over the rock units and low-permeability Quaternary units often act as seals (aquitards) for rock aquifer systems. Near-surface aquifers in Quaternary sediments are found throughout most of Canada, and scientists use surficial sediment maps to provide information on the nature and distribution of unconsolidated sediments, on their morphology (landforms), general thickness and history (origin and age). Locally, surficial sediments may reach hundreds of metres in thickness; the hydrogeological characteristics within and between units may be quite variable (there may be significant lateral facies changes over short distances or, alternatively, there may be a number of till sheets involved). Widely different descriptions of similar material often exist because geological descriptions of rock and sediments tend to be qualitative in nature. This can lead to a wide range of issues and errors when attempting to integrate various data sources into regional studies.

A simplified "geological descriptor" coding system has been developed at the Geological Survey of Canada to facilitate integration of subsurface Quaternary data from such diverse sources as well-drillers descriptions (found in thousands of provincial water-well databases) to state-of-the-art sedimentological logs (developed by expert geologists) (Sharpe et al., 2003, see Figure 3.6a; Parent et al., 2007).

It is also important to appreciate the 3D architecture of these unconsolidated sediments in order to understand the groundwater occurrence, quantity, quality and flow. Each map legend should provide information on the genesis; grain size and thickness of these sedimentary units in order to help define potential aquifer areas or zones of naturally protected aquifers (Table 3.1).

Depending on the quality of existing information, field surveys may be required to supplement existing mapping, to identify sediment types, to validate air photo interpretation and to collect samples and relevant stratigraphic data in natural (river banks) or artificial cross sections (sand pits, or auger holes). Samples should be analyzed for grain size or mineralogical or chemical composition (with clay or till content) to check the potential effect of chemical interaction between groundwater and sediments. Other specialized analyses (^{14}C dating, microflora or microfauna, etc.) can also be used for sediment identification and correlation. Borehole drilling may be required to complete the 3D mapping. A description of the geological units is made on drill cuttings or on intact sediment samples recovered from a split spoon, a Shelby tube or continuous core (Rotosonic drill), or, in the case of rock aquifers, a diamond-drilled core. Air photo interpretation takes into account observed geomorphology, field data, drilling information, existing maps and results from laboratory analyses to produce the surficial map. The resulting air photo interpretation is transferred directly to the digital base map using photogrammetric software (Paradis et al., 2001).

3.4.2 Geophysical surveys

Geophysical surveys are non-intrusive investigation techniques which allow scientists to

TABLE 3.2 CHARACTERISTICS OF MAIN GEOPHYSICAL METHODS USED IN HYDROGEOLOGY

(MODIFIED FROM MICHAUD ET AL., 2008)

A) SURFACE GEOPHYSICS

METHOD	DEPTH OF INVESTIGATION	RESOLUTION	APPLICATION
Electrical Resistivity	Tens of metres, controlled by electrode spacing	Good vertical resolution, no detection of thin beds	All types of sediments, depth to bedrock
Induced Polarization	Tens of metres, controlled by line length	Good lithologic contact resolution, no detection of thin beds	All types of sediments, depth to bedrock
Georadar	30 m, limited to fluid, high electrical conductivity soil and clay	Excellent resolution in the range of tens of centimetres	Very efficient in sandy materials, stratigraphic contact, internal structure, water table
Electromagnetic Survey (EM-31, EM-34)	1 to 60 m, depending on the electrical conductivity of the soil and the antenna spacing	Good vertical resolution (≈ 1 m), depending on the measurement station spacing	All types of sediments, depth to bedrock, water table, contaminated plume
Seismic (low depth reflection)	50–60 m, varying as a function of the power source	Metre range	Useful in fine grained sediments, depth to bedrock, internal structure
Seismic (refraction)	Vary as a function of the power source and the spreading length, always less than the seismic reflection for the same power source	Good resolution, propagation velocity increasing with depth, cannot detect thin beds	Depth to bedrock, lithologic contact, water table

B) DOWNHOLE GEOPHYSICS

LOG TYPE	MEASUREMENT	RADIUS OF INVESTIGATION	APPLICATION
Natural Gamma	Number of gamma rays (produced by decay of K, U, and Th)	0.3 m	Grain size (high counts associated with K in clay minerals)
Electrical Conductivity	Quadrature component of magnetic field induced by alternating magnetic field in transmitter coil	2-3 m	Formation conductivity (grain and/or pore water conductivity)
Magnetic Log	Magnetic Susceptibility	1-1.5 m	Presence of magnetite and other magnetic minerals (lithology)
Spectral gamma-density	Number of gamma rays returned to probe due to compton scattering	0.3 m	Water table, bulk relative soil density
Spectral gamma-ratio	Ratio of high-energy/low-energy gamma counts	0.3 m	Variation in heavy mineral content, void ration, or moisture content
Temperature	Temperature (±0.005°C) (temperature gradiant =dT/dz)	Within borehole	Thermal history (equilibrium temperature), lithology (as related to thermal conductivity), anomalies due to groundwater flow
Seismic Velocity (P-wave/S-wave)	Arrival times of seismic signal (compression/shear) from surface (determination of P-wave/S-wave velocity)	Within borehole	Variation in lithology, compaction, identification of reflecting horizons

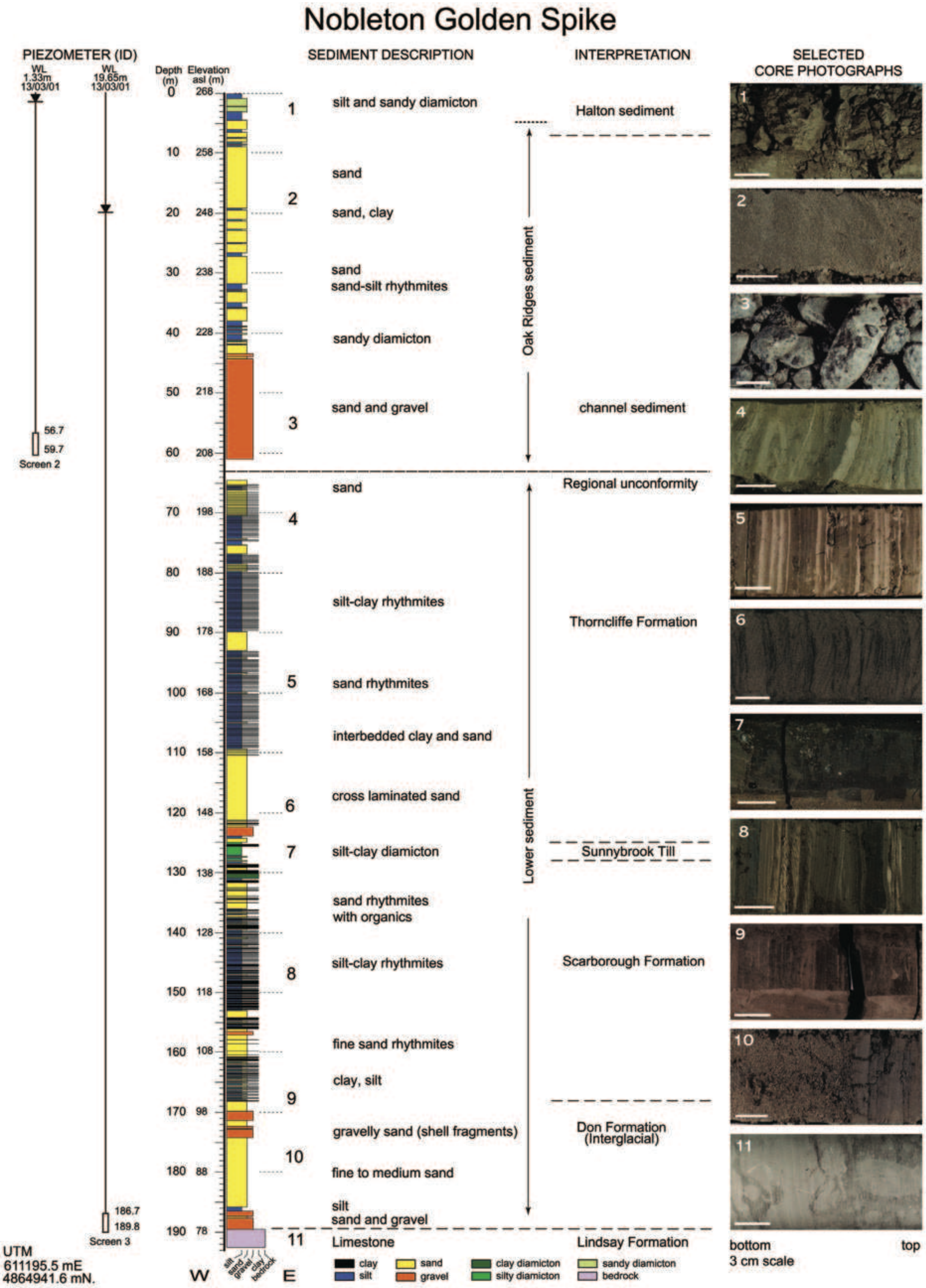
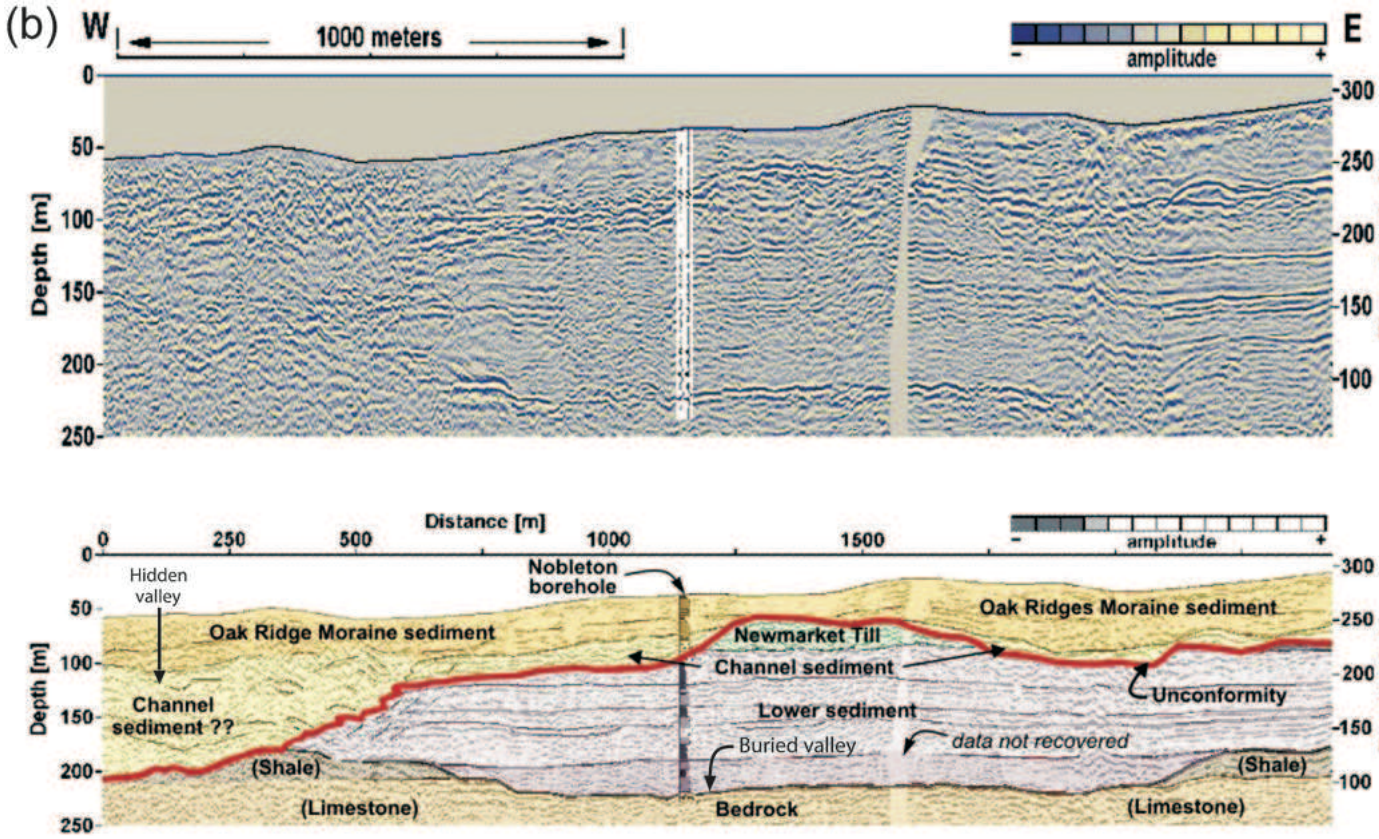


Figure 3.6 a) Continuous core sediment log (192 m) from a buried channel aquifer, Nobleton, Ontario (Sharpe et al., 2003). **b)** Seismic reflection profile (upper panel) and its interpretation (lower panel) showing the complex sediment architecture in the Oak Ridges Moraine (Pugin et al., 1999). See position of Nobleton borehole. Note buried valley on the eroded shale bedrock surface which is overlain by around 200 m thick Quaternary sediments. Red line is a regional unconformity that cuts older sediments and is filled with thick channel aquifer sediments and the Oak Ridges Moraine aquifers.



acquire additional point source or profile data such as depth to the water table, the lateral extent, the continuity, the geometry and the internal structure of subsurface geological units. These geophysical techniques are based on the fact that there are distinct and fundamental differences in how various media respond to electrical and physical *stimuli*. The geophysical survey procedure selected depends on the depth and types of geological material to be characterized (Table 3.2).

The most widely used surface geophysical methods for regional characterization are electrical resistivity, georadar and seismic reflection (Table 3.2a). The electrical resistivity procedure identifies materials according to their electrical resistance and water content. Water-saturated clay, for instance, has low resistivity, whereas dry sand shows high resistivity. Georadar helps define and position water tables, and/or subsurface sandy units along with their internal structure. Seismic reflection induces shock waves into the ground, which are captured by geophones after reflection. A seismic reflection profile can express depth to water, total thickness of the sediments, internal sedimentary structures and contacts between different geological units (Figure 3.6b). Resistivity and flow rate profiling (Table 3.2b) are the most common downhole geophysical methods. The resistivity profile is generated between two fixed spacing points on a probe moving downhole. This electrical procedure clearly detects both resistive and non-resistive material. Flow rate profiling evaluates the relative proportion of incoming water along a well as it is being pumped.

The acquisition of geophysical data minimizes regional survey costs while providing key hydrostratigraphic information. Such data can either be used in the early stage of regional work to orient the drilling program, or for completion

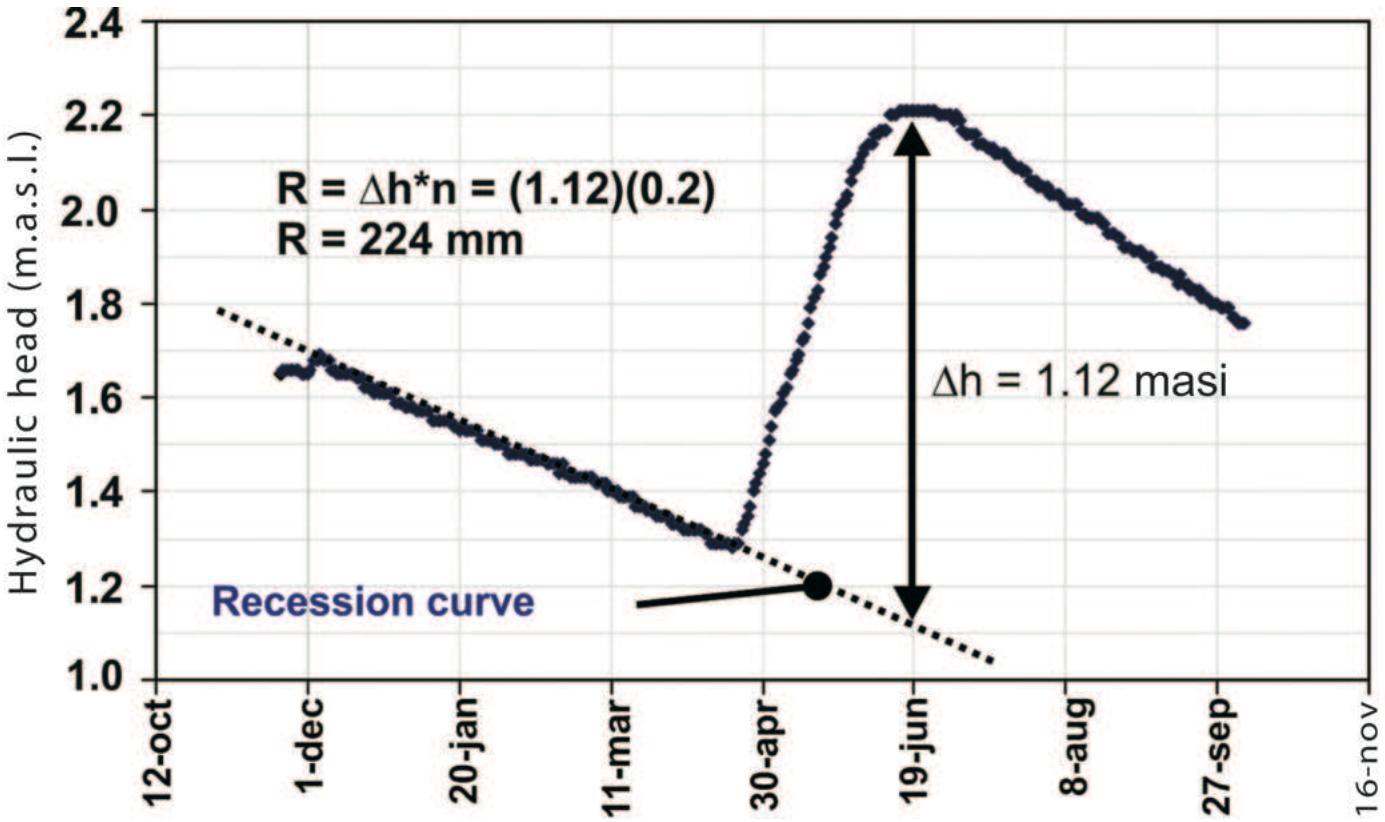


Figure 3.7 Well hydrograph illustrating how recharge (R) is estimated using porosity (n) and difference in hydraulic heads (Dh) on the recession curve, at the peak of an infiltration event (snowmelt in this case, assuming that n is air filled).

and validation of the hydrostratigraphic model when the drilling program is finished.

3.4.3 Hydrogeological surveys

At this stage of the investigation, those geological units which have been identified are classified as either permeable (aquifer) or of low-permeability (aquitard) and a hydrostratigraphic model is constructed. This model should be represented in 3D (e.g., Logan et al., 2005; see Section 3.6). Stratigraphic cross sections of rock and/or sediment sequences then allow the assembly of drilling information which, when integrated with geological and geophysical field surveys, reveals the stratigraphy and architecture of buried geological units and the connectivity of their aquifers. The use of cross sections produces depth-to-unit maps and isopach maps; these, in turn, help develop the 3D hydrostratigraphic framework (see section 3.6). Basin study is the main approach used to help infer subsurface geology and stratigraphy (Sharpe et al., 2002), and it therefore represents a key step in the development of 3D conceptual models (Smirnoff et al., 2008; see section 3.3).

Once the generalized hydrostratigraphic model has been created in 3D, hydrogeological characterization of the various conceptual units should be undertaken and other hydrogeological components of the model, recharge and discharge, for instance, added. Hydrogeological characterization at the regional scale involves (1) identification of the aquifer properties within the geological units; (2) estimation of aquifer recharge, and where recharge may be focussed; and (3) definition of the groundwater flow regime. The aquifer potential of geological units is determined by evaluating those parameters that allow quantification of these units' capacity to receive, contain and transmit groundwater (Table 3.1). These parameters include porosity, hydraulic conductivity, transmissivity, saturated thickness and storativity (for definition and methods of measurement, see Chapter 2). The permeable (aquifers) and the low-permeability units (aquitards) must all be characterized for their hydraulic properties at a spatial resolution adequate for the regional representation (e.g., Desbarats et al., 2001) and numerical modelling (see section 3.6).

Estimating the recharge of regional aquifer systems is crucial to quantify the hydrological cycle of a region, but is difficult to evaluate. Recharge (R), which is usually expressed in mm/year, depends on runoff, evapotranspiration (ET), change in storage (S) and on the transfer of water from neighbouring aquifers (and aquitards; see also Chapter 4). Recharge may be evaluated through hydrological, hydrogeological or hydrogeochmical methods (Healy and Cook, 2002; Coes et al., 2007; Bredenkamp, 2007). Hydrological methods include hydrological balance, surface water hydrograph separation, empirical correlation and hydrological modelling (Chapman, 1999; Piggott and Sharpe, 2007). The hydrological balance uses daily or monthly precipitation measurements (P), temperature (T), solar radiation, and wind speed to estimate the ET. Some of the measurement methods suggested include the Thornthwaite, the Penman, the Hargreaves, the Hamon and the Turc (Lopez-Urrea et al., 2006). Hydrological balance is the first step towards a partial resolution of the general equation to estimate recharge (Freeze and Cherry, 1979):

$$R = P\text{-}ET\text{-}Runoff \pm \Delta S \qquad (3.1)$$

To solve equation 3.1, we require data on P and runoff, an estimate of ET, and an evaluation of storage changes. If stream hydrographs are available for all or parts of the study area, these can be separated to obtain the baseflow contribution from aquifers and surface runoff on the watershed scale upstream of the gauging station (Neff et al., 2005).

Well hydrographs and hydrogeological modelling, surface water and groundwater interaction models, for example, can be used for estimating hydraulic parameters such as recharge (Purkey et al., 2006; Camporese et al., 2009). Well hydrographs are obtained via long- term (one or more years) water level monitoring in observation wells located within a chosen aquifer. A quantitative recharge estimate is determined by multiplying the water level fluctuation to the porosity of the investigated aquifer unit (Figure 3.7).

The hydraulic head (h) is the sum of hydraulic pressure (p) and elevation (z), and is usually reported in metres above sea level (masl). Hydraulic heads are calculated from water levels measured in observation wells. The water level (elevation) must be surveyed relative to a known reference, usually the mean sea level. This work commonly uses total station field measurements or the two-GPS technique. Recently, however, high quality digital elevation models (DEM; satellite imaging) and Lidar (aerial laser geophysics using light detection and ranging) have been utilized to vertically position measuring points, such as surface water and soil surface at well sites, which have been precisely located in the field,. The DEM method generally provides a metric precision, whereas the Lidar gives a centimetre precision.

Water levels and elevations should be measured in observation wells or private wells distributed over the study region in order to develop an understanding of the groundwater flow regime.

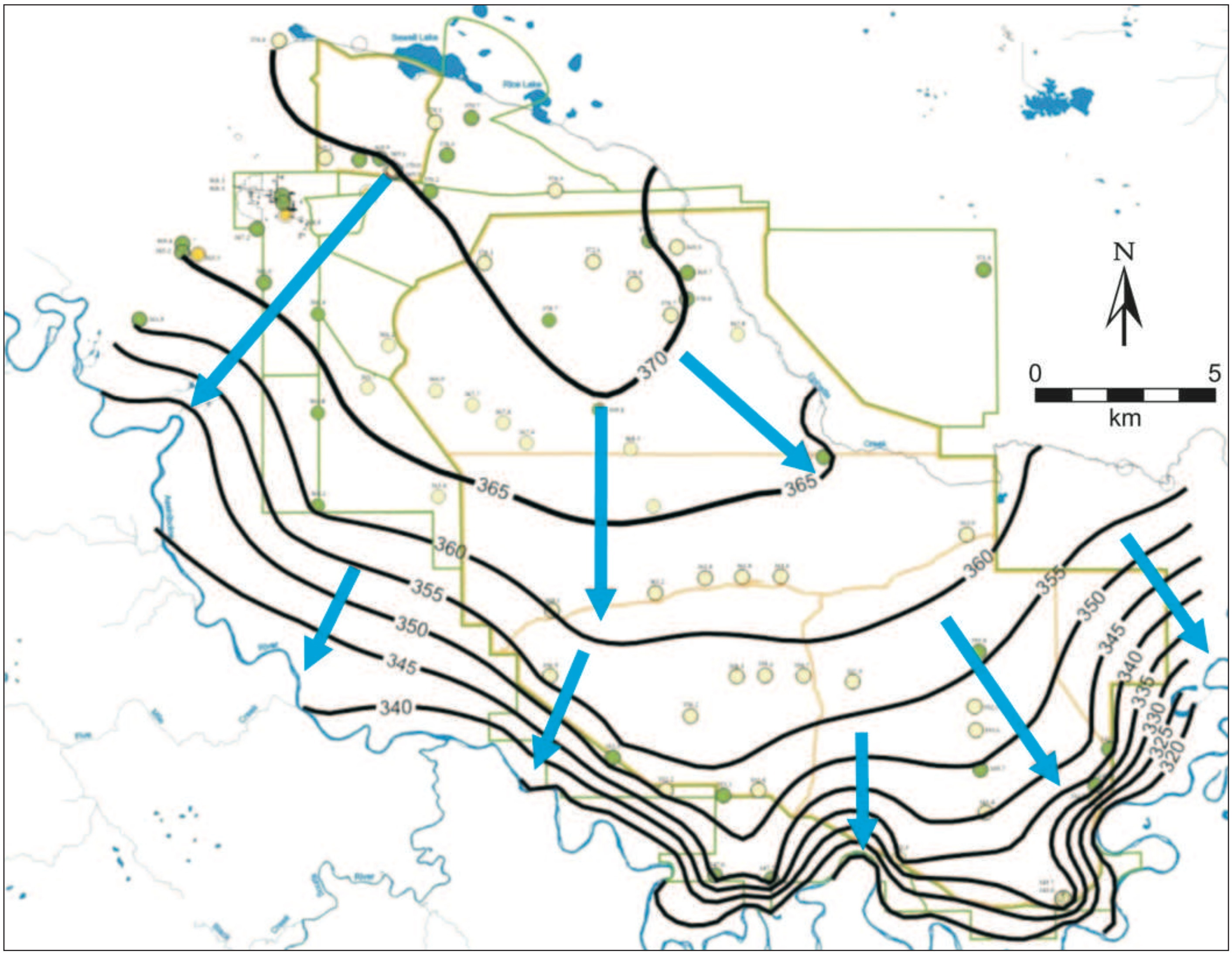


Figure 3.8 Piezometric surface map example (southern part of the Assiniboine delta aquifer). The black contours represent lines of equal hydraulic heads in metres above sea level. The arrows indicate groundwater flow directions (perpendicular to contour lines). Green circles are locations of hydraulic head measurement (adapted from Gauthier et al., 2003).

Water level measurements must be collected within a short period of time (weeks) to produce a representative snapshot of the hydraulic heads (see Chapter 2). Care must be taken to use only those wells where the completion zone is known so that the hydraulic heads can be assigned to a specific aquifer, or even to the upper or lower part of an aquifer.

Hydraulic heads gathered in this fashion can be used to develop a piezometric surface map, which represents a plan view of their distribution (Figure 3.8). This map is constructed by interpolating and contouring the measured water elevations in wells. Contour lines in the sample provided here are spaced at the metre scale (e.g., every 5 metres). The resultant surface map defines the direction and gradient of the groundwater flow regime. Groundwater flow is usually assumed to be perpendicular to the lines of equal hydraulic head, and occurs at all elevations, from high to low (Figure 3.8). However the actual direction of groundwater flow may deviate somewhat from this assumption, particularly in fractured-rock aquifers, because these aquifers are anisotropic. Piezometric surface maps usually have arrows indicating groundwater flow direction. One map is prepared for each

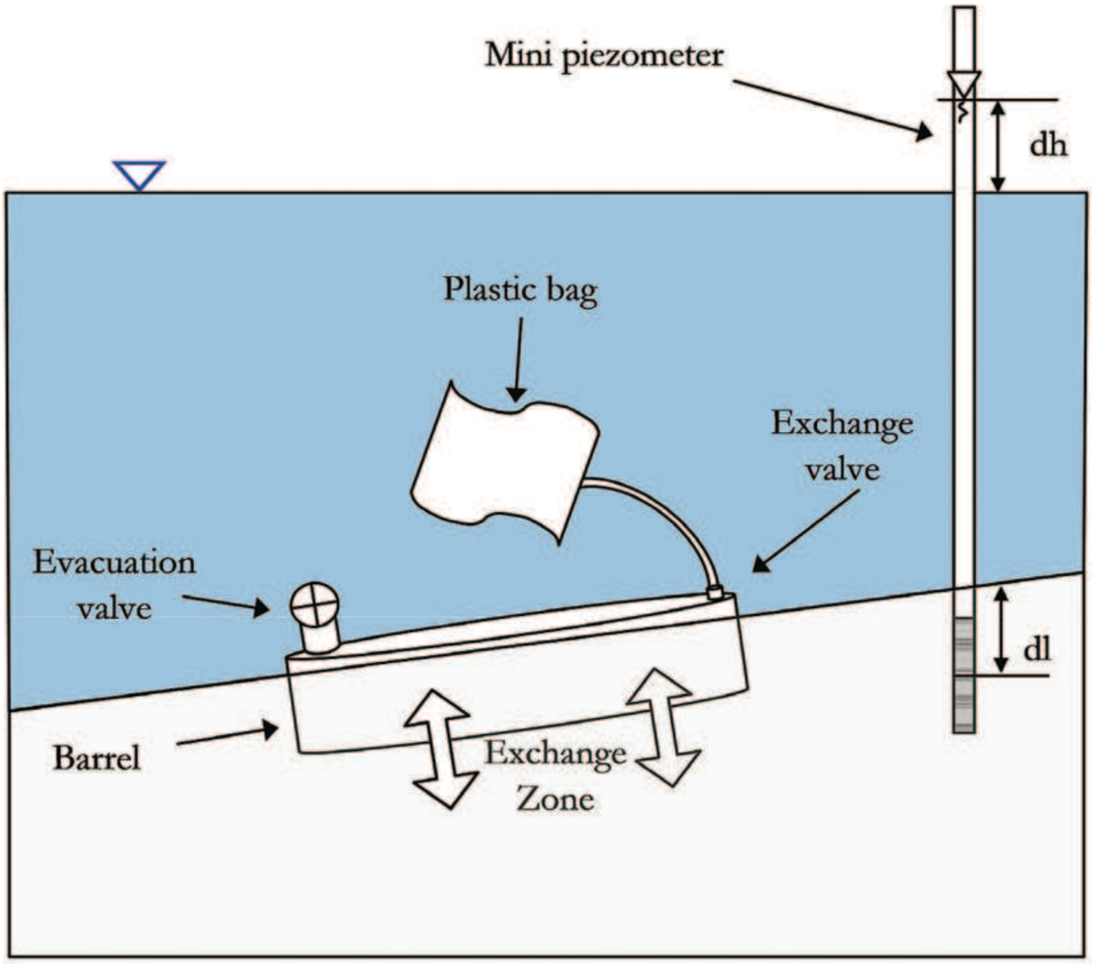


Figure 3.9 Instrumental setup for riverbed seepage tests (as per Coes et al., 2007, Purkey et al., 2006). The mini-piezometer installed into the riverbed at depth is used to measure the difference between groundwater and stream levels (denoted by dh). The barrel and plastic bag instruments are used to collect groundwater samples and to evaluate the groundwater flow rate (Q).The blue inverted triangle indicates river water level, and the black line between the blue and grey zones is riverbed. This device can also help evaluate hydraulic conductivity (K) of the river bed using Q=K × dh/dl × A, where A is the open area of the barrel.

aquifer and includes the measurement points for easier verification of interpolated levels. Other measuring points such as water elevation in dug wells, in rivers, creeks, lakes and ponds, and water outcrop elevation in sand pits or ditches, or a DEM (Desbarats et al., 2002) may also be used to create a surface map of water table aquifers, although the hydraulic link of these points with the aquifer must be confirmed before including them on the map. This can be done rapidly by visual observation of geological material on the shores or on the bottom of the water course being studied. Seepage tests and the installation of mini piezometers can also be used in river or lakebeds to determine whether groundwater is discharging into the surface water body or, conversely, whether surface water is recharging the aquifer (Figure 3.9). When surface water bodies and aquifers are hydraulically linked, the water table elevation can be extracted from a topographic map detailing those locations where topographic elevation contour and surface water bodies meet.

Regional hydrogeological studies as described above may also be supported by regional data sets obtained by remote sensing through satellite images. Hydrogeological surveys are often based on the use of spatially explicit water budget models, thus land surface surveys can be important in estimating parameters at varying detail levels. Knowledge of spatial distribution of land use and land cover (LULC) is often a required input within the algorithms for estimating interception of precipitation and surface runoff. Leaf area index (LAI), defined as the half of the all-sided green leaf area per unit of ground surface area projected on the horizontal datum, is also used mainly to compute evapotranspiration rates (Latifovic et al., 2010). The use of Earth Observation (EO) images in the hydrogeological context of Canadian populated areas is a practical solution for the estimation of the LULC and LAI because these images can cover large areas and require lower purchase and processing costs compared to traditional aerial photograph methods. Landsat Thematic Mapper (LTM) optical images are popular in this regard because they allow homogeneous mapping of the current LULC, coupled with the advantage of evolving in a numerical environment to facilitate both data management and spatial modelling (Chalifoux et al., 2006).

3.4.4 Hydrogeochemical surveys

The major goals of regional hydrogeochemistry are to characterize water quality, understand its variability, infer water origin and recognize the processes controlling quality changes be they natural or anthropogenic. One obvious objective of a regional survey is to establish whether water is drinkable and/or whether it can be used for other purposes such as irrigation, livestock needs or industrial activities. This assessment is determined by comparing analytical results with water quality guidelines (Health Canada, 2010; CCME, 2011; WHO, 2011; EPA, 2011). Water types are identified by the presence of major anions (atoms or molecules with a net negative charge: chlorides, bicarbonates and sulphates) and cations (atoms or molecules with a net positive charge: calcium, sodium, magnesium and potassium) dissolved in water. These can be illustrated graphically using Piper, Stiff or radial diagrams (e.g., Hounslow, 1995; Appelo and Postma, 1993).

Water quality is modified by natural processes as fresh water mixes with saline water, or water and rock interaction, which release natural elements such as iron, sulphur, fluorides, manganese, carbonates, arsenic, uranium, etc., or by human activities like fertilizer use, salt deicers, and underground storage tanks (Table 3.3). Potential contamination problems are identified by comparing concentrations of measured elements or dissolved chemicals with regional background values and drinking water criteria through reference to maximal acceptably safe concentrations and/or established odour and standards.

The choice of geochemical parameters to be analyzed depends on the investigated hydrogeological context and land use. These parameters usually include physicochemical characteristics (on-site temperature, pH, Eh, electrical conductivity, dissolved oxygen), and inorganic characteristics (TDS, anions, cations), coupled with organic and microbiological characteristics. Any regional study usually begins with a systematic physicochemical and inorganic survey of groundwater, followed by organic and/or microbiological analyses in selected zones as necessary, particularly those zones affected by anthropogenic activities. Additional parameters, such as the examination of stable or radiogenic isotopes, may be required for better quantitative understanding of regional water source and mixing,

TABLE 3.3 COMMON QUALITY PROBLEMS OF GROUNDWATER

(ADAPTED FROM SAVARD ET AL., 2008)

AESTHETIC PARAMETER				
TOTAL HARDNESS	**MCL[a] (MG/L)**	**AO[a] (MG/L)**	**PROBLEMS RELATED TO PARAMETERS ABOVE GUIDELINES**	**MAIN SOURCES**
Chlorides		≥250	Bad taste	Deicing salts
Iron		≥0.3	Water colouration, cloth stain, favours bacterial growth in tanks and pipes and alters taste and odour	Natural
Fluorides	1.5		Dental fluorosis	Natural
Manganese		≥0.05	Water colouration, cloth stain, favouring bacterial growth in tanks and pipes and alters taste and odour	Natural
TDS		≥500	Bad taste, drinkable potential depends man constituents	Ca and Mg salts, NaCl
NO_3+NO_2	10 (in N)		Methemoglobinemia[b], potentially carcinogen	chemical or organic fertilizers
pH		6.5 ≥ pH ≥8.5	Low pH: corrosion of metals High pH: mineral deposition	Natural
Sodium		≥200	Harmful for persons with heart problems, bad taste	Natural (rock, seawater, formation water)
Sulphides		≥0.05	Odour of rotten eggs	Natural

a AO–Aesthetic objective (taste, odour); MCL–maximum contaminant level (to protect human health). < 80 : corrosion of pipe works; >200 : poor quality but acceptable for consumption; > 500 : unacceptable for most domestic usage (deposits in pipes) (CCME, 2011)

b Decreases oxygen transport in babies' blood (Health Canada, 2010)

age dating (e.g., ^{3}H, ^{14}C, $\delta^{2}H$, $\delta^{18}O$; Clark and Fritz, 1997), and/or the fingerprinting of contaminant sources (e.g., $\delta^{15}N$, $\delta^{18}O$, Kendall and Aravena, 2000; $\delta^{37}Cl$, Vengosh et al., 2002).

For purposes of a regional survey, groundwater samples should be collected from existing private, municipal and industrial wells, springs and seeps, and newly installed observation wells or driving points. Physicochemical parameters must always be measured on site with field probes at all sampling locations, whereas the inorganic and organic parameters require water samples to be collected (using specific bottles and protocols), and shipped to analytical laboratories. Depending on the selected parameters and analytical methodology, sampling protocols may include on-site water filtration, addition of preservatives in bottles, quality assurance and control (QA/QC), and the use of particular containers, holding times, sampling equipment, sample volumes, etc.

These analytical results should be added to the regional database, and integrated in subsequent reports using various graphical and mapping formats. The dot map, wherein dot sizes are proportional to the parameter concentration, is the most practical format for regional representation, although usually only parameters with concentrations above specified guidelines, or those used to describe hydrogeological settings (confining conditions based on dissolved oxygen), or those developed to detect sources of contamination are shown on maps or graphs. The hydrogeochemical distribution can also be linked or compared with geological or land use maps to locate potential sources of natural or anthropogenic contaminants. Examples of graphs, maps with distribution of water types, and interpretation in terms of processes may be found in Cloutier et al. (2006, 2008).

Regional hydrogeochemistry studies should ultimately lead to depict a complete inventory of water quality, distribution of water types, and (when combined with groundwater quantity available), to delineate those parts of the regional aquifer system under study which require specific protective measures, and those that are favourable for human extraction. The hydrogeochemical survey allows researchers to make recommendations in terms of safe yield, and groundwater treatment needs, in addition to identifying prohibited zones of withdrawal. Hydrogeochemists working on large-scale studies may need to propose a monitoring network to check water composition over time in those areas where anthropogenic contamination occurs, as well as to assess deterioration, or improvement, of quality due to natural process (dilution, denitrification).

3.5 PARAMETER ESTIMATION, INTEGRATION AND EXTRAPOLATION OF DATA

The Chateauguay regional groundwater assessment is a classic example of recharge estimation using remote sensing. Forty-seven items, ranging from bare soil to dense forest, were selected from Latifovic et al. (2010) and adapted for hydrogeological research in order to establish guidelines for an optimal use of medium spatial resolution remote sensing imagery with LULC definition (Croteau, 2007). LAI measurements were acquired *in situ*, mainly within forested areas of variable density using a digital hemispherical photography (DHP) technique. These measurements were compared with values of the Infrared Simple Ratio vegetation index from coincident Landsat TM pixels to map LAI. The published relationships of Landsat vegetation indices with LAI were used to estimate the LAI for areas with uniform vegetation (crops, pasture and grasses). The final 250 m resolution LULC and maximum LAI maps were integrated with the other input parameters (climate data, slope, drainage distance and soil profiles) into the hydrological model HELP (see Chapter 4; Schroeder et al., 1994) to generate the regional water budget parameters. The resultant recharge estimates agreed within ±10% with independently derived estimates using hydrographs separation of recorded river flow rate. This remote sensing method estimated both the groundwater and the surface runoff contribution to river flow.

Hydrogeological parameters are often measured in the field as a component of "local or site scale" investigations. A pumping test, for example, might be carried out using one water supply well and several observation wells tens to hundreds of metres away. This pumping test, however, only yields a value for hydraulic conductivity and storage, representing the aquifer portion being tested. Regional groundwater assessments, however, require the hydraulic properties of aquifers to be delineated at a scale of kilometres. Extrapolating local scale parameters to a regional scale is often referred to as up-scaling, and there are various techniques, of varying complexity and reliability, available to quantify the necessary hydrogeological parameters required for regional studies. These techniques depend on study space and time scales in addition to requiring an understanding of the physical processes leading to the heterogeneous nature of geological deposits.

Maps plotted at detailed spatial scales (1:1000, for example) cover small surfaces typical of local studies, whereas small-scale maps (such as 1:100,000), cover the thousands of square kilometres typical of watershed/regional characterization. Carrying out field work at local scales, while, at the same time, generating results and maps at the regional scale involves handling the space up-scaling problem, insofar as moving from a local to a regional scale is required for modelling of regional groundwater flow and transport. Heterogeneities of specific aquifer parameters are scale-dependent because measured attributes usually increase with the size of the investigated aquifer volume. The hydraulic conductivity values for any given unit are small when obtained over a soil sample in the laboratory (cm); they are higher when measured in field conditions with slug tests (metres), and even higher when compiled from pumping or tracer tests (>100 m; see Kruseman and de Ridder, 2000). In all cases, the parameters, which reflect an aquifer's physical properties, are assumed to be constant in time.

Other hydrogeological parameters such as groundwater recharge, runoff or evapotranspiration are all-dynamic, insofar as they can vary not only on a daily/seasonal basis but

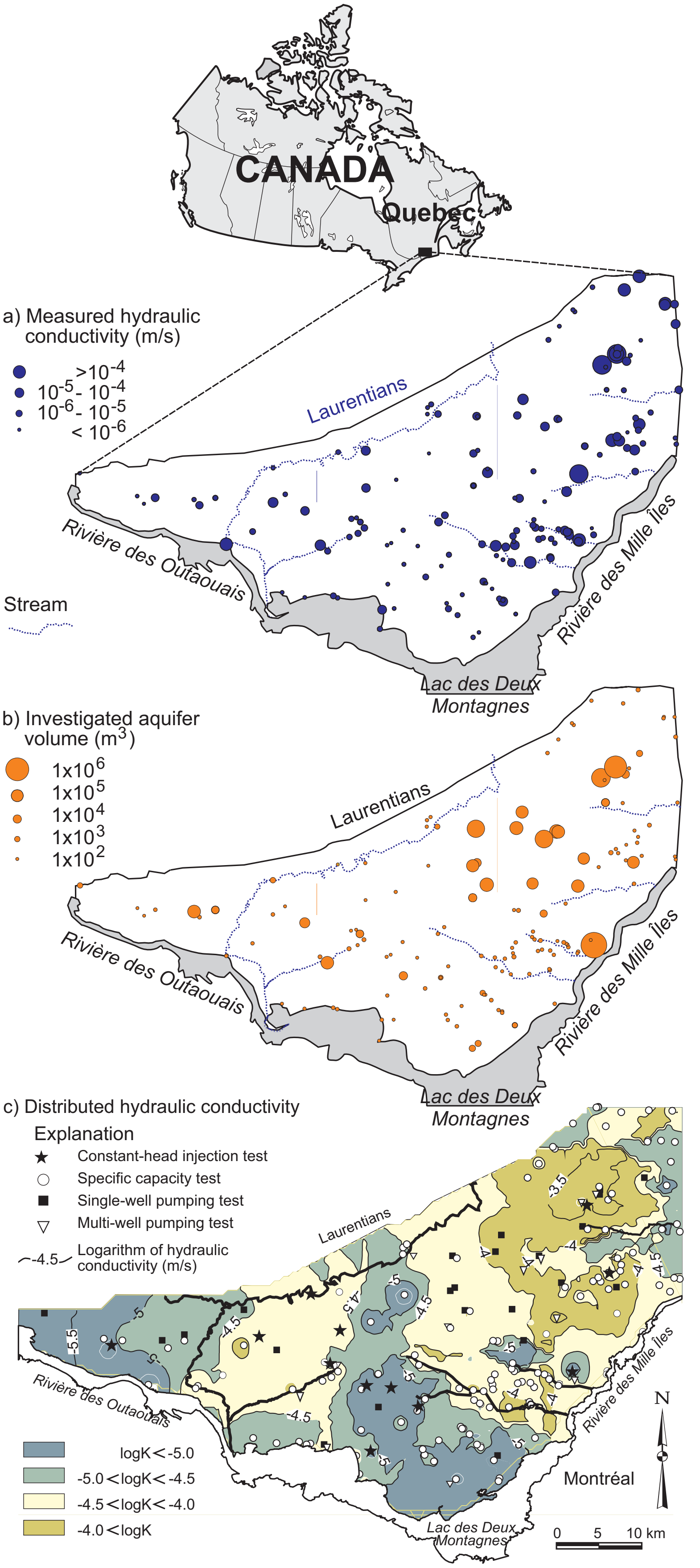


Figure 3.10 Southwestern Quebec study area showing: (a) spatial distribution of measured hydraulic conductivities; (b) interpolated horizontal log—hydraulic conductivity for the sedimentary rock aquifer system; and (c) investigated aquifer volumes (modified from Nastev et al., 2004).

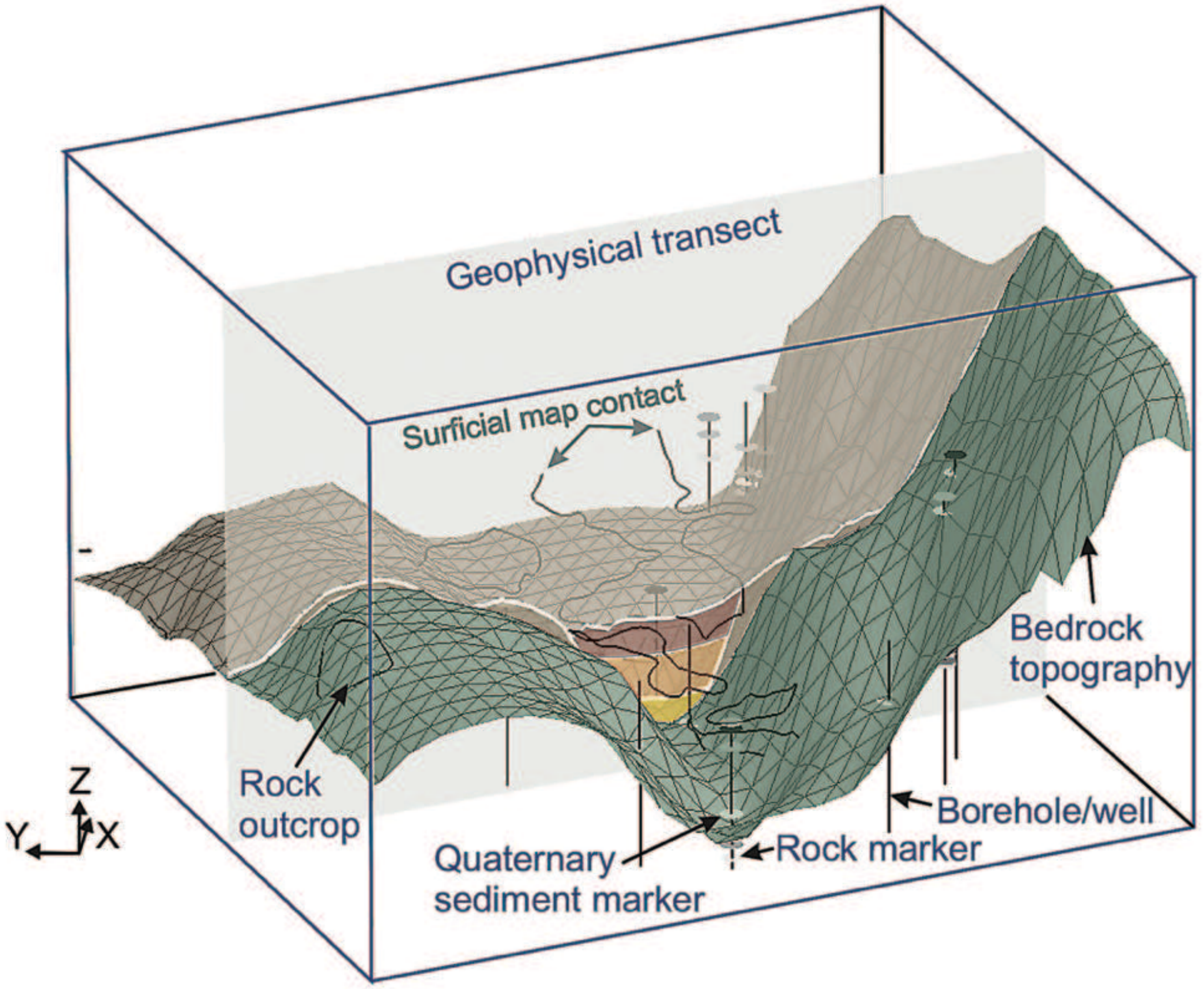


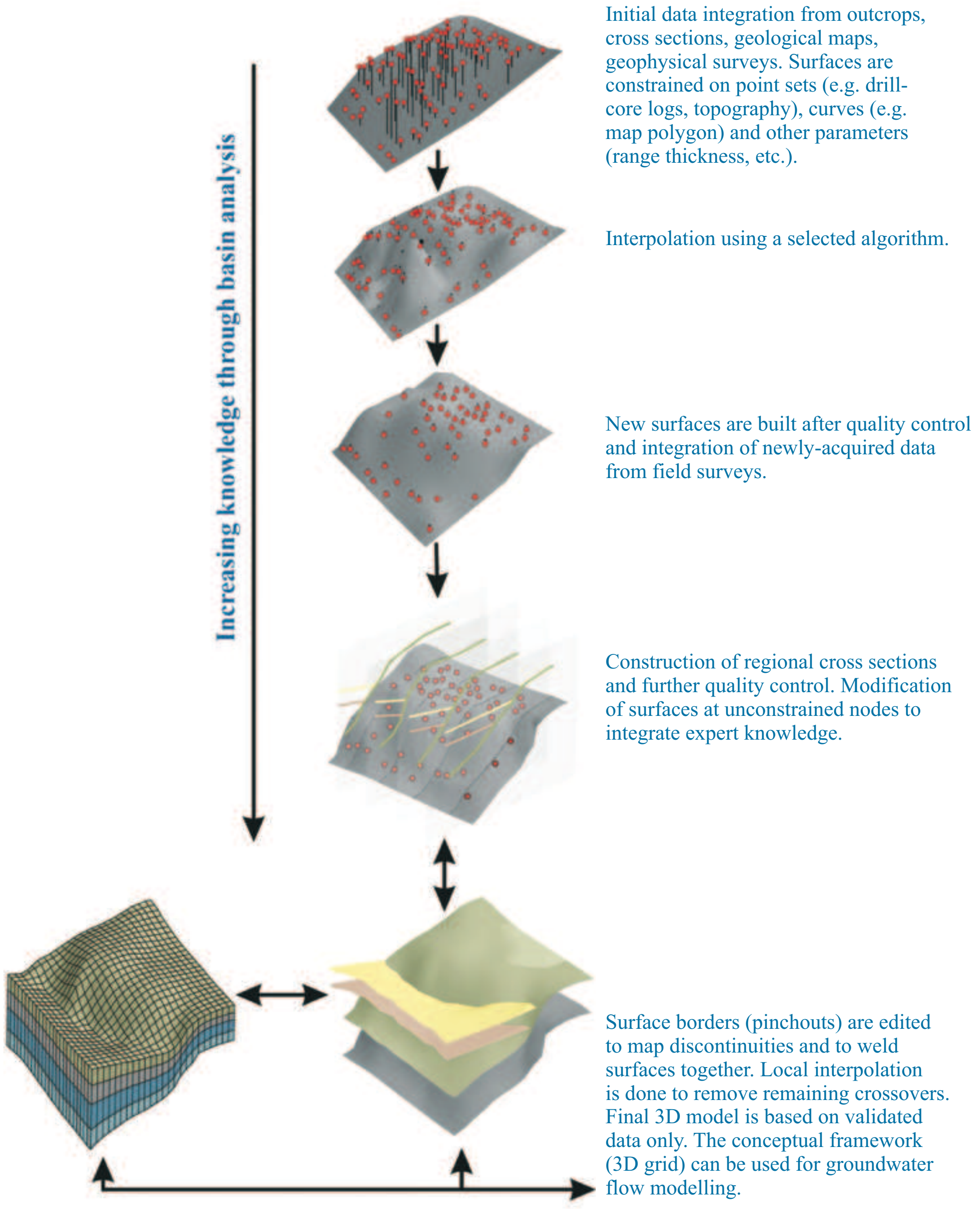
Figure 3.11 This three-dimensional representation of the bedrock surface in the southwestern Quebec aquifer system, is based on the integration of information drawn from surficial map contacts, rock outcrops, geophysical transects and well logs (after Ross et al., 2005).

also on an annual basis due to soil storage changes, land use, and climate conditions. As a result, researchers must use multiple-scale investigations to obtain representative estimates, and to refine the required knowledge because of the uncertain variability of the targeted parameters associated with each measurement technique.

One simple approach for the integration of measured field data and the interpolation of representative hydraulic conductivities (while accounting for the effects of test scales) was developed during the assessment of the St. Lawrence Lowlands sedimentary rock aquifer system (Nastev et al., 2004) as aquifer volumes were also considered in addition to measured hydraulic conductivities and distances. Hydraulic properties measurements were obtained from a number of locations and by a variety of field testing methods (packer tests, specific capacity, and single and/or multi-well pumping tests). A total of 179 hydraulic properties' measurements were made and used to generate the hydraulic conductivity field over the specified study area (Figure 3.10). These "point" hydraulic conductivity measurements were then used to generate a regional map of the whole aquifer using inverse-distance interpolation, although the method was modified to account for distance and for a second weighing function relative to the investigated aquifer volume.

The magnitude of any hydraulic conductivity at a given interpolation point is influenced both by hydraulic conductivities measured at the closest sample points and by the samples having the largest investigated volumes. Thus, small volume measurements are weighed down, whereas large volume measurements are up-weighed.

Numerical modelling of the regional groundwater flow system confirmed accuracy of the interpolation procedure by correctly reproducing the average value of hydraulic conductivity while, at the same time, largely preserving the variance of the initial data set (Anderson and Woessner, 1992).



Initial data integration from outcrops, cross sections, geological maps, geophysical surveys. Surfaces are constrained on point sets (e.g. drill-core logs, topography), curves (e.g. map polygon) and other parameters (range thickness, etc.).

Interpolation using a selected algorithm.

New surfaces are built after quality control and integration of newly-acquired data from field surveys.

Construction of regional cross sections and further quality control. Modification of surfaces at unconstrained nodes to integrate expert knowledge.

Surface borders (pinchouts) are edited to map discontinuities and to weld surfaces together. Local interpolation is done to remove remaining crossovers. Final 3D model is based on validated data only. The conceptual framework (3D grid) can be used for groundwater flow modelling.

Figure 3.12 Suggested procedure for integration of data into geological models and subsequent translation into numerical models (after Ross et al., 2005).

3.6 THREE-DIMENSIONAL MAPPING AND NUMERICAL MODELLING

Three-dimensional representation of regional aquifer systems is essential for constructing hydrogeological architecture used for groundwater flow modelling and the representation of aquifer delineation. Three-dimensional mapping of aquifer systems uses advances in GIS technologies as well as the guiding conceptual models described in section 3.3.2. A hydrostratigraphic representation can be produced through the integration of compiled data assembled within a newly generated geological model with the data set of a geo-referenced x-y-z space (Figures 3.1 and 3.11).

A basin study is used to define the various hydrogeological contexts of a region, by combining high-quality data (Pugin et al., 1999; 2009; Sharpe et al., 2003) with an understanding of the relationship between aquifers and aquitards (i.e., the regional hydrostratigraphic architecture which controls groundwater flow in the basin) operating under the influence of recharge rates related to climate and land use.

Geological maps of Quaternary sediments and rock lithologic units are essential 2D planes for modelling various spatial scales. Researchers use geological principles to integrate various subsurface data (such as drill-core logs) to produce cross sections, outcrops and 2D geophysical transects. Semi-automated or automated interpolation techniques allow scientists to generate the continuous three-dimensional subsurfaces (Figure 3.11) required for hydrogeological modelling. This approach has been successfully applied to regional systems in southwestern Quebec, the Oak Ridges Moraine and the Chateauguay aquifer systems (e.g., Savard et al., 2013; Sharpe et al., 2002; Nastev et al., 2005).

Model construction is based on available software, personnel and funds. Minimally, researchers should have a 2D GIS linked to a relational database, although 3D software which allows realistic capture and rendering of conceptual models in natural settings (Figure 3.12) is preferred. The first step is to establish a model construction protocol based on data support, data quality, available resources and goals of the modelling process. The model results should be assessed by peer review. The modeller must then repeat and refine some or all previous steps until the result is deemed plausible given the level of data support (this iterative process includes potentially rejecting the original conceptual geological model for a new one.) Model confidence is achieved by capturing and displaying the level of data support in the database (both through real and through interpolated points.) The 3D model should be portrayed graphically as a probability estimate. Both 2D and 3D products should clearly illustrate those control points which served to delineate the units of interest (e.g., permeable Quaternary formations) or specific attributes zones (e.g., distribution of hydraulic conductivities or groundwater types).

There are several methods by which scientists construct 3D representations, be they based either on expert knowledge of geological modelling (as stated above), surface delineations (Ross et al., 2005) or statistical reconstruction of volumes (Smirnoff et al., 2007). Logan et al. (2005) have provided a useful description of a rules-based approach. Subsequent steps for creating the final hydrogeological model involve the creation of a sound conceptual model, which includes predictive depositional models (Russell et al., 2006).

Once the 3D geological model is completed, the numerical modelling expert creates a grid or mesh with cells or nodes, and elements representing contact surfaces between the various units of the 3D hydrostratigraphic model (Figure 3.12). Boundary conditions (e.g., no flow, constant head and imposed flux) of the numerical model are defined according to the hydraulic heads observed in the field and by their delineated hydrostratigraphic contexts.

Currently there are two major modelling approaches: deterministic and probabilistic (stochastic) (e.g., Anderson and Woessner, 1992); it should also be noted that several commercially available software programs exist for modelling based on representations using finite difference, finite element or finite volume methods. These approaches are used to subdivide the domain into smaller cells, and to numerically represent the aquifer system.

When the deterministic approach is employed,

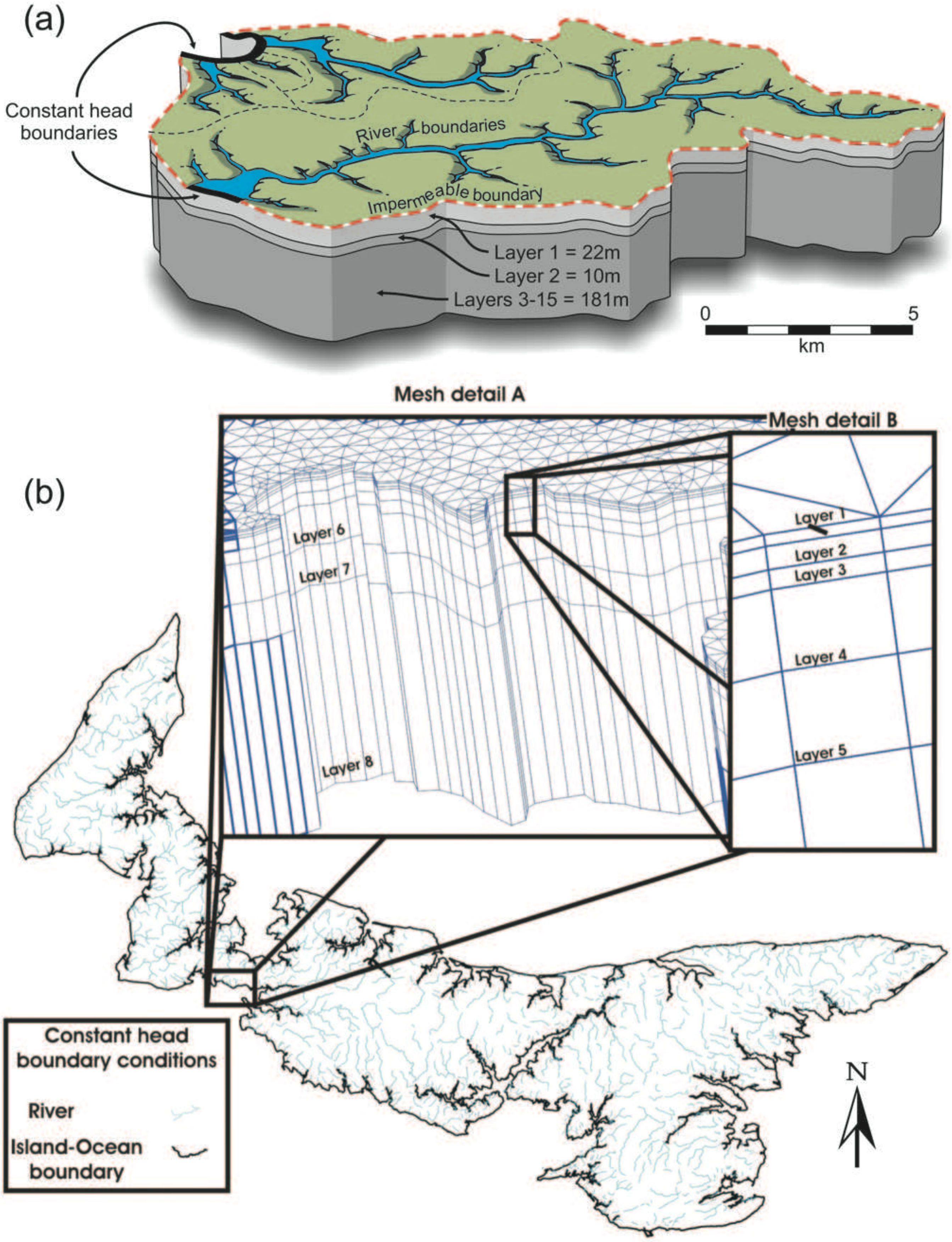


Figure 3.13 a) Conceptual model, including boundary conditions, for the aquifer of the Wilmot watershed (Prince Edward Island) which covers 87 km^2 (Jiang and Somers, 2007). **b)** Vertical discretization illustrating mesh detail (eight layers), triangular grid and boundary conditions (island map) used in the numerical flow model representing the entirety of Prince Edward Island (modified from Vigneault et al., 2007).

specific parameters (e.g., hydraulic conductivities, storage and porosity) are assigned to each unit according to field measurements and literature data. The probabilistic approach assigns ranges of values to each of the units. Aquifer recharge is generally applied over the entire study area in both approaches.

Human extraction of groundwater is taken into account either as a point source (for large users), or as uniformly imposed negative fluxes over portions of the study surface (e.g., private wells). Model calibration is performed through comparison of the observed and the modelled hydraulic heads by changing various unit parameters (such as hydraulic conductivities), or by varying the recharge rates of the aquifer system. As a general rule, the deterministic model is considered calibrated when the root means square of modelled and measured heads are within 10%. This is in contrast to probabilistic modelling, where several scenarios of hydrogeological parameters can be generated.

Basin-analysis methods in sedimentary basins, lead to a sound conceptual hydrostratigraphic model (Figure 3.13a), which is then used to finalize the digital numerical model to which hydraulic properties are attributed.

We present below two modelling examples (intermediate and regional scales) using the deterministic approach (the most frequently used in the modelling of regional groundwater flow).

The first example illustrates thicknesses of the 15 hydrostratigraphic layers used in the conceptual model representing Prince Edward Island's Wilmot watershed (Figure 3.13a; Jiang and Somers, 2007). High values of hydraulic conductivities were assigned to layers 1 and 2 to represent highly fractured sandstone; progressively decreasing hydraulic conductivities were assigned to the underlying 13 layers successively simulating the diminishing fracture aperture and connectivity associated with depth. Hydraulic conductivities used were estimated using field pumping tests and laboratory permeability tests. The boundary of the Wilmot River watershed, which is hydraulically connected to the aquifer, is included in the model, along with the constant head boundaries. Once the model was digitized and completed, modelling of the groundwater flow and nitrate transport proceeded at the local scale of the Wilmot watershed (~85 km^2; numerical model not represented here). Because the goal of this project was to understand the impact of agricultural practices and climate change on groundwater contamination by nitrate, this initial conceptual model study was adapted for all of PEI, and eventually covered approximately 5,660 km^2 (Figure 3.13b). Eight hydrostratigraphic layers were simulated; each represented by 500 m cells (close to half a million cells), with the upper layers being the most permeable (Vigneault et al., 2007). This modelling exercise predicted that, should current agricultural practices be maintained, the related nitrate input to groundwater would attain steady-state conditions at concentrations 11 % higher than present, a situation that would lead to large increases in the nitrate contamination of private domestic wells (concentrations above the recommended health threshold of 10 mg/L) For details see Vigneault et al., 2007.

Numerical models simulating regional groundwater flows are also used to delineate zones sensitive to increased human extraction of groundwater, or to study a reduction of recharge due to climatic conditions.

The groundwater flow in the southwestern Quebec's fractured-rock aquifer system (covering approximately 1,500 km^2) was simulated with seven

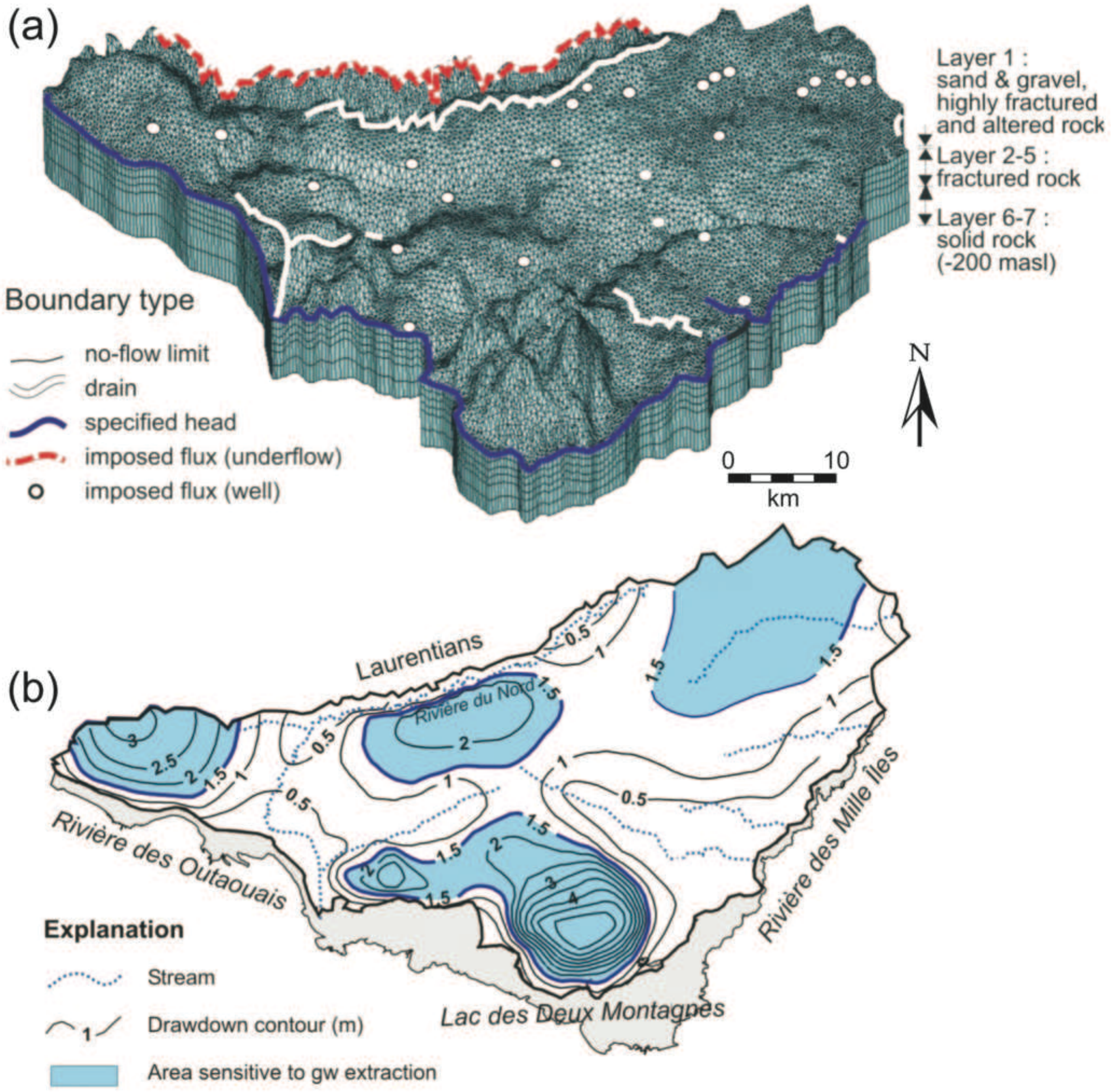


Figure 3.14 a) Numerical model with finite element grid (Nastev et al., 2005). **b)** Simulated drawdown in metres relative to currently observed hydraulic heads for the southwestern Quebec fractured rock aquifer system; gw stands for groundwater (modified from Nastev et al., 2006).

hydrostratigraphic layers (Figure 3.14a; Nastev et al., 2005). A numerical model was used to estimate impacts of increased annual extraction rates on groundwater levels (Figure 3.14b). Additional groundwater extraction (pumping) was simulated by uniformly imposing a negative flux representing a uniform pumping of $6.1\times10^6 m^3$/year to the finite elements of the top layer (layer 1; equivalent to 5 mm/year of water extracted for the entire surface of the layer). The resulting spatial distribution of drawdown allowed for the delineation of those zones most vulnerable to increased pumping

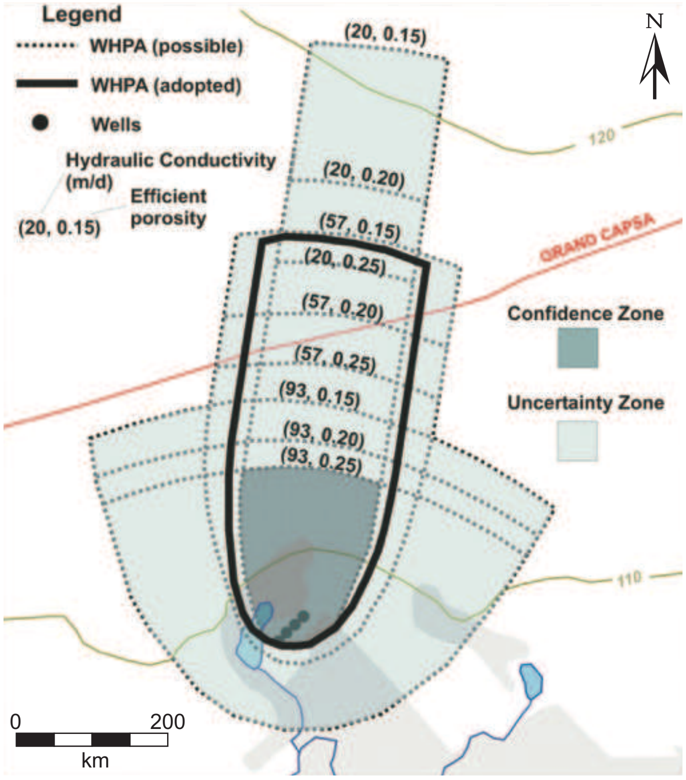


Figure 3.15 Delineation of confidence and uncertainty zones of a wellhead protection area (WHPA) based on various values of hydraulic conductivity (after Paradis, 2000).

according to the various aquifer properties and hydrostratigraphic contexts (Figure 3.14b).

The examples and text presented here constitute a very brief introduction to numerical modelling, and by no means represent a complete review on this important topic. Numerical modelling also addresses itself to several other applications not discussed here. These include the simulations of safe yield, transport of contaminants, evolution of groundwater quality, etc.

3.7 QUANTIFICATION OF UNCERTAINTIES IN HYDROGEOLOGICAL PARAMETER ESTIMATION

Construction of a sound conceptual hydrogeological model involves many participants, several sets of measurements, and various types of data interpretation, manipulation and transformation. Errors associated with data sets and data

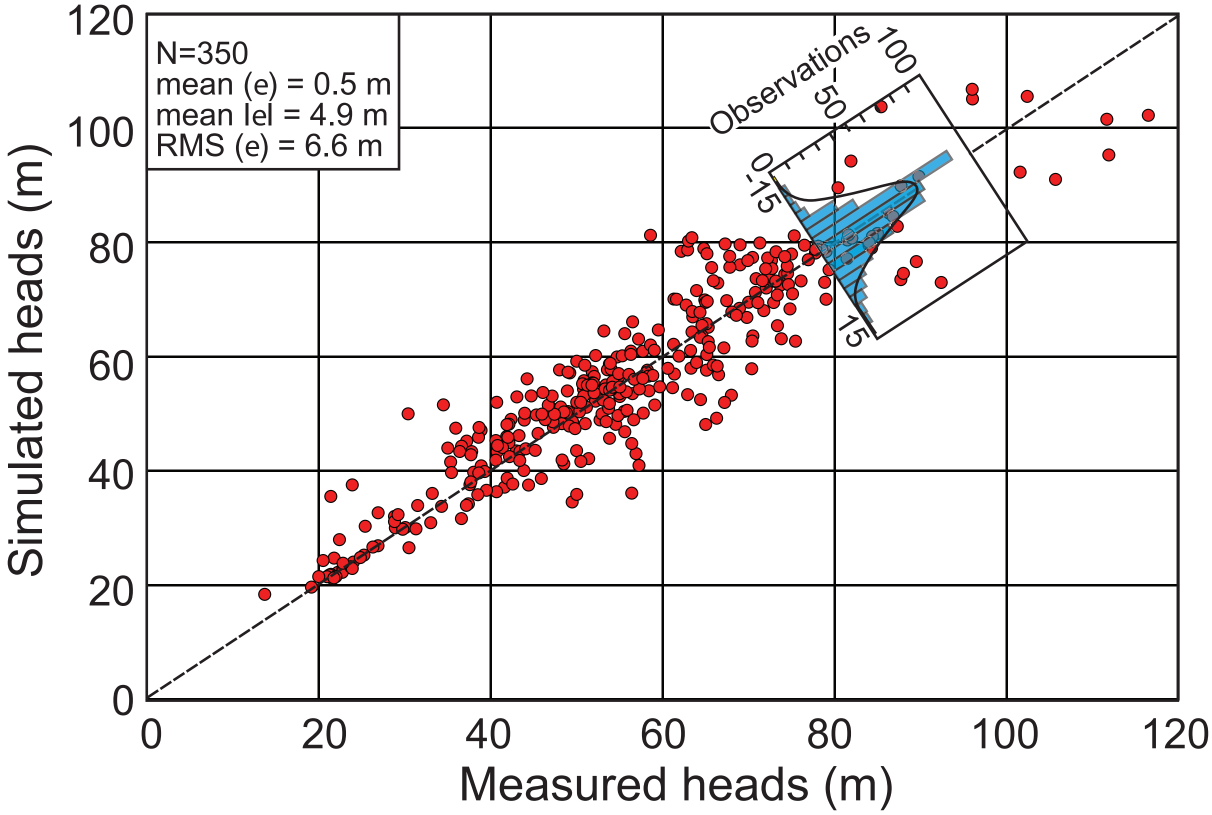


Figure 3.16 Illustration of differences between measured and simulated hydraulic heads using computer modeling of regional groundwater flow (adapted from Nastev et al., 2005).

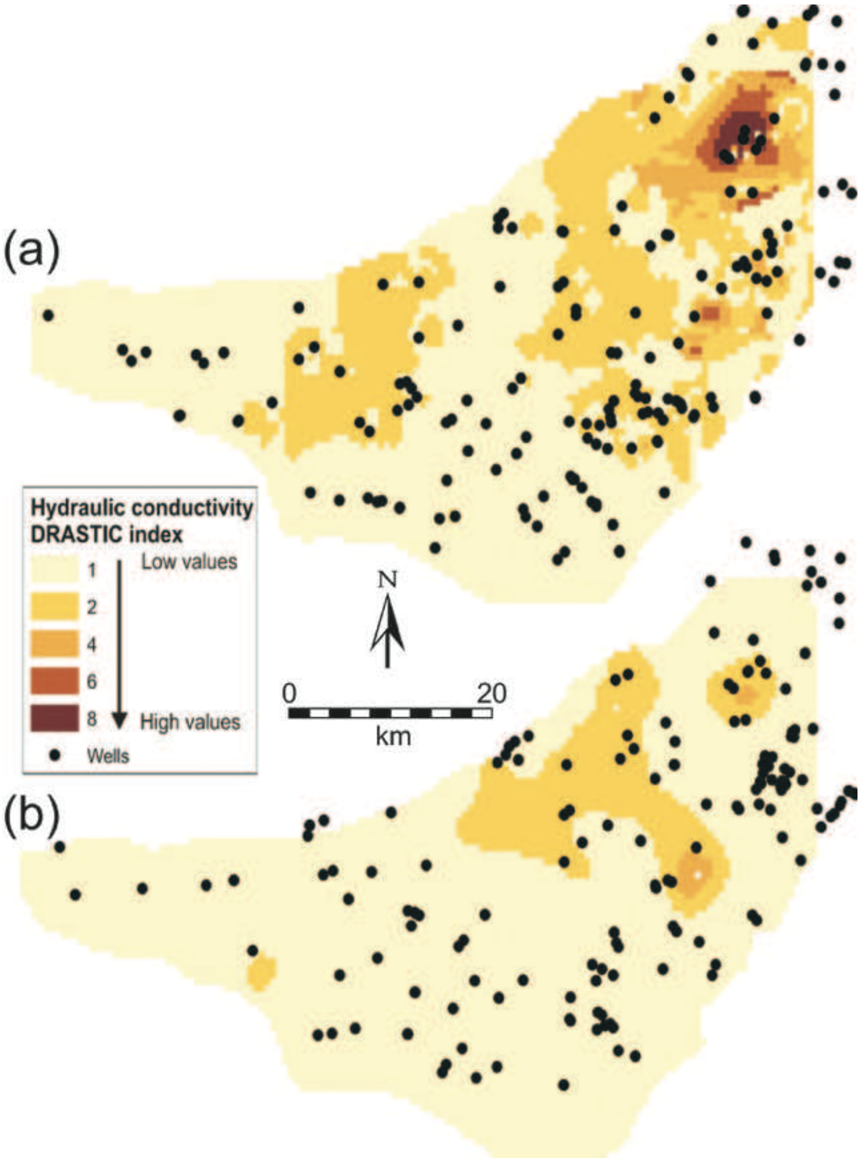


Figure 3.17 Illustration showing the distribution of hydraulic conductivity based on measurement points before (a) and after (b) correction of errors (adapted from Murat et al., 2004).

manipulation are seldom estimated, but they must be considered in order to provide a more realistic picture to users of regional characterization estimates. Hydrogeological mapping procedures contain the potential for five main sources of errors (Murat et al., 2004): in relation to conceptualization, measurement, storage media, data processing and data transformation.

Conceptual mistakes arise from differences between the reality and the reference model. For example, the groundwater flow direction in a heterogeneous aquifer (the reality) may be different than in a homogeneous aquifer (the reference model). Measurement errors, the main mistake source, are often related to instrument accuracy and calibration as well as the measurement method and individual taking the measurement. Well water level, for example, can be measured using a variety of methods ranging from probes to electronic pressure transducers. Each method has its own different accuracy level. The reference point for measurement can also often lead to error (e.g., well casing top vs. ground surface). Storage media errors relate to the media degradation for information storage and distribution. In one such case, the contact between two geological formations shown on an altered aerial photograph was not exact. Data processing error refers to mistakes in data handling, modification and transformation. Handling refers to the adaptation or movement of data from one computer system (or software) to another. Modification underlines the fact that changing a reference system or applying translation or rotation can modify database content without creating new knowledge. In fact, this can often be an important source of error, one that refers to the issue of "units". Water well record databases cover decades of data and it is not uncommon for drillers to use feet and gallons per minute (IGPM or USGPM), which measurements must then be converted to the international metric system. Data transformation error results when new knowledge

TABLE 3.4 EXPECTED MAIN PRODUCTS OF REGIONAL AQUIFER SYSTEM ASSESSMENTS

ASSESSMENTS	
COMPILED PRODUCTS	**DERIVED PRODUCTS**
NUMERICAL DATABASE **2D REPRESENTATIONS (THEMATIC MAPS)** Geology of rock units Geology of Quaternary and recent sediments Depth to rock surface Quaternary sediment thickness Hydrogeological contexts Hydraulic heads Hydrogeochemistry (e.g., water types) Hydraulic conductivity Land Use and Land Cover (LULC) Leaf Area Index (LAI) Vulnerability **2D REPRESENTATIONS (CROSS SECTIONS)** Relationships between rock and Quaternary sediments Hydrostratigraphy	**3D REPRESENTATIONS** Geological model Hydrostratigraphic conceptual model Hydrogeological conceptual model **GRAPHS & MAPS PRODUCED BY 3D NUMERICAL MODELLING** Compilation of hydraulic properties Estimation of errors Groundwater flow and transport Predicted groundwater behaviour (quality & quantity) **SCIENTIFIC REPORTS INCLUDING RECOMMENDATIONS ON SUSTAINABLE DEVELOPMENT OF GROUNDWATER**

is created by calculation (e.g., calculation and/or interpolation of hydraulic conductivity).

Errors can be randomly or systematically distributed over the data set, spatially (e.g., position), descriptively (e.g., soil texture) or temporally (e.g., date of collection). When using quantitative data, errors can be estimated through mathematical models, either analytically, stochastically or geostatistically. The analytical model estimates the contribution of each input parameter in single simulations.

Errors in the calculation of a well head protection area (WHPA), for example, can be estimated by assuming physically reasonable values of hydraulic conductivity and effective porosity that differ from the measured values (Figure 3.15) but still within the range of the data uncertainty. In this case, an uncertainty zone can then be determined and considered when dealing with groundwater protection at the local scale (see also Paradis et al., 2007). The difference between measured and simulated hydraulic heads with a numerical model may be illustrated and it is used to change inputs parameters in order to calibrate the groundwater flow model (Figure 3.16).

Stochastic modelling estimates result from a random sample of input parameter with a known distribution function (e.g., Monte Carlo can use thousands of simulations from which uncertainties can be estimated; Coburn et al., 2007). Geostatistical models are used to identify input errors that can be illustrated using the nugget effect on a graph; a pure nugget effect model gives equal weight to all points and hence less to the central sample and more to the peripheral ones (structured models attribute a relatively high weight to the central sample; Armstrong, 1998).

Many methods of groundwater recharge estimation have been developed because recharge is a key, albeit difficult to evaluate component of the water budget. For that reason, the variability of recharge values obtained through different evaluation methods is often very high (up to one order of magnitude). The main causes for variability relate to (1) scales of methods applied, ranging from point-source to regional scale; (2) heterogeneity and spatial distribution of geological units, their topography and geomorphology; and (3) the need to use other variables like runoff and evapotranspiration also estimated with high uncertainties (López-Urrea et al., 2006).

It is true that uncertainties associated with recharge estimation can be reduced by using a combination of several direct and indirect approaches (Scanlon et al., 2002) and by calculating a mean value (see also Chapter 4).

Scientists studying the southwestern Quebec aquifer system, quantified and illustrated the uncertainty associated with hydraulic conductivity (K) estimates as a layer of information (Murat et al., 2004). A map of hydraulic conductivity drawn from a combination of existing data and field measurements, without taking into account uncertainties (Figure 3.17a), is very different than a map of hydraulic conductivity for the same area with corrections made for uncertainties (Figure 3.17b). The corrected map of hydraulic conductivities takes into account errors due to a number of factors: (1) modifications of the initial data set due to eliminating defective values like non-indicated pumping duration; (2) well diameter too small; (3) insufficient pumping rate or short duration of the aquifer tests; (4) transformations of data such as calculation of K by applying different equations for slug, packer or pumping tests; and (5) data interpolation (Murat et al., 2004).

Looking into the future, it should be noted that potential technical problem may be generated by the rapid evolution of software used to manage numerical databases. Recently we have seen that rapid technological changes can make a-few-years-old data files out-of-date, particularly when the software that operates them becomes obsolete. Other emerging issues exist regarding climate change and its impact on future national resources. These problems will increase if an improved Canadian assessment of aquifer systems does not exist. It is important to note that forecasting future groundwater availability constitutes a real challenge, one that can be eased with comprehensive initial modeling of local climatic conditions.

Final products of regional assessments accompanied by estimated uncertainties provide a realistic picture of how decision makers and other potential users should use hydrogeological results. Values of such results cannot be employed in absolute terms but they should be regarded as broad indications and used with caution.

3.8 EXPECTED OUTPUTS AND SUMMARY

Every step in regional assessment of groundwater systems is a building block leading to an integrated understanding of large aquifers or multi-aquifer systems (Table 3.4). Data collection, the structuring of that data into a database, and the field work—gathering geological and hydrogeological information, basin analysis and 3D mapping, coupled with the numerical modelling and estimation of knowledge uncertainty—should be carried out with great care. The interactive multidisciplinary team responsible for the assessment of groundwater in any given region must deliver both compiled and derived hydrogeological products (Table 3.4). The series of maps and cross sections for a given region should be organized into a hydrogeological atlas (Rivard et al., 2007) to provide a useful integrated product, which allows for easy dissemination of information to a variety of interested groups. Transfer of data to potential users can also be facilitated directly through transmission of the complete numerical database, although only advanced users can have editorial access to perform specific queries and upgrades.

The final assessment must quantify errors in the estimation of parameters, and in the assumptions and constraints used for modelling. Currently several examples of integrated derived products exist, presented as maps and atlas components, or as graphs and maps in specific thematic reports (e.g., Savard and Somers, 2007; Savard, 2013).

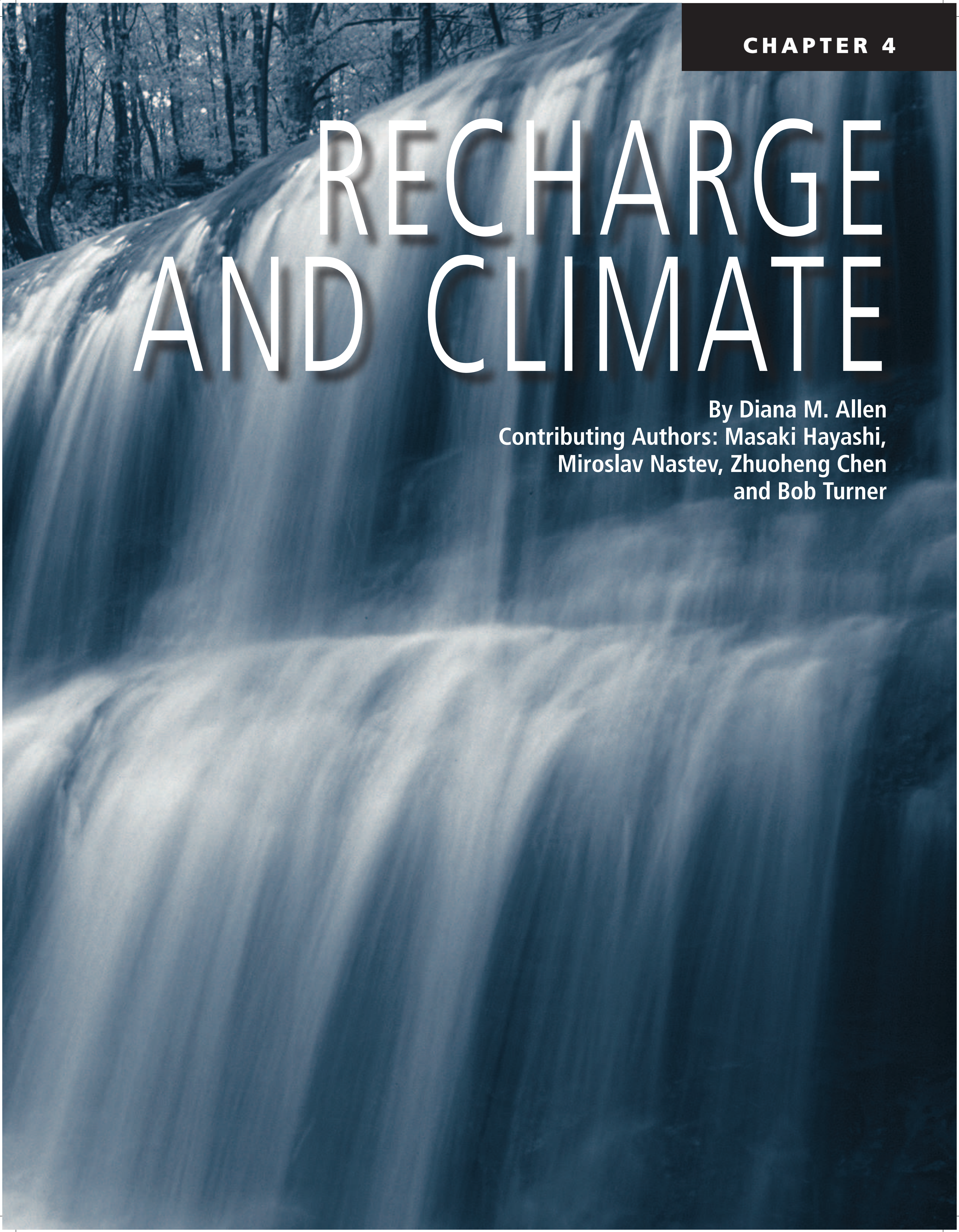
The integrated approach to groundwater assessment presented in this chapter is a synthesis of current knowledge on how researchers conduct a comprehensive regional hydrogeological characterization. Issues still remain, however, relative to

- the up-scaling of the aquifer properties measured at local scales
- the simulation of extremely complex processes such as groundwater recharge or mass transport at regional scales
- the estimation of current groundwater availability
- the estimation of aquifer sustainability
- the post-project updates of generated databases
- the use of regional groundwater flow models for management purposes
- the forecasting of future groundwater use and impacts of climate change

We would like to underline the importance of coordinated efforts among interested agencies and stakeholders for the production of a comprehensive assessment of Canadian groundwater resources, in addition to the urgency of quantifying the current availability of Canadian groundwater. Other countries have recognized groundwater availability and sustainability as a priority issue, and have acted upon that recognition in order to accelerate the processes for producing national inventories (e.g., U.S. Geological Survey, 2002). Canada has begun the preliminary course of making a similar step towards speeding up this country's groundwater inventory program (e.g., Senate Canada, 2005), but we need more!

The sustainability of drinking groundwater in Canada depends on timely decisions by managers and policy makers, as well as on efficient and rigorous scientific regional assessments.

PART III:
THEMATIC OVERVIEWS



CHAPTER 4

RECHARGE AND CLIMATE

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4.1 INTRODUCTION

Recharge, the water that enters an aquifer, is a critical parameter for understanding, modelling and protecting groundwater systems from overexploitation and contamination (Lerner, 1997; Lerner et al., 1990; Scanlon et al., 2002). Defining recharge rates and their temporal variability in response to climatic fluctuation and anthropogenic stresses is integral to groundwater management and planning (Allison, 1988; Sami and Hughes, 1996; Simmers, 1987). The spatial patterns of recharge determine where groundwater recharge occurs, which is crucial for protecting groundwater (i.e., source protection) and for remediating contaminated sites (Allison, 1988; Bradbury et al., 1992). Contrary to widespread belief, the amount of recharge does not indicate the sustainable rate of groundwater extraction, because if groundwater is extracted at the rate equal to recharge, there will be no water left to sustain stream baseflow and the riparian and wetland vegetation that are dependent on the shallow water table (Sophocleous, 2000; Bredehoeft, 2002; Devlin and Sophocleous, 2005).

Recharge is controlled by a number of factors, ranging from climate, land cover / land use, topography, and the characteristics of the soil and geologic substrate. Some of these factors vary with time (such as climate and vegetation), while all vary spatially. In addition, recharge to shallow aquifers may be subsequently extracted by evapotranspiration without contributing to long-term aquifer replenishment (de Vries and Simmers, 2002). Therefore, recharge is temporally and spatially variable, making its estimation difficult.

As a whole, the scientific community has developed simple and sophisticated methods for measuring and estimating recharge (e.g., Scanlon et al., 2002), but because natural systems are so dynamic, and the processes so complex, accurate estimates of recharge are often difficult to obtain. Simmers (1987) identified one of the main problems with recharge estimation: "No single comprehensive estimation technique can yet be identified from the spectrum of methods available; all are reported to give suspect results." With this in mind, it is important to recognize the limitations of groundwater recharge estimation techniques and the consequent limitation on our ability to predict how an aquifer system will respond to natural and anthropogenic change.

4.2 WHAT IS GROUNDWATER RECHARGE?

Recharge is the process by which groundwater is replenished. Thus, recharge contributes to the overall volume of fresh water available in the ground. Water can enter the ground either directly from rainfall and snowmelt (direct recharge), indirectly from influent streams and rivers (indirect recharge), or from a concentrated source resulting from the horizontal surface flow of water in the absence of well-defined channels (localized recharge) (Lerner et al., 1990).

Groundwater is found in both unconfined and confined aquifers (Figure 4.1). Unconfined, or water-table, aquifers are shallow and frequently overlie one or more confined aquifers. They are recharged through permeable soils and subsurface materials above the water table. Unconfined aquifers usually contain younger water (light blue arrows in Figure 4.1) with shorter travel paths, and less mineralization. Surface contamination, originating, for example, from agriculture or other land surface activities, can potentially be transported down to the water table of an unconfined aquifer and pose a threat to water quality. Consequently, unconfined aquifers are generally more vulnerable to contamination originating from surface or near surface activities. Confined aquifers usually occur at depth, and may overlie other confined aquifers. Confined aquifers may be recharged at some distance from a point of extraction and, in some cases, very deep aquifers may be recharged in remote mountain ranges. Typically this groundwater is

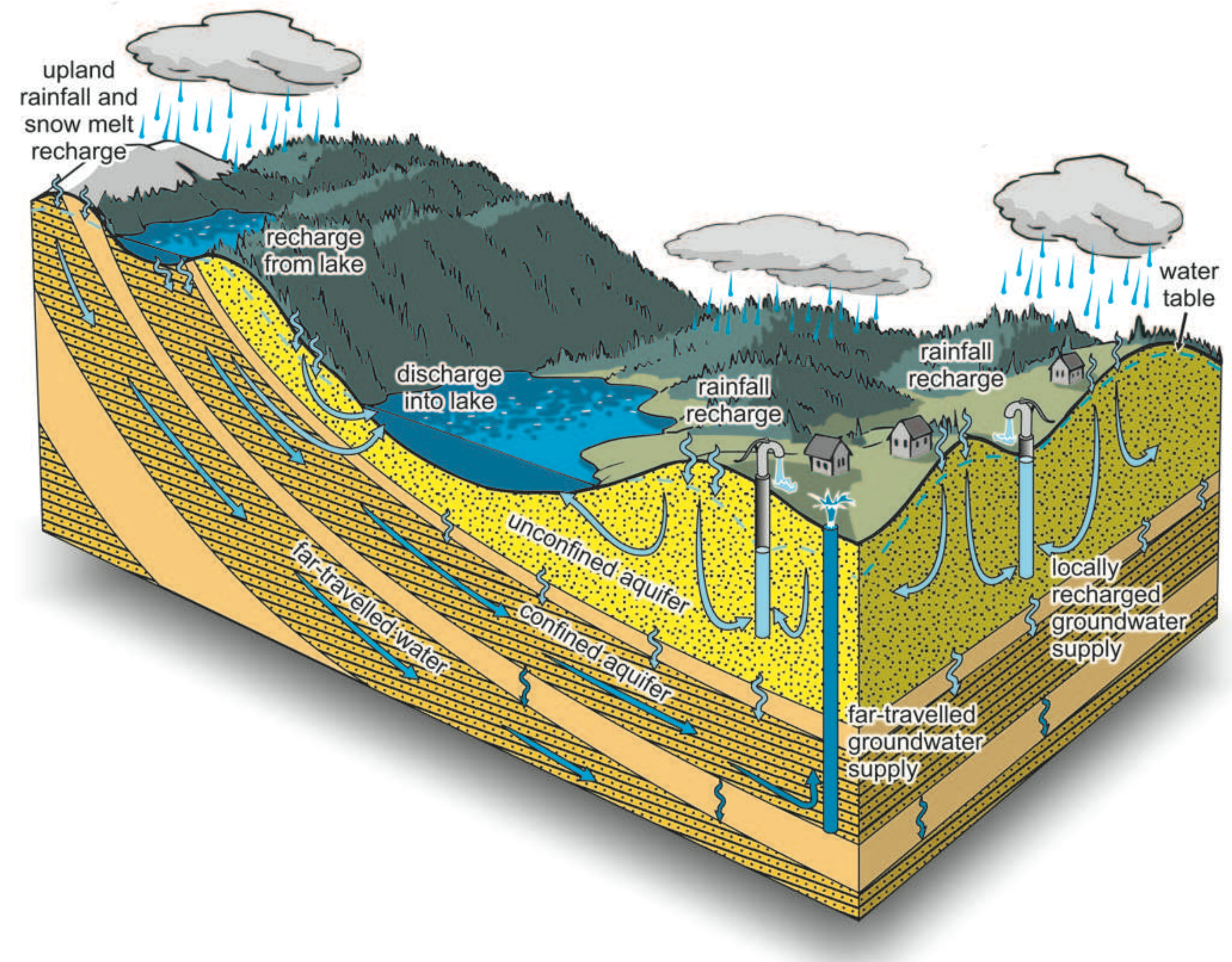


Figure 4.1 Groundwater in unconfined and confined aquifers showing various rrecharge and discharge pathways. Groundwater is recharged both at high elevation and low elevation from snowmelt and rain. Groundwater typically flows from areas of high to low elevation, and often discharges in lakes or streams situated at low elevation.

older (dark blue arrows in Figure 4.1) and often more mineralized due to its longer contact with the rocks and sediments. Water infiltrating bedrock in the mountains may flow downward and then move laterally into confined aquifers. In some regions, confined aquifers extend for many hundreds of kilometres beneath the land surface, and may cross natural surface watershed boundaries or jurisdictional boundaries. As such, groundwater in a confined aquifer may recharge in one watershed and discharge in another, or perhaps recharge in one province or nation, and discharge in another. Confined aquifers can also be recharged through cracks or openings in the less permeable layers above or below them. Even low permeability clay tills have been shown to provide pathways from the surface to confined aquifers (van der Kamp, 2001). Confined aquifers in complex geological formations may be partly exposed at the land surface, or the low permeability confining layer may be breached, allowing direct recharge from infiltrating precipitation.

Direct and indirect recharge processes in the shallow subsurface are illustrated in Figure 4.2, which shows water directly reaching the water table of an unconfined aquifer through the vadose

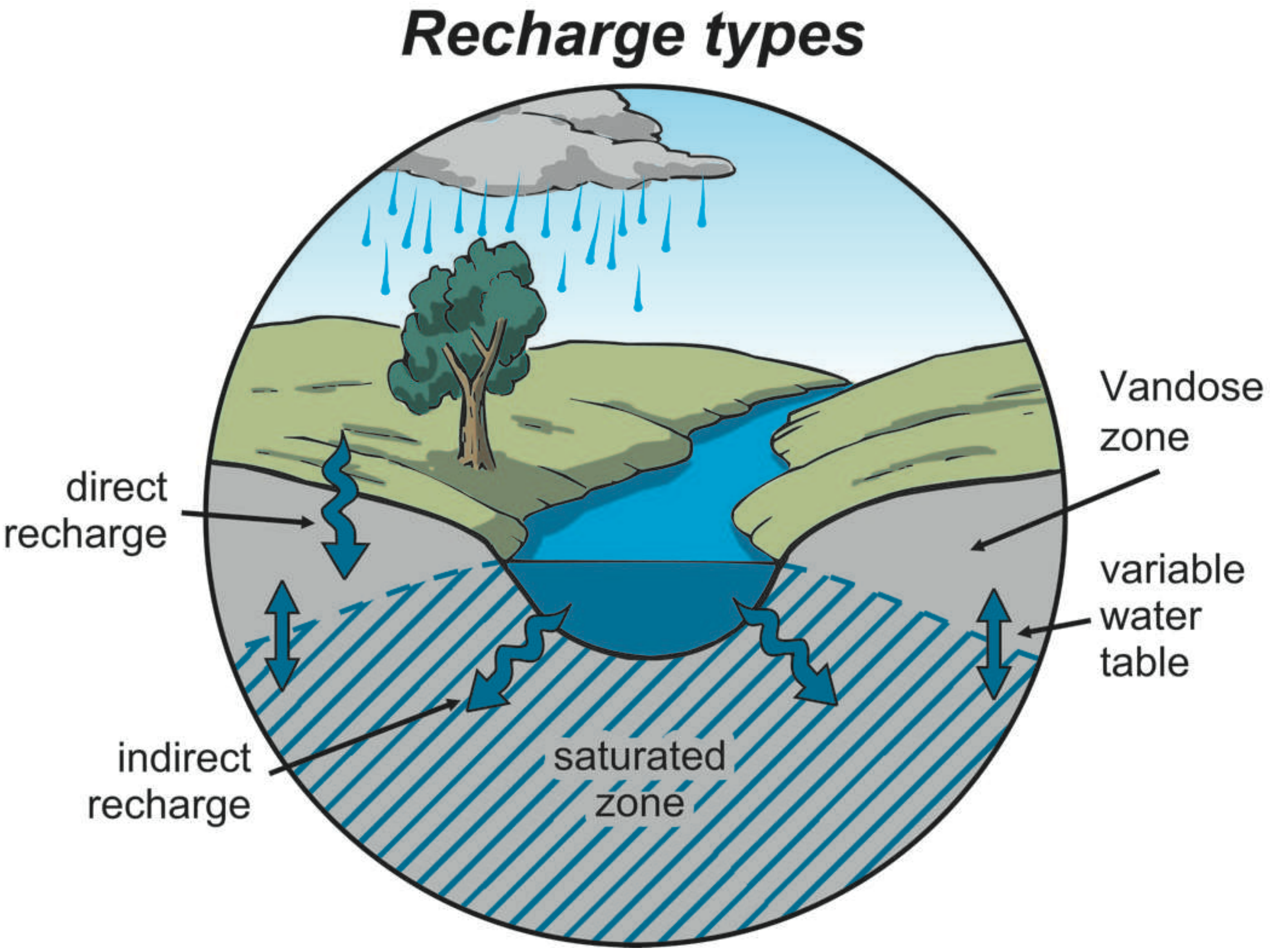


Figure 4.2 Direct recharge occurs directly from precipitation (rainfall, snowmelt) when water enters the unsaturated zone and percolates downward to the saturated zone. Indirect recharge occurs through influent streams, rivers and lakes, contributing water to the saturated zone. In both cases, the water table responds dynamically, and its height varies seasonally.

zone and also entering the groundwater system via an influent stream. In some areas, groundwater systems are recharged by both direct and indirect mechanisms. For example, the unconfined Grand Forks aquifer in south-central British Columbia (Box 4-1) receives recharge both directly from precipitation and from the Kettle River, which meanders through the valley.

Direct recharge is the focus of this chapter and, hereafter, is referred to simply as groundwater recharge. A detailed treatment of indirect mechanisms of groundwater recharge, through the interaction with surface water systems, is discussed in Chapter 5.

The rate of direct recharge in arid and semiarid environments is very small because evapotranspiration demands often exceed available precipitation. Short-term additions of groundwater to shallow aquifers may be subsequently extracted by evapotranspiration without contributing to aquifer replenishment (de Vries and Simmers, 2002). As a result, indirect and localized recharges play important roles in these environments. For example, in southern parts of the Prairie Provinces, the driest region in Canada, lateral flow of snowmelt and storm runoff concentrates water into topographically closed

depressions, causing depression-focused groundwater recharge (Box 4-2).

4.3 RECHARGE, DISCHARGE AND GROUNDWATER FLOW

A **recharge area** is where the net direction of groundwater flow is downward, thereby contributing to groundwater storage in the aquifer. Most areas, unless composed of solid rock or covered by pavement in developed areas, allow a certain amount of infiltrated water to percolate through the unsaturated zone and reach the aquifer. Areas that transmit the most water are often referred to as "**high**" or "**critical**" **recharge areas**. In the case of unconfined aquifers, precipitation moves downward to the water table. In the case of confined aquifers, groundwater from distant areas, or from overlying or underlying aquifers, can contribute to recharge. The geometry of the aquifer (where it outcrops) and the permeability of the overlying and underlying geologic units all determine where recharge to confined aquifers occurs. Recharge in shallow aquifers can also occur in association with streams, rivers and lakes as discussed above.

Discharge areas are the opposite of recharge areas. They are the locations where groundwater leaves the aquifer and perhaps flows to the surface. Groundwater discharge occurs where groundwater flow is directed upward. In shallow aquifers, discharge occurs where the water table intersects the land surface. Springs and seeps may flow into freshwater bodies, such as lakes or streams, or they may flow into saltwater bodies. Groundwater can also move vertically upward from the water table as a consequence of evapotranspiration mechanisms. These processes effectively remove water from the saturated and unsaturated zones. Discharge from deep aquifers can occur through semi-permeable confining beds into shallower aquifer systems, and likewise, leakage from shallow unconfined aquifers can recharge deeper aquifers. Pumping wells are also an anthropogenic cause of groundwater discharge, affecting the rates as well as areas of recharge and discharge.

Groundwater usually flows from areas of high elevation to areas of low elevation (see Figure 4.1). However, mountains are not needed for recharge to occur, or for groundwater to flow. Recharge can occur at low elevations, and even small topographical changes can influence groundwater flow at local scales. Generally, the more permeable the rock or sediments and the steeper the topography, the faster the groundwater flow. The presence of pumping wells can also artificially increase the rate at which groundwater flows, because groundwater is drawn towards the well using a pump.

4.4 HOW OLD IS THE GROUNDWATER?

The time that groundwater spends in the ground is referred to as the **residence time**, and this can vary from days to millions of years, depending on the geology and physiographic setting. During its time in "residence", groundwater is said to exist in **storage**, although, while in storage, groundwater continues to flow from its recharge area to a discharge area or point of extraction.

Groundwater flow in aquifers comprised of low permeability rock, even in steep terrain, will often be sluggish, moving at rates of only a few centimetres per year. As a result, groundwater in deep, confined aquifers can be hundreds, or even millions, of years old. Very old groundwater is found in deep aquifers throughout the Prairies (Bachu and Underschultz, 1995) and other areas of Canada, such as the Canadian Shield (Clark et al., 2000; see also Chapter 11). Should this old groundwater be extracted, it could take thousands or millions of years to replenish the aquifer by natural processes.

Groundwater in unconfined, high permeability aquifers flows much more quickly than in confined aquifers, particularly when the topography is steep. Residence times for shallow groundwater are typically on the order of months or tens of years. These types of aquifers are replenished more quickly than confined aquifers, often on an annual basis, and, because of their shallow nature, are often connected to surface water bodies.

4.5 WHAT FACTORS CONTROL SHALLOW GROUNDWATER RECHARGE?

Groundwater recharge to shallow aquifers occurs when water from precipitation enters the soil's unsaturated zone (infiltration), percolates downward under the force of gravity through the root zone (drainage), and is ultimately added to the saturated zone of the groundwater system (recharge). The complex series of processes that control shallow groundwater recharge are both time dependent and spatially variable (Balek, 1988). This is how recharge contributes to the temporary or permanent increase in groundwater storage.

Shallow groundwater recharge is controlled by a number of factors. The climate of an area exercises the most important control on recharge because it determines not only the amount and timing of precipitation, but also temperature, relative humidity, and wind and air movement, all of which are important factors influencing evapotranspiration. Local physical and biological conditions at the land surface affect the amount of water infiltration. These conditions include topography (slope), the nature of the land use or land cover (vegetation or

TABLE 4.1 TOTAL PRECIPITATION FOR SELECTED MONTHS WITH ANNUAL TOTALS AND MEAN DAILY TEMPERATURE FOR DIFFERENT CANADIAN CITIES

PLACE	PRECIPITATION (MM)					MEAN DAILY TEMPERATURE (°C)
	JANUARY	APRIL	JULY	OCTOBER	TOTAL ANNUAL	
Vancouver, B.C.	153.6	84.0	39.6	112.6	1199	10.1
Summerland, B.C.	29.7	25.6	30.2	18.0	326.7	9.0
Edmonton, Alta.	22.7	26.3	95.2	19.8	482.7	2.4
Calgary, Alta.	11.6	23.9	67.9	13.9	412.6	4.1
Regina, Sask.	14.9	23.5	64.4	21.8	388.1	2.8
Saskatoon, Sask.	15.2	23.9	60.1	16.7	350.0	2.2
Winnipeg, Man.	19.7	31.9	70.6	36.0	513.7	2.6
Toronto, Ont.	52.2	68.4	74.4	64.1	792.7	7.5
Ottawa, Ont.	70.2	72.4	90.6	79.4	943.5	6.0
Montreal, Que.	78.3	78.0	91.3	77.8	978.9	6.2
Quebec, Que.	89.8	81.2	127.8	101.7	792.7	7.5
Moncton, N.B.	119.2	99.3	103.3	103.8	1223.2	5.1
Halifax, N.S.	149.2	118.3	102.2	128.7	1452.2	6.3
Charlottetown, P.E.I.	106.4	87.8	85.8	108.6	1173.3	5.3
St. John's, Nfld.	150.0	121.8	89.4	161.9	1513.7	4.7
Whitehorse, Yukon	16.7	7.0	41.4	23.8	267.4	-0.7
Yellowknife, N.W.T.	14.1	10.8	35.0	35.0	280.7	-4.6
Iqaluit, N.T.	21.1	28.2	59.4	36.7	412.1	-9.5

All figures based on the 30-year period 1971 to 2000 inclusive. Source: Environment Canada (2002). Stations typically located at airports.

pavement), characteristics of the soil and geologic substrate, depth to the water table, and other factors. Recharge is promoted by cool wet climates, natural vegetation cover, flat topography, permeable soils, a water table that lies at some depth (not at surface), and the absence of low permeability confining beds. Some of these factors vary with time (e.g., land use), while all vary spatially.

4.5.1 Climate across Canada

The climate of a region also plays an important role in groundwater recharge. Although climate is influenced by regional to very local effects, it is most commonly described in terms of precipitation and temperature.

Precipitation (P) is a major component of the hydrologic cycle, and the most important climate variable controlling recharge. Precipitation reaches the Earth's surface in many different forms, including rain, freezing rain, snow, sleet, and hail. Some 71% of total precipitation in southern Canada comes from rainfall events. In northern Canada, more than 50% of total precipitation comes from snowfall events (Zheng et al., 2001). The form of precipitation and its timing are as important as the amount that falls.

Canada's land area does not receive uniform precipitation. The west coast receives 2,500 to

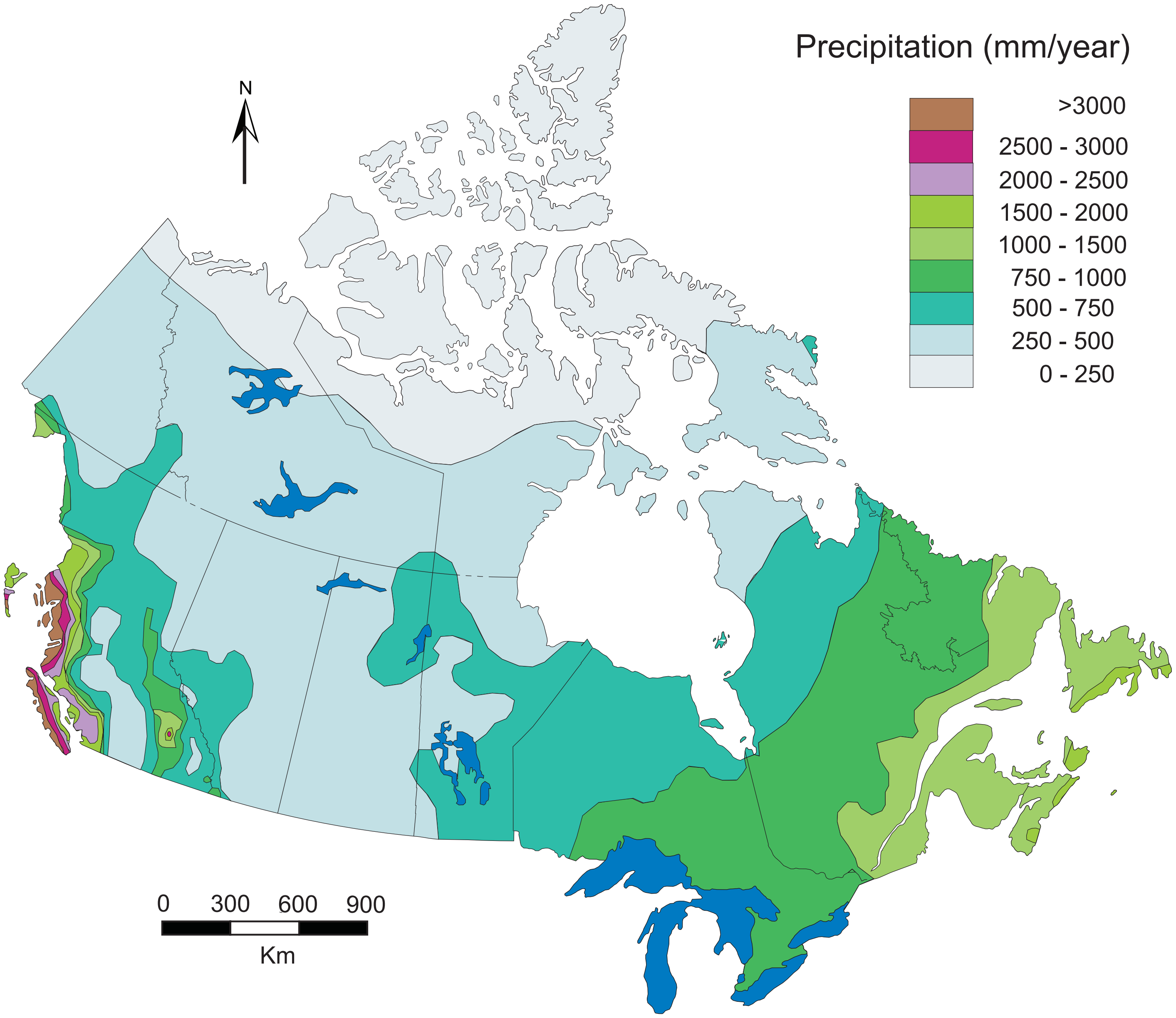


Figure 4.3 Variation in mean annual precipitation (mm/year) across Canada (based on Canada precipitation map, Department of Energy, Mines and Resources, Forestry (now Natural Resources Canada), 1991).

over 4,000 millimetres of precipitation annually, compared with 1,000 to 1,250 millimetres on the east coast, and 250 to 500 millimetres on the Prairies (Figure 4.3). The extreme north receives little precipitation, no more than 120 to 150 millimetres per year, which falls mainly as snow. Table 4.1 provides representative seasonal precipitation values (for the months of January, April, July, and October) as well as total annual precipitation for different cities across Canada.

Temperature (T) also varies regionally, although not as dramatically as precipitation. Maximum summer temperatures range from 15°C to about 20°C, and winter lows range from about 5°C on the west coast to below -20°C in Iqaluit. Mean daily temperatures for selected Canadian cities are shown in Table 4.1.

4.5.2 Evapotranspiration and potential recharge

Evapotranspiration (ET) is the sum of evaporation and plant transpiration, and varies both regionally

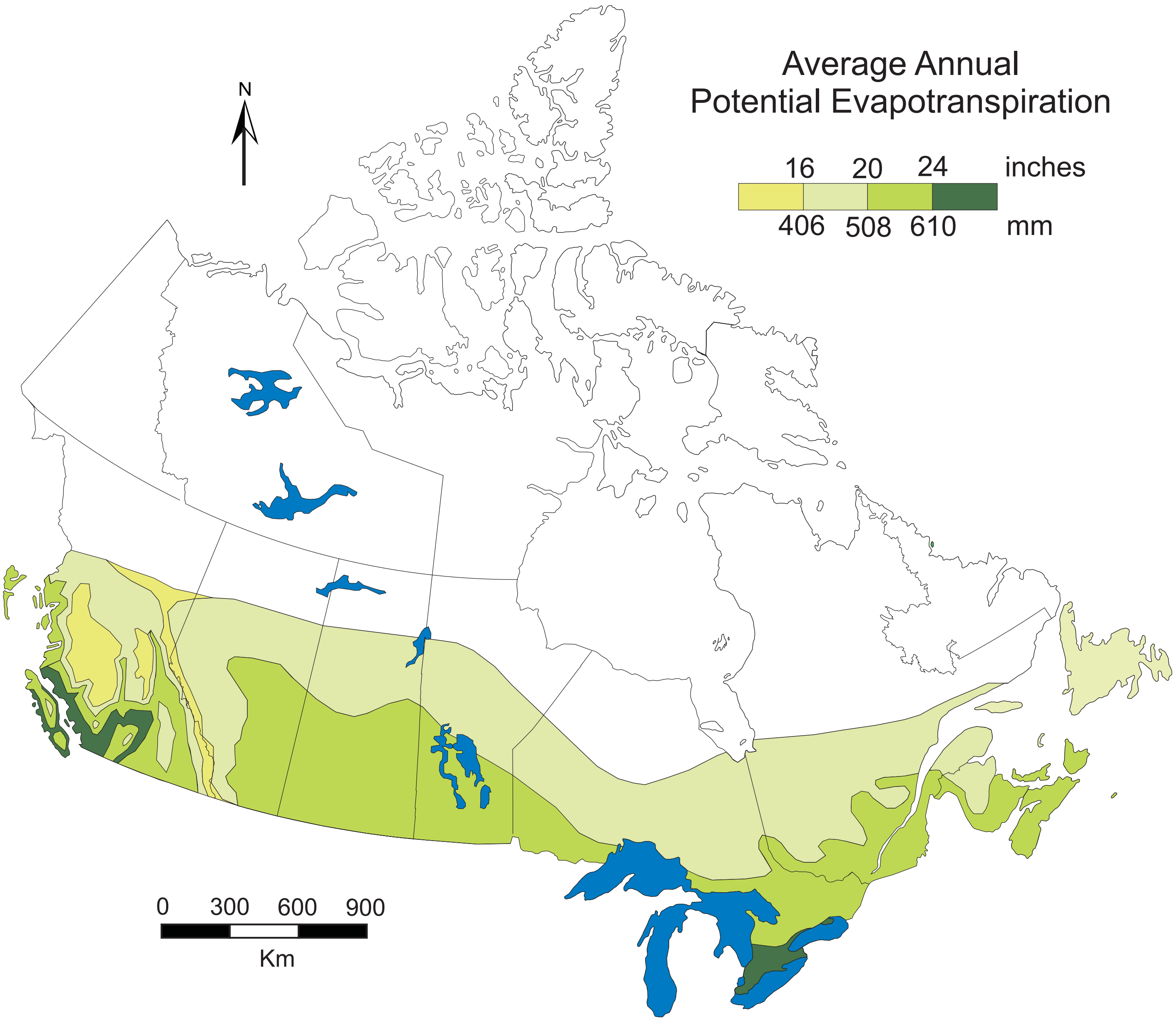


Figure 4.4 Average annual potential evapotranspiration (PET) in millimetres and in inches from ground and plant surfaces for areas where there is a continuous vegetation cover and sufficient soil moisture for plant use (based on National Atlas of Canada, 1974).

and seasonally. Evapotranspiration is closely tied to both precipitation, in terms of moisture availability, and temperature. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception, and water bodies. Transpiration accounts for water movement within a plant and subsequent loss of water as vapour through stomata in its leaves. Evapotranspiration is an important part of the water cycle. It is not only closely related to plant growth and carbon uptake but also an important hydrological component affecting runoff, atmospheric circulation, and groundwater recharge and discharge. ET is of key concern in climate change research.

Potential evapotranspiration (PET) is a measure of the atmosphere's ability to remove water from the surface through evaporation and transpiration, assuming an unlimited water supply. Actual evapotranspiration (AET) is the quantity of water actually removed from a surface due to

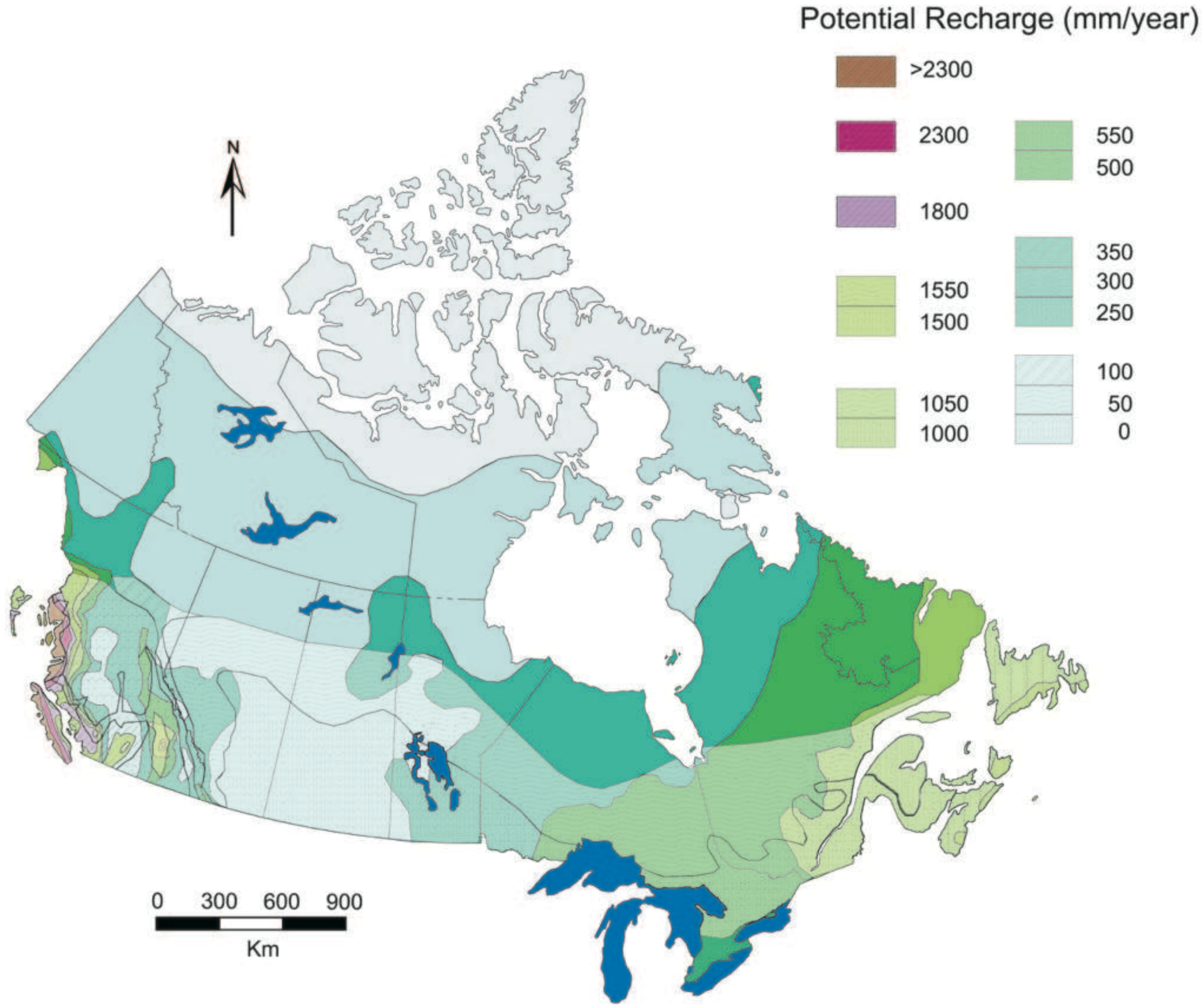


Figure 4.5 Annual potential recharge (precipitation minus potential evapotranspiration) across Canada.

evaporation and transpiration. AET can never be greater than PET, and it can be lower if there is not enough water available to be evaporated, or if plants are unable to readily transpire. Average annual AET cannot exceed average annual precipitation because precipitation sets the limit on how much water is available. Figure 4.4 is an average annual potential evapotranspiration map of Canada.

Potential recharge is the difference between precipitation and potential evapotranspiration, and represents the net amount of water available for groundwater recharge. Not all potential recharge may enter the ground due to runoff. Figure 4.5 is a map of potential recharge constructed by subtracting the mid-range mean annual PET from mean annual precipitation in each Canadian zone. (A more accurate representation of potential recharge would require estimates of AET; however, Fig 4.5 provides a regional picture of how recharge potential might vary across the country.) Potential recharge for Northern Canada is not shown due to lack of potential evapotranspiration data. Recharge potential is expected to be

greater in areas that are moist and that have relatively low evapotranspiration (e.g., West Coast, Kootenays, Rockies, Southern Ontario and St. Lawrence Lowlands, and Maritime provinces). Canada's climate generally favours groundwater recharge (compared to that of other countries around the world), particularly in our coastal regions where moist conditions and relatively low evapotranspiration are common.

Of course, the climate of any region includes variability over time, and these changes invariably affect groundwater recharge (see end of this chapter).

Local surface conditions within a region, including topography, vegetation, soil, and aquifer permeability, also affect recharge. Recharge can vary substantially even when the same climate conditions prevail throughout a region.

4.5.3 Physical and biological controls on infiltration

Infiltration is the process by which water on the ground surface enters the soil. Infiltration is governed by gravity and capillary forces. While smaller pores offer greater resistance to gravity, very small pores will pull water through capillary action in addition to and even against the force of gravity. Infiltration occurs via two different types of mechanisms: piston or translatory flow (wherein precipitation stored in the unsaturated zone is displaced downward by the next infiltration or percolation event without disturbance of the moisture distribution), and preferential flow, in which flow occurs through preferential pathways or macropores (e.g., root channels, animal burrows).

The rate at which water can infiltrate soil depends on a number of factors, including soil texture and structure, presence of preferential pathways, vegetation types and cover, soil temperature, water content of the soil, topography, and rainfall intensity. Coarse-grained sandy soils have large spaces between the grains that allow water to infiltrate quickly. Macropores (large pores) can greatly enhance the permeability of fine-grained soils by forming preferential pathways for water.

Vegetation influences recharge through interception and transpiration, and other less commonly characterized, yet potentially significant, processes such as stemflow and throughfall (Le Maitre et al., 1999; Taniguchi et al., 1996). The vegetation canopy and the top layer of undecomposed leaf litter create porous soils by protecting the soil from pounding rainfall, which can close natural gaps between soil particles. Plant roots also play an important role in the recharge process by enabling plants to draw water from deep in the vadose zone (and even from the saturated zone) and by creating preferential flow paths and channels that aid infiltration (Le Maitre et al, 1999).

When the soil temperature drops to below freezing, a layer of frozen soil can develop below the ground surface. This frozen soil inhibits infiltration, especially if it is so heavily saturated that the pores are filled with ice. Frozen soils throughout most of Canada inhibit water filtration from melting snow, leading to a spring pulse of runoff and streamflow.

When soil becomes saturated during rainfall or snowmelt, its moisture content increases, resulting in a lowering of the soil's capacity to accept infiltrating water. The infiltration process can continue only if there is room available for additional water at the soil surface. Available volume for additional water in the soil depends on the soil's porosity and on the rate at which previously infiltrated water can move away from the surface. The maximum rate at which water can enter soil in any given condition is described as the **infiltration capacity**. When this rate is less than the infiltration capacity, all the water will infiltrate. When rainfall rate exceeds infiltration capacity, surface ponding occurs. Porosity is followed by **runoff** over the ground surface once depression storage is filled. Runoff includes water travelling over land and through small rivulets to reach a stream, and **interflow**, water that infiltrates the soil surface and travels by means of gravity towards a stream channel (always situated above the main groundwater level), eventually empting into that channel. Technically, interflow is not groundwater because it occurs above the water table.

Land surface topography also plays an important role in determining infiltration. Generally, steep terrain favours runoff, and flat terrain favours infiltration. Microtopography can result in depressions that hold water or snow, effectively allowing more time for infiltration to occur because runoff water is contained (see Box 4-2).

Horton (1933) suggested that infiltration capacity declines rapidly during the early part of a storm and then, after a couple of hours, tends towards an approximately constant value for the remainder of the event. Water that had previously infiltrated fills the available storage spaces and reduces the capillary forces drawing water into the pores. Clay particles in the soil may swell as they become wet and thereby reduce pore size. On ground which is not protected by a layer of forest litter, raindrops can detach soil particles from the surface and wash fine particles into surface pores where they can impede infiltration.

Rainfall intensity is perhaps a less obvious control on infiltration. One might expect that the more

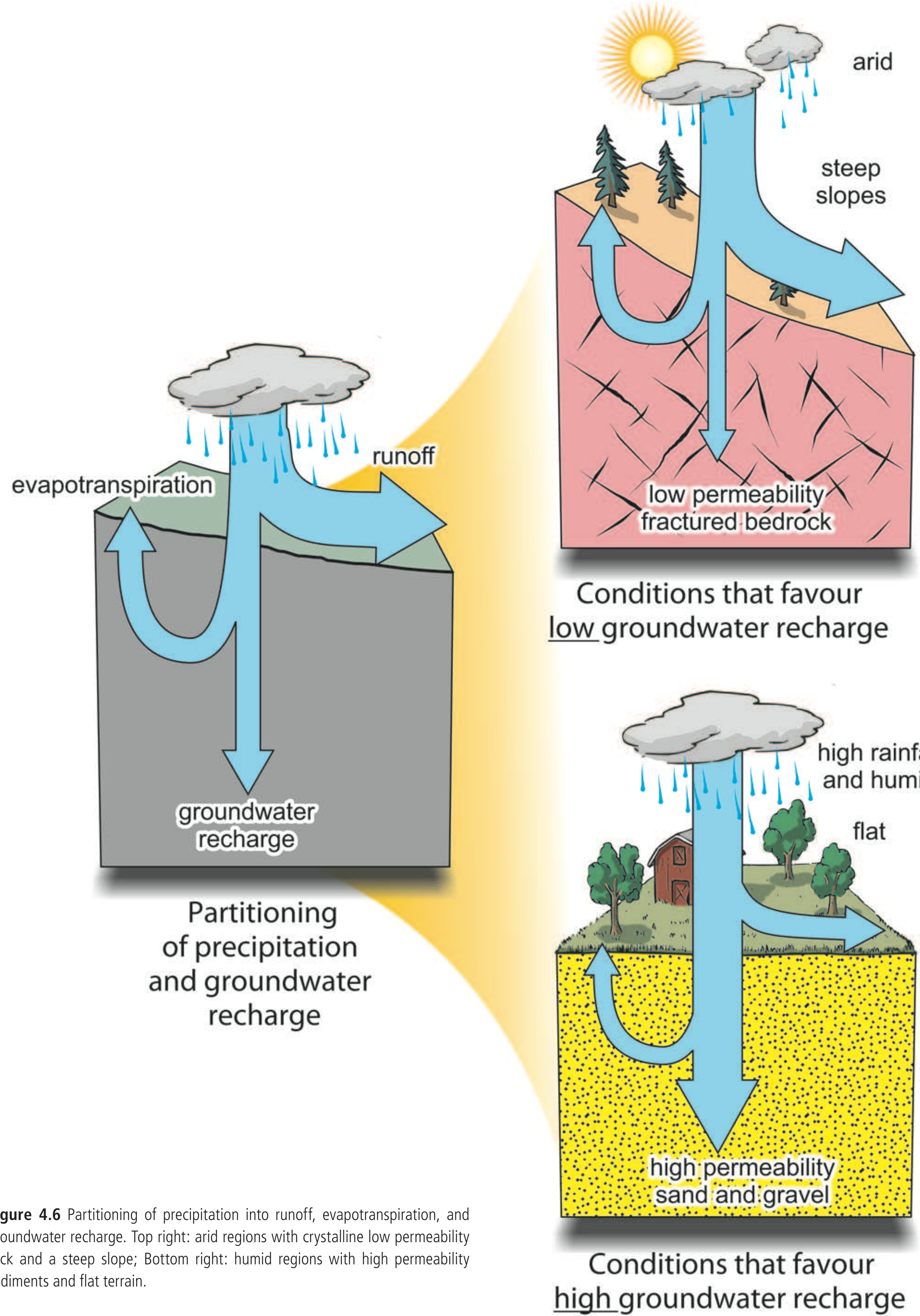


Figure 4.6 Partitioning of precipitation into runoff, evapotranspiration, and groundwater recharge. Top right: arid regions with crystalline low permeability rock and a steep slope; Bottom right: humid regions with high permeability sediments and flat terrain.

it rains, the more infiltration will occur. Intense rain events, however, often result in more runoff because the precipitation rate exceeds the infiltration rate. Climate change projections suggest that while many areas of Canada will receive more annual precipitation, this precipitation may occur as extreme rainfall events. Thus, projections for increased mean annual or mean monthly rainfall may not result in greater groundwater recharge.

4.5.4 The shallow recharge process

Precipitation landing on the ground can do one of three things: infiltrate, reside as depression storage, or run off. Once water has infiltrated, it may remain as water in soil storage. This water is also available to plants for uptake through their root systems, or it can be lost by evaporation (upward movement of water by capillary action through the soil matrix), or percolate down to the water table, where it becomes groundwater recharge.

The general partitioning of precipitation into a runoff component, evapotranspiration, and groundwater recharge is illustrated in Figure 4.6. The top right figure represents conditions that favour low groundwater recharge, including arid climate, bare soil and/or exposed bedrock, and steep topography. The lower right figure represents conditions that favour high groundwater recharge, including a humid climate with high precipitation, and generally flat topography with sparse vegetation.

The role of vegetation is not explicitly considered in this figure. Forested areas may be areas of high evapotranspiration. Because water transpired through leaves comes from the roots, plants with deep reaching roots can transpire water more constantly, especially during dry periods when the shallow root zone dries out. In dry conditions herbaceous plants transpire less than woody plants because herbaceous plants lack a deep taproot. Woody plants keep their structure over long winters while herbaceous plants in seasonal climates must grow up from seed contributing little to evapotranspiration during the spring. Factors that affect evapotranspiration include a plant's growth stage or level of maturity, percentage of soil cover, solar radiation, humidity, temperature, and wind. Forests reduce water yield through evapotranspiration.

Landslope and permeability of sediments or rocks lying within the unsaturated zone exercise important controls on the amount and timing of groundwater recharge. Materials with high permeability, such as sand and gravel, favour groundwater recharge: unconfined aquifers comprised of sand and gravel typically have high groundwater

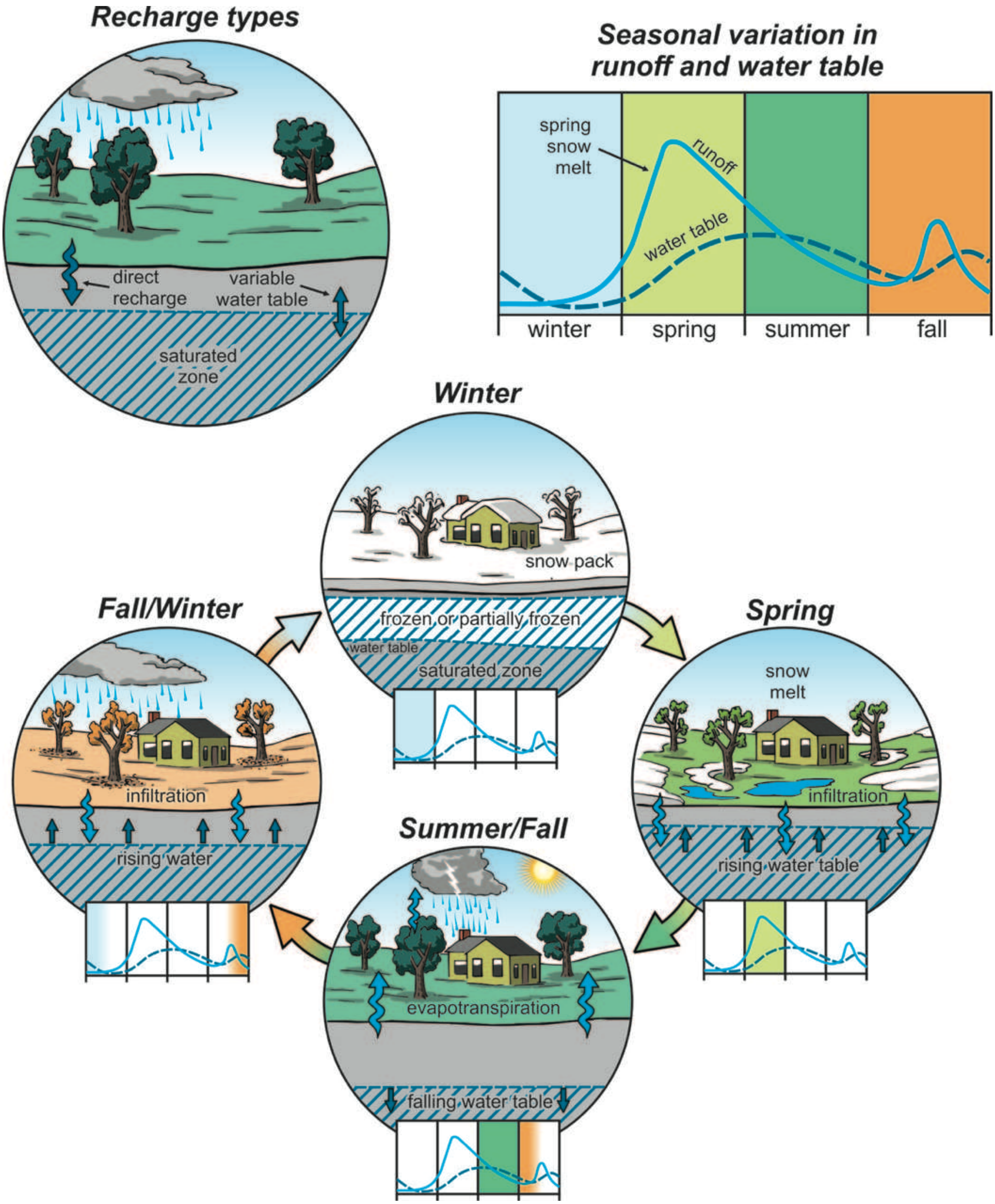


Figure 4.7 Seasonal responses of the water table in response to variable groundwater recharge, or no recharge.

recharge rates. In contrast, materials of low permeability, such as crystalline rock, tend to inhibit groundwater recharge. Consequently, groundwater yields from fractured rock aquifers are generally low and can become unsustainable when pumped for long periods. Fractures and faults, however, have been observed to act as conduits for groundwater recharge and, when tapped by a well, will often yield higher quantities of groundwater when compared to unfractured areas. Should the water table lie within bedrock, infiltrated water will likely move as interflow within the unsaturated zone, ultimately discharging down slope. Bedrock recharge is uncertain in many areas, particularly in mountain regions. Even in these terrains, however, some percipitation can infiltrate the bedrock to recharge groundwater (Smerdon et al., 2009).

Anthropogenic factors, such as roads, buildings, agriculture, or forest harvesting, can impact natural infiltration and groundwater recharge. Urban locations often have reduced infiltration and groundwater recharge: in response, some developers and/or municipalities across the country are experimenting with innovative engineering designs for capturing storm water runoff in collection ponds or through the creation of infiltration galleries. The impacts of agriculture and forestry on groundwater recharge are complex. Removal of natural vegetation for agriculture often leads to greater runoff with soils becoming more vulnerable to erosion and compaction. Agricultural regions often require some form of artificial precipitation, or irrigation, during summer. When potential evapotranspiration is greater than actual precipitation, the soil will dry out, unless irrigation is used. The effect of logging on groundwater is not as wel-understood. Although the removal of trees effectively reduces evapotranspiration losses, thereby promoting groundwater recharge (e.g., Bent, 2001), the loss of the tree canopy and root systems can be expected to bolster increased runoff. Insufficient scientific studies exist on this subject.

4.6 AQUIFER RESPONSES TO INFILTRATION AND RECHARGE

Recharge is usually accompanied by a rise in water level within aquifers. In unconfined aquifers, this rise tends to coincide with higher stream flows or lake levels. Groundwater level peaks, however, are often delayed in comparison to peak levels of surface water bodies. Figure 4.7 provides a conceptual model of an unconfined aquifer illustrating seasonal variations in direct groundwater recharge and the resultant water table response. The model does not represent any specific area of the country, but demonstrates runoff and recharge processes which cause water level variations in aquifers.

Except for those areas with milder climates, most ground in Canada is frozen during the winter, and precipitation falls as snow. Runoff is at a minimum. Water levels in an aquifer, however, may still remain high as a result of the previous year's fall and early winter recharge. This situation continues until spring, when the ground thaws and melt water from snow or spring rain are finally able to infiltrate the soil. Surface runoff typically increases during this time and may even persist into summer depending on the runoff source. Snow pack and/or glaciers at high elevation, for example, melt late in spring and deliver water via stream runoff to lower elevations well into summer. Most of Canada is warm during the summer, and evapotranspiration rates are high. Runoff is generally low, apart from the occasional summer precipitation event. These conditions produce a gradual decline in the water table, which persists into the fall. High spring-summer water

demands in Canada for plant growth, combined with higher evaporative losses from soil and surface water bodies, result in declining water levels. The fall usually brings somewhat wetter conditions to most parts of the country, with consequent small increases in runoff and water table levels. In colder regions, this fall precipitation may occur as snow.

The magnitude and timing of increasing water table levels vary from year to year, depending on the climate and anthropogenic factors. Some years are simply wetter than others, and some are colder. Therefore, groundwater levels, as depicted in a well hydrograph, vary seasonally from year to year when viewed over the long term.

Water table elevation also varies on short time scales although these variations depend on recharge nature, aquifer permeability, depth to the water table, and amount of available storage in the aquifer. Long and moderate-volume precipitation events tend to result in greater overall recharge as compared to intense, short-duration rain events. A comparison between two aquifers of the same material reveals that the one with the deeper water table will experience a delay in water level response due to deeper water level. High-permeability materials are able to transmit water more readily than low-permeability materials and, consequently, the response is more rapid. Aquifer storage availabilty also acts to mediate the response, as aquifer materials with high storage capacities have a much smaller overall change in water level following a recharge event. Consewuently, some aquifers record precipitation events very effectively, showing high frequency variation. Most aquifers, however, only record long-term water level changes accompanying seasonal precipitation variations. The recharge response of confined aquifers tends to be less

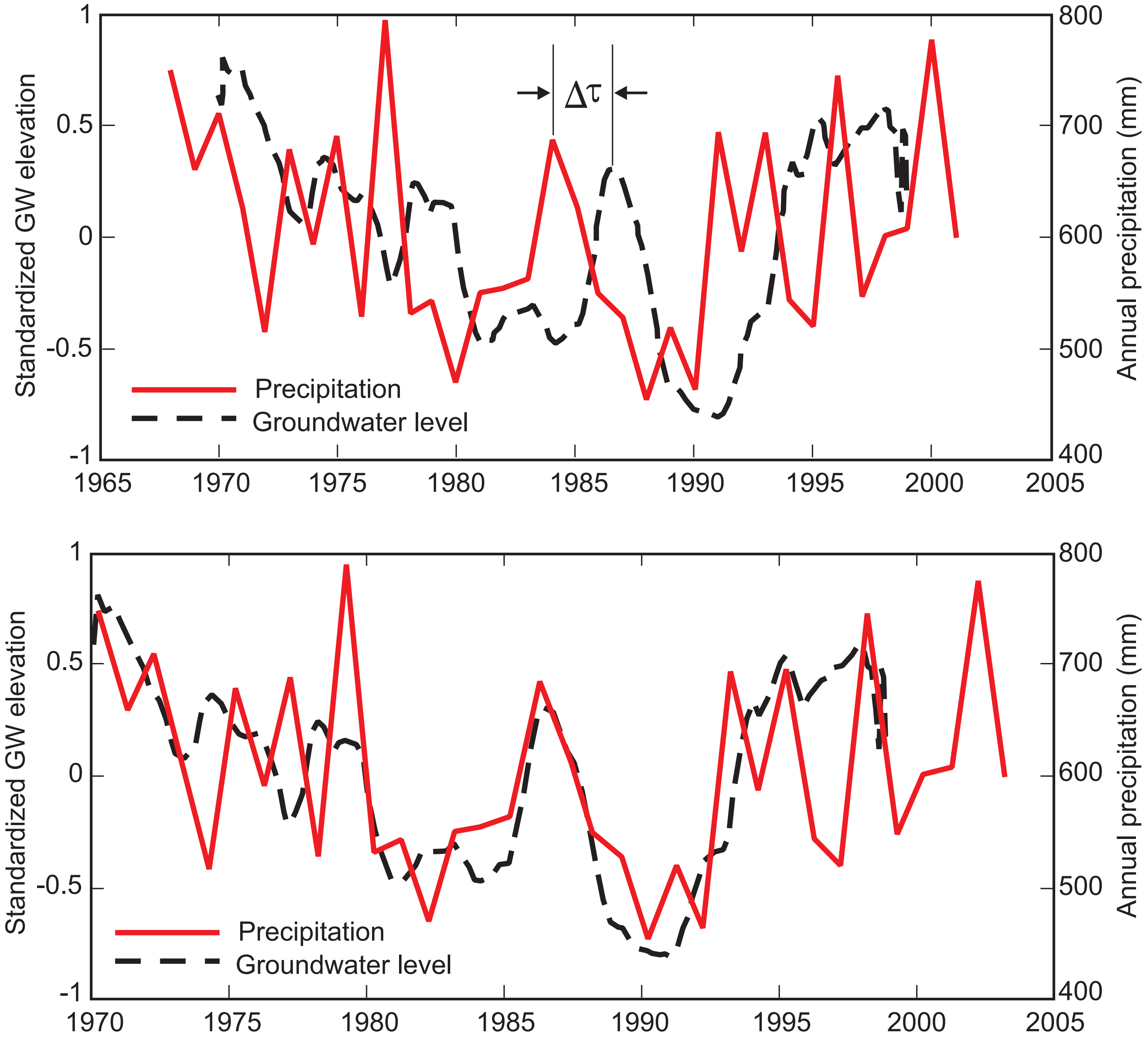


Figure 4.8 Annual precipitation and average standardized groundwater levels in 24 monitoring wells in the Winnipeg area.

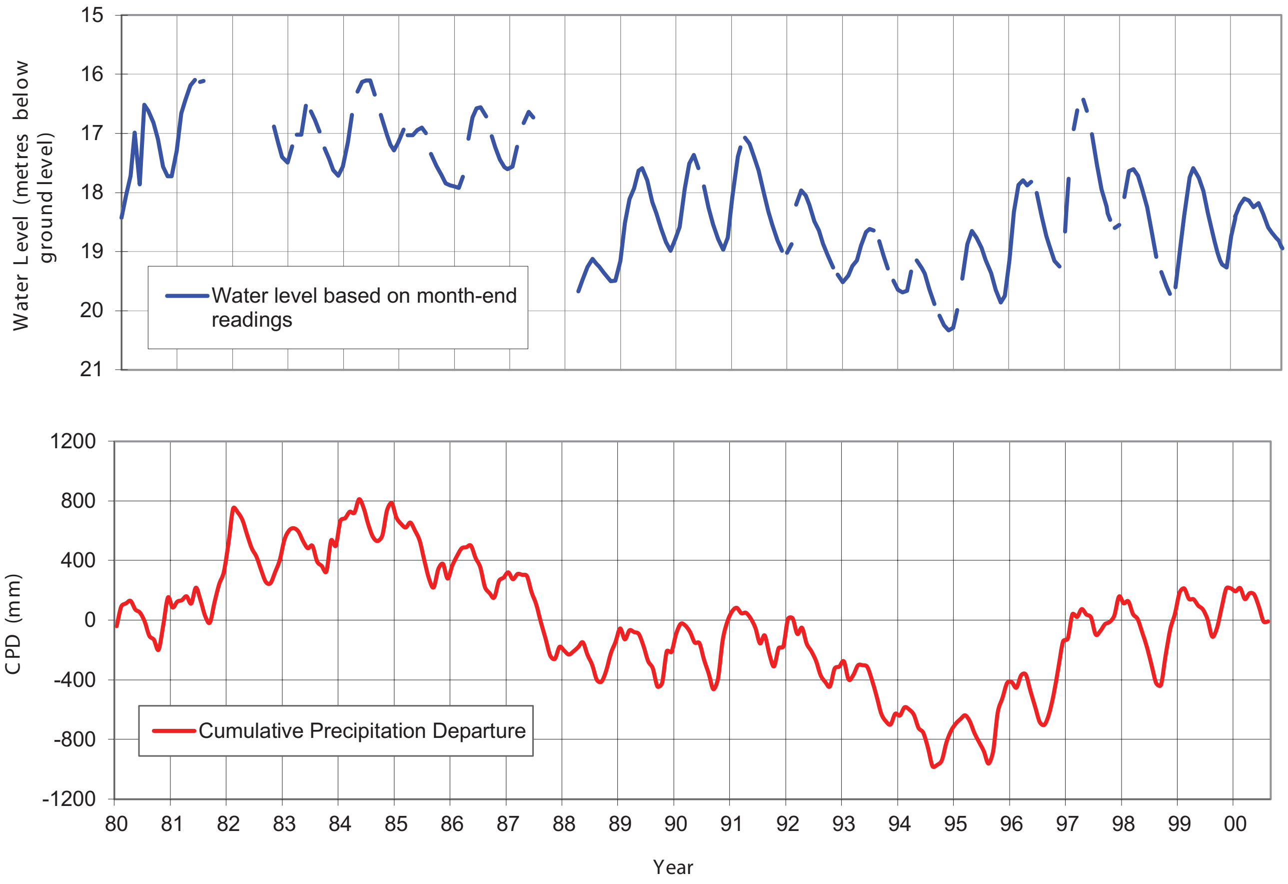


Figure 4.9 Aquifer water level and cumulative precipitation departure (CPD) for Abbotsford, British Columbia. Trends in groundwater level in this highly permeable aquifer are linked to precipitation trends as evidenced by the strong correlation between groundwater level and CPD prior to 1992. These trends are believed to be associated with phases of the El Niño Southern Oscillation (ENSO), namely, El Niño and La Niña (Fleming and Quilty, 2006). Water levels in the aquifer do not appear to correlate as well after 1990, suggesting some other factors, such as anthropogenic influences.

dramatic than that of unconfined aquifers. This is because the former are generally isolated from the near surface climate effect, or subject to recharge in distant areas. Confined aquifers, do, however, exhibit a strong response to barometric pressure variations and tides (Spane, 2002).

Two examples are provided to illustrate aquifer response to precipitation. Figure 4.8 charts annual precipitation (solid red) at the Winnipeg International Airport and standardized average water level (dashed black) calculated from 24 groundwater monitoring wells in the Winnipeg area. Standardizing groundwater levels is accomplished by determining the average water level and plotting the deviation from that water level at each measurement point. The values are referenced to zero deviation. The upper graph in Figure 4.8 illustrates the relationship between the variation of annual precipitation and generalized groundwater response. The groundwater response to recharge has a time delay (Δt) of approximately 2.2 years. When the annual precipitation graph is shifted backward by 2.2 years, the two curves correlate more closely (see lower graph). Groundwater flow systems have different abilities to retain and transport water, and goundwater residence time can vary from days to tens of thousands of years.

Figure 4.9 shows water level variation and cumulative precipitation departure (CPD) for a provincial observation well in Abbotsford, British Columbia. Cumulative precipitation departure can be used to assess water level fluctuations in observation wells completed in shallow unconfined aquifers. The CPD method involves calculating the difference between monthly precipitation and the mean monthly precipitation for a given historic period. A strong correlation between a CPD curve and a hydrograph indicates that precipitation has a major influence on water level at that well. A poor correlation indicates that the water level is controlled by another factor, such as a nearby river or anthropogenic influences (e.g., overwithdrawal). CPD is established for an arbitrary reference date and, therefore, comparison of different aquifers is possible only if consistent dates are used. For example, groundwater levels in Abbotsford are shown to correlate with the CPD in years prior to 1970. After 1970, the CPD curve and groundwater levels begin to diverge, with groundwater levels becoming lower up to 1976, and then rising to the end of the period of record. The reason for these differences in trends is uncertain, but could be related to anthropogenic causes such as pumping up to 1976, followed by intensive irrigation application as this area of the Lower Fraser Valley has intensive agriculture, particularly raspberry production.

Thus, while changes in groundwater level, in terms of year to year and season to season variability, are most commonly associated with relatively short-term variability in precipitation and temperature, groundwater levels also respond to anthropogenic and other influences. Most notable is the response of groundwater level to pumping. During the summer months it is not uncommon for groundwater levels to decline because of groundwater use. If the rate of pumping is sustainable, then groundwater levels will generally recover to levels representative of natural recharge conditions. The topic of groundwater sustainability is discussed in more detail in Chapter 6; however, it is

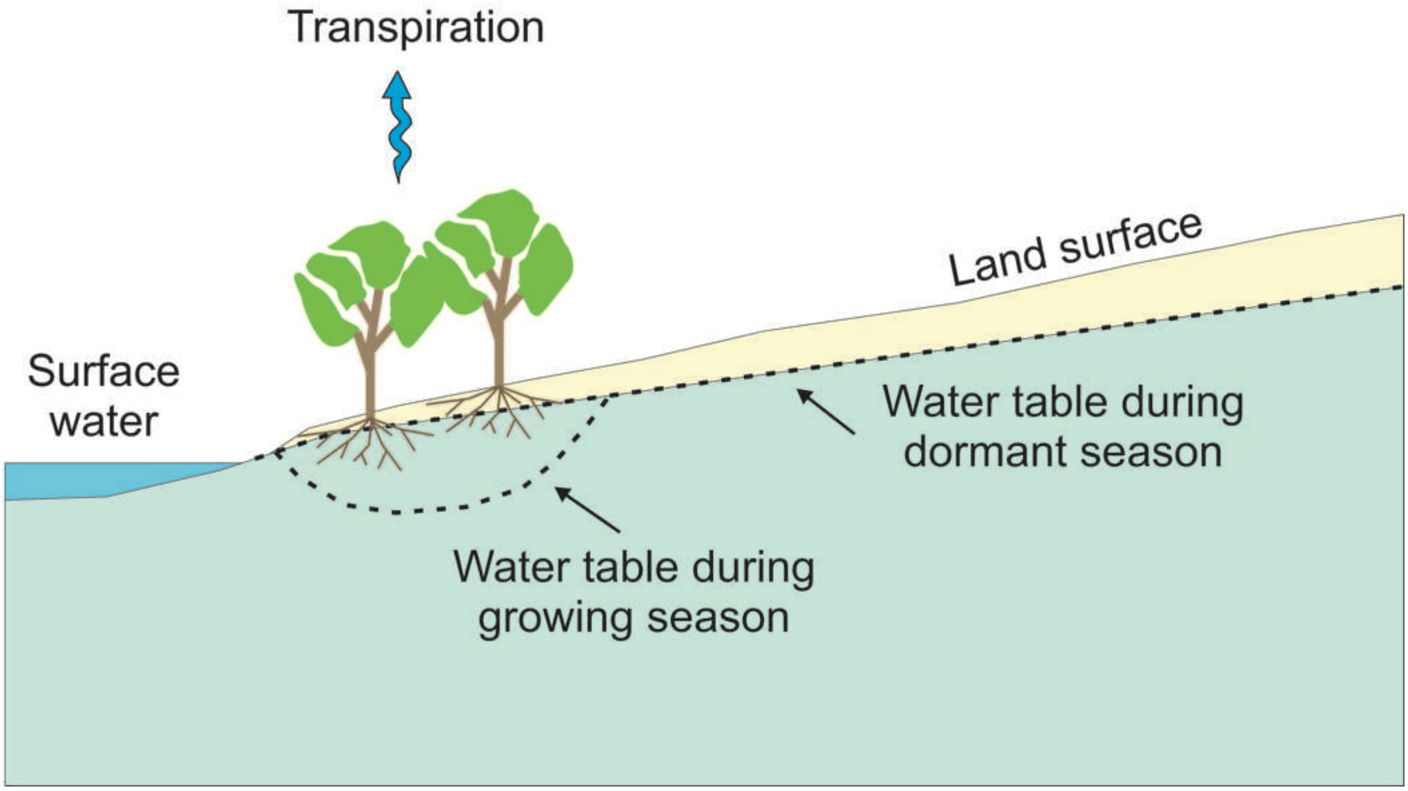


Figure 4.10 The effect of plants on the position of the water table (modified from United States Geological Survey, 2006).

worth mentioning here that some methods used to estimate recharge rely on groundwater fluctuation records which show water level rise and decline. When anthropogenic factors come into play, the natural system becomes difficult to interpret.

One more factor that can lead to natural shifts in groundwater level is vegetation demand. Vigorous vegetation growth during the summer months leads to higher transpiration losses. When the water table is below the depth of the plant's roots, plants will be dependent on water supplied by precipitation or irrigation. Figure 4.10 shows that where the water table is near the land surface (close to lakes and streams) roots can penetrate into the saturated zone below the water table, allowing transpiration directly from the groundwater system. Transpiration of groundwater commonly results in a drawdown of the water table much like the effect of a pumping well (cone of depression—the dotted line surrounding the plant roots in Figure 4.10) Daily fluctuations in groundwater level have also been observed to the extent that water levels vary by over one metre within 24 hours in response to the opening and closing of leaf stomata (Meyboom, 1966).

4.7 METHODS FOR ESTIMATING RECHARGE

There are as many methods available for quantifying recharge as there are different sources and processes of recharge. Each of these methods has its own limitations in terms of applicability and reliability. Recharge mechanisms, rates, and patterns in porous media are reasonably well studied and understood (Allison, 1988; Scanlon et al., 2002), but constraining and quantifying recharge rates and patterns in fractured rock systems are less studied, and generally less understood (Cook and Robinson, 2002; Scanlon et al, 2002).

The objective of any recharge study should be identified prior to the selection of an appropriate study method as this objective may dictate the required space and time scales of the recharge estimates (Scanlon et al., 2002). Groundwater resource evaluations, for example, require more information on recharge at large spatial and temporal scales, whereas assessments of aquifer vulnerability to pollution require more detailed information at local and shorter time scales.

Recharge estimation procedures are usually classified into three main categories: 1) physical—involving the direct determination of soil moisture flux, or catchment water flux, 2) chemical—utilizing natural solutes, tracers, and isotopes, and 3) modelling—often a combination of approaches providing greater confidence in the resultant recharge estimates.

Most recharge estimation methods are based on using measured or estimated values for some components of the water balance equation (Eq. 4.1) in order to predict other missing components. Determination of water balances can be carried out annually at the catchment (or aquifer) scale, or within a soil column located in the unsaturated zone. The various components of water balance equations are measured in millimetres per year. Freeze and Cherry (1979) calculate the water balance equation for a catchment as:

$$P = Q + ET + \Delta S_W + \Delta S_S + \Delta S_G \qquad (4.1)$$

where P is precipitation input, Q is the sum of the surface and groundwater (unsaturated and saturated) runoff, ET is evapotranspiration, ΔS_W is the change in storage of surface water, ΔS_S is the change in the soil moisture or change in storage in the unsaturated zone, and ΔS_G is the change in storage in the saturated groundwater zone. This equation assumes that the catchment is closed, and that there is no net inflow or outflow of groundwater to or from other catchments. Total change in storage is calculated as:

$$\Delta S = \Delta S_W + \Delta S_S + \Delta S_G \qquad (4.2)$$

Assuming no long-term climate change effects or groundwater and/or surface water mining, the changes in storage should approach zero in a natural system ($\Delta S = 0$). Therefore, Equation 4.1 can be simplified to:

$$P = Q + ET \qquad (4.3)$$

Equation 4.1 can be subdivided further to describe differences in the recharge and discharge areas. Thus, in the recharge area:

$$P = Q_W + Q_S + R + ET_R \qquad (4.4)$$

where Q_w is the surface water component of average annual runoff (the portion that does not infiltrate the soil), Q_s is the component of runoff that moves laterally through the unsaturated zone, R is the average annual recharge (water that percolates into the saturated zone), and ET_R is the average annual evapotranspiration in the recharge area.

Rearranging this equation gives an expression for groundwater recharge:

$$R = P - ET_R - Q_W - Q_S \qquad (4.5)$$

The total amount of runoff in the discharge area can be calculated by:

$$Q = Q_W + Q_S + D - ET_D \quad (4.6)$$

where D is the average annual discharge, and ET_D is the evapotranspiration in the discharge area (note that the sign of ET_D is negative). P is negligible in the discharge area compared to the other terms as discharge areas normally constitute a small percentage of the catchment area.

The change in groundwater storage is zero under natural steady-state conditions, thereby balancing recharge R and discharge D:

$$\Delta S_G = 0 = R - D \quad (4.7)$$

Short-term changes in storage ΔS_G can be realized, however, during spring and fall in many regions of Canada, as groundwater recharge occurs in response to spring melt or significant rainfall. Groundwater levels rise and the change in groundwater storage remains positive for some period of time. This rise results in a pulse of groundwater flow that gradually moves through the system, eventually discharging into streams, rivers, lakes, or the ocean. Annually, or perhaps, on average, over several years, the amount of recharge generally equals the amount of discharge, otherwise we would see a gradual rise or fall of water levels in the aquifer. Over time, the amount of groundwater held in storage usually remains constant. Of course, unsustainable pumping can lead to gradual water table declines and a loss of groundwater from storage. Irrigation over long periods may lead to a rise in the water table (water table mounding). This is becoming a significant problem in many arid regions around the world and is linked to groundwater salinization. Climate change may also alter the long-term stability of groundwater recharge and discharge dynamics.

The use of catchment water balance approaches for determining groundwater recharge requires careful measurements of all the various components.

4.7.1 Physical methods

Physical methods for estimating recharge all seek to quantify recharge directly from precipitation. Many rely on measuring components of the water balance equations above to determine recharge. In soil moisture methods, for example, recharge is estimated from the soil profile when losses to evapotranspiration (ET) are subtracted from the precipitation to give an **effective precipitation** value (e.g., Penman, 1948; Grindley, 1967). Soil moisture methods, therefore, rely on accurate measurements of actual evapotranspiration (AET) (Rushton and Ward, 1979), using instruments such as lysimeters, neutron probes, and time-domain reflectometry (TDR), which measure soil moisture content (Howard and Lloyd, 1979). Alternatively, actual evapotranspiration can be calculated as a fraction of potential evapotranspiration (PET), which is calculated from meteorological data using various models (Ragab et al., 1997).

The water balance approach is also used to estimate recharge for a watershed or catchment. Commonly, recharge is determined based on the assumption that the amount of baseflow in a stream is equal to the amount of recharge to the catchment. When the stream is at its lowest level (baseflow only), the surface runoff component is assumed to be zero, so that all the water in the stream is sourced from groundwater. Baseflow represents groundwater being discharged from aquifer storage (although the assumption may not be true for short time periods). Furthermore, the

A **lysimeter** is a measuring device, which can be used to measure the amount of actual evapotranspiration. By recording the amount of precipitation that an area receives and the amount lost through the soil, the amount of water lost to evapotranspiration can be calculated. Lysimeters are of two types: weighing and non-weighing. For a weighing type, the lysimeter consists of a buried container of soil equipped with a weighing device and a drainage system to measure evapotranspiration and percolation. The idea is that precipitation is measured locally, and the drainage through the lysimeter and volume of water stored in the lysimeter are measured by weighing periodically. The amount of water lost by evapotranspiration can be worked out by calculating the difference between the weight before and after the precipitation input.

A **neutron probe** is a device used to measure the quantity of water present in soil. A typical neutron probe contains a pellet of americium-241 and beryllium. Americium-241 is unstable and decays by alpha particle emission, with a by-product of gamma rays. In the neutron probe, the alpha particles collide with the light beryllium nuclei, producing fast neutrons, which then collide with hydrogen nuclei present in the soil as water molecules. During this collision process, they lose much of their energy. The detection of slow neutrons returning to the probe allows an estimate of the amount of hydrogen present. Since water contains two atoms of hydrogen per molecule, this therefore gives a measure of soil moisture.

Time-domain reflectometry (TDR) is an electronic instrument used to estimate soil water content. A very fast step voltage is introduced into a probe that is inserted into the soil or other porous medium. The velocity at which the pulse travels is related to the dielectric constant (characterizing the ability to store rather than to conduct energy) and this is a function of the soil moisture content. The technique can be used in combination with lysimeters and neutron probes to estimate evaporation from soils if measurements are taken at different intervals.

water balance method is based on identifying the groundwater recession portion of a streamflow hydrograph, using hydrograph separation techniques (e.g., Mau and Winter, 1997; Hannula et al., 2003; Halford and Mayer, 2000; Cherkauer and Ansari, 2005; Rutledge, 2007; Lim et al., 2005).

Catchment scale water balances are also typically based on assumptions that surface water and groundwater divides (imaginary boundaries across which water does not flow) coincide, which does not happen in many regions. Divides, in a surface water system, are often identified by the stream network, and the network of streams draining into a single stream defines the catchment area. In some cases, the groundwater catchment boundary coincides with the surface water catchment, although groundwater often moves more regionally, passing from one catchment to the next. In this case, there may be a net gain of groundwater to and a net loss of groundwater from the catchment. Some underlying assumptions for these catchment-scale water balance methods include: 1) the stream fully penetrates the homogeneous and isotropic aquifer; 2) the recharge is uniform over the aquifer; 3) the aquifer is underlain by impermeable rock; 4) there are no groundwater losses from evapotranspiration; and 5) there are no upstream flow diversions or flow controls.

Groundwater recharge can also be estimated using records of water table fluctuations (e.g., Healy and Cook, 2002). This procedure is referred to as a water table fluctuation method or well-hydrograph method, and is commonly used (Freeze and Cherry, 1979) with varying degrees of success (Sophocleous, 1985). The onset of a rain event causes a rapid rise in water table elevation to a peak level, followed by a steep recessional curve towards a new equilibrium value (Mew et al., 1997). The rate of elevation change in the water table during a groundwater recharge period is a function of groundwater recharge and the aquifer's specific yield (Sy). Kazman (1988) and Sophocleous (1985) point out that there is no precise correlation between a change in water table elevation and rainfall. Although levels rise during most rainfall events, they will not always produce the same water level change within a particular aquifer. This is because the specific yield may vary depending on moisture content, depth to the water table, and the rate at which these parameters change (Nachabe et al., 2005). A constant value of specific yield is usually employed in this procedure, although this can lead to overestimation of recharge (Sophocleous, 1985).

Johansson (1988) demonstrated that when the water table is deep enough, equilibrium water content develops in the upper portion of the soil profile. As a result the actual specific yield will be close to a constant value and will overestimate less. Regardless of the potential for changes in Sy, this particular parameter is often difficult to estimate with confidence, leading to uncertain recharge estimates.

4.7.2 Chemical methods

Estimation of groundwater recharge is often carried out by using solute or isotopic tracers to estimate vertical water movement in the subsurface. Hydrograph separation methods for determining baseflow and stormflow components can also be used. Uncertainties exist in all of these procedures, particularly related to the groundwater sampling.

Recharge estimations can be based on the concentration, and spatial and temporal distribution of natural tracers, such as tritium (^{3}H), the ratio of helium-3 to tritium (^{3}He/^{3}H), chlorine-36 (^{36}Cl), chloride (Cl), and gasses, such as chlorofluorocarbons (CFCs), that are introduced into the groundwater system through precipitation (Cook and Solomon, 1997; Cook and Bohlke, 2000). A multitude of other tracers artificially introduced into the ground may also be used. The rate of tracer movement is directly related to the rate of groundwater movement. Measurements of these tracer concentrations in both unsaturated and saturated zones may allow for direct groundwater dating, and identification of different sources for groundwater recharge (Clark and Fritz, 1997).

Many studies use a method based on chloride mass balance to estimate recharge. Tracer studies in the unsaturated zone utilize the position of the tracer peak, the shape of the tracer profile through the soil, and the total tracer concentration to estimate recharge (e.g., Sharma and Hughes, 1985; Scanlon et al., 2007). Recharge estimates in the saturated zone can be made by measuring concentration of chloride in groundwater if the amount of chloride deposited by the atmosphere is known. This determination assumes that chloride is conservative and is deposited in both wet and dry periods. A portion of the chloride will be recharged to the groundwater by percolation; therefore, the amount of recharge can be calculated by dividing the annual amount of wet and dry chloride deposition by the average chloride concentration of the groundwater. Net infiltration rates are then estimated from measured chloride concentrations using the relationship:

$$I = (P \times C_0) \times C_s \qquad (4.8)$$

where I is average net infiltration (mm/year); P is average annual precipitation (mm/year); C_0 is the effective average Cl concentration in precipitation (mg/L), including the contribution from dry fallout; and C_s is the measured Cl concentration in subsurface water (mg/L), which can be pore water, perched water, or groundwater. This calculation provides an actual groundwater recharge mean when several groundwater samples are used (Johansson, 1988). Although the method has been used successfully around the world, particularly in arid areas (Beekman and Xu, 2003), it cannot be used in areas where there are chloride sources other than precipitation (e.g., saltwater intrusion, saline soils). For those locations where chloride data is lacking, specific conductance data collected at stream-gauging sites can be used as a proxy.

Radioactive isotopes such as ^{3}H and ^{36}Cl are also useful for groundwater recharge studies. These isotopes decay, leading to lower and lower concentrations over time. Nuclear testing in the mid-20th century increased atmospheric isotope levels, resulting in precipitation which contained elevated isotope concentrations. For example, the peak tritium concentration in rainfall occurred during 1963. Recognition of this peak in an unsaturated soil column can be used to determine the rate of recharge. Ratios of ^{3}He/^{3}H can also be used to determine recharge rates. ^{3}He is the daughter product of ^{3}H decay, and, in the unsaturated zone, is lost to the atmosphere. When ^{3}H decays in the saturated zone, ^{3}He is isolated from the atmosphere and its concentration increases as the groundwater becomes older (Cook and Solomon, 1997). The ^{3}He/^{3}H ratio method is advantageous when the unsaturated zone is too thin and infiltration rates too high, resulting in the peak not being ovserved. Additionally, this dating method, similar to others (using carbon-14, krypton-81 and chlorine-36), provides groundwater ages considered to be “apparent ages” because parcels of groundwater with different ages are frequently mixed in aquifers, often causing significant uncertainty and non-uniqueness in models of groundwater transport and mixing. The number and accuracy of groundwater age dating methods have dramatically increased within the last two decades, and groundwater age dating is now a fairly mainstream hydrogeological tool.

Chlorofluorocarbons or CFCs have long atmospheric residence time and their atmospheric concentrations are spatially uniform and fairly well known (Plummer and Busenberg, 2000). CFC concentrations peaked in the late 1990s, and have been decreasing since then. Measured CFC concentrations in groundwater can be compared with their atmospheric concentration to obtain an apparent CFC age and, therefore, an apparent recharge rate.

Separation of the baseflow and stormflow components of a stream hydrograph can also be accomplished using chemical methods. The basic principle is that the older water is groundwater stored in the catchment prior to a rainfall event, while the new water is that added during a particular event. The concentration of one or more tracers, such as chloride, oxygen-18 or deuterium, is calculated at many points throughout the hydrograph period, and the release of each component determined from the total discharge coupled with initial and current concentrations. The hydrograph can then be separated into each of its components: baseflow, new stormflow and old stormflow at different times.

4.7.3 Modelling approaches

The third group of recharge estimation methods involves modelling. Modelling can be done in a direct sense, whereby recharge estimates are determined through calculations involving a number of climate and soil input parameters. Or it can be done indirectly, using methods for modelling recharge which require independent means to verify the results (Hill and Tiedeman, 2007). Sometimes this involves using other models, or it may be done by model calibration to field measurements. Inverse modelling methods involve varying the recharge rates to reproduce a set of field observations (e.g., Howard and Lloyd, 1979; Rushton and Ward, 1979). Such procedures often lead to non-unique recharge estimates because different parameter combinations can lead to the same result.

The modelling methods are based on equations generally solved numerically with a computer. Some of these methods are based on a simple water balance equation (Eq. 4.1), while others rely on partial differential equations, such as Richards' Equation (see Gardner, 1972). A growing number of computer codes are available for estimating recharge, each with varying degrees of sophistication. Some simple models are one-dimensional, considering only vertical water movement within a soil column. The Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al., 1994), for example, uses a water balance approach to determine net recharge at the base of a soil column. This code has been used in a number of Canadian studies (e.g., Box 4-1 and Box 4-3), and has been linked with groundwater flow models to predict changes in groundwater levels and baseflow. Research is ongoing to combine climate data, land surface/hydrology models, and groundwater models, at ever increasing scales.

4.8 REGIONAL VARIATIONS IN RECHARGE

Groundwater recharge across Canada is not uniform because of wide varities in land surface conditions and climate. Neither is recharge constant at any particular location. Nevertheless, a description of the general character of recharge for each of Canada's hydrogeological regions is possible (see Chapter 8).

Table 4.2 charts mean annual precipitation, estimated mean annual recharge, and method of estimation for several aquifers across the country. Recharge estimates were generally based on field measurements or modelling. Figure 4.11 depicts these results graphically, categorized according to hydrogeological region.

Below are the summaries of the climate and recharge conditions for each region.

4.8.1 Cordillera

Cordillera climate varies from mild, humid conditions along the southwest coast to subarctic conditions in high mountains and in the north. Climate is dominated by Pacific Ocean air masses and orographic (mountain) effects. Precipitation can exceed 4,000 mm along the Pacific coast, although locally it can be as low as 600 mm (Gulf Islands). Eastward from the coast, annual precipitation decreases from 1,200 to 1,500 mm in

TABLE 4.2 MEAN ANNUAL PRECIPITATION AND ESTIMATED GROUNDWATER RECHARGE FOR DIFFERENT STUDY REGIONS ACROSS CANADA

LOCATION	HYDROGEOLOGICAL REGION	UNCONFINED AQUIFER TYPE (S-SURFICIAL) (B-BEDROCK)		MEAN ANNUAL PRECIP. AT NEAREST STATION	MEAN ANNUAL RE-CHARGE	RECHARGE AS % OF PRECIP.	METHOD USED
		S	B	MM/YR	MM/YR		
Grand Forks, BC[1]	Cordillera	X		510	81	16%	Recharge modelling
Abbotsford, BC[2]	Cordillera	X		1573	1018	65%	Recharge modelling
Gulf Islands, BC[3]	Cordillera		X	883	137	16%	Recharge modelling
Oliver, BC[4]	Cordillera	X		328	60	18%	Recharge modelling
Belcarra, BC[5]	Cordillera		X	2331	757	32%	Hydrograph analysis
Northern Alberta, AB[6]	Plains	x		424	45	11%	Modelling and observations
Prairies, SK[7]	Plains	X		350	2		Field measurement
Dalmeny Aquifer, SK[8]	Plains	X		350	5		Flow rates from springs
Sandilands, MB[9]	Plains	X		610-539	217	36%-40%	CFC age dating, average of three sandy sites
Toronto-Oak Ridges Moraine, ON[10]	Southern Ontario Lowlands	X		886	60-210	7%-24%	Water balance and numerical 3D model
Grand River Basin, ON[11]	Southern Ontario Lowlands	X		950	200	21%	Recharge modelling
Ottawa, ON[12]	St. Lawrence Lowlands		X	914	238	26%	Stream hydrograph analysis
Chateauguay, QC[13]	St. Lawrence Lowlands		X	956	103	11%	Recharge modelling
Mirabel, QC[14]	St. Lawrence Lowlands		X	1065	70	7%	Inverse modelling
Cote Nord, QC[12]	Precambrian Shield		X	1009	428	42%	Stream hydrograph analysis
Portneuf, QC[12, 15]	St. Lawrence Lowlands		X	1056	244-426	20%-40%	Stream hydrograph analysis
Rimouski, QC[12]	Appalachians		X	972	302	31%	Stream hydrograph analysis
Sherbrooke, QC[12]	Appalachians		X	1238	327	26%	Stream hydrograph analysis
Saguenay, QC[12]	Shield		X	1116	119	11%	Stream hydrograph analysis
Trois Rivieres, QC[12]	St. Lawrence Lowlands		X	1041	316	30%	Stream hydrograph analysis
Miramichi, NB[12]	Appalachians		X	1081	369	34%	Stream hydrograph analysis
Sussex, NB[12]	Appalachians		X	1044	626	60%	Stream hydrograph analysis
Grand Falls, NB[12]	Appalachians		X	1029	289	28%	Stream hydrograph analysis
Nepisiguit Falls, NB[12]	Appalachians		X	1041	286	27%	Stream hydrograph analysis
Pennfield, NB[12]	Appalachians		X	1374	479	35%	Stream hydrograph analysis
Moncton, NB[12]	Maritimes		X	1008	317	31%	Stream hydrograph analysis
Fredericton, NB[12]	Maritimes		X	1186	383	32%	Stream hydrograph analysis
Annapolis, NS[16]	Maritimes		X	1209	170	14%	Stream hydrographs, water budget, modelling
Bangor, PEI[12]	Maritimes		X	1289	364	28%	Stream hydrograph analysis
O'Leary, PEI[12]	Maritimes		X	1084	316	29%	Stream hydrograph analysis
Wilmot, PEI[10]	Maritimes	X	X	1078	400	37%	Unknown
Maritimes Basin, NB, NS, PEI[17]	Maritimes		X	1100	148	13%	Stream hydrographs, water budget method, modelling

1 Scibek and Allen (2006a) 2 Scibek and Allen (2006b) 3 Appaih-Adjei and Allen (2009) 4 Toews and Allen (2009) 5 Holt (2004) 6 Smerdon et al. (2008) 7 Hayashi et al. (1998b) 8 van der Kamp and Hayashi (1998) 9 Hinton (2003) 10 Rivera (personal communication, 2007) 11 Jyrkama and Sykes (2007) 12 Michaud et al. (2002) 13 Croteau (2006) 14 Nastev (personal communication) 15 Larose-Charette (2000) 16 Rivard et al. (2007) 17 Rivard et al. (2008)

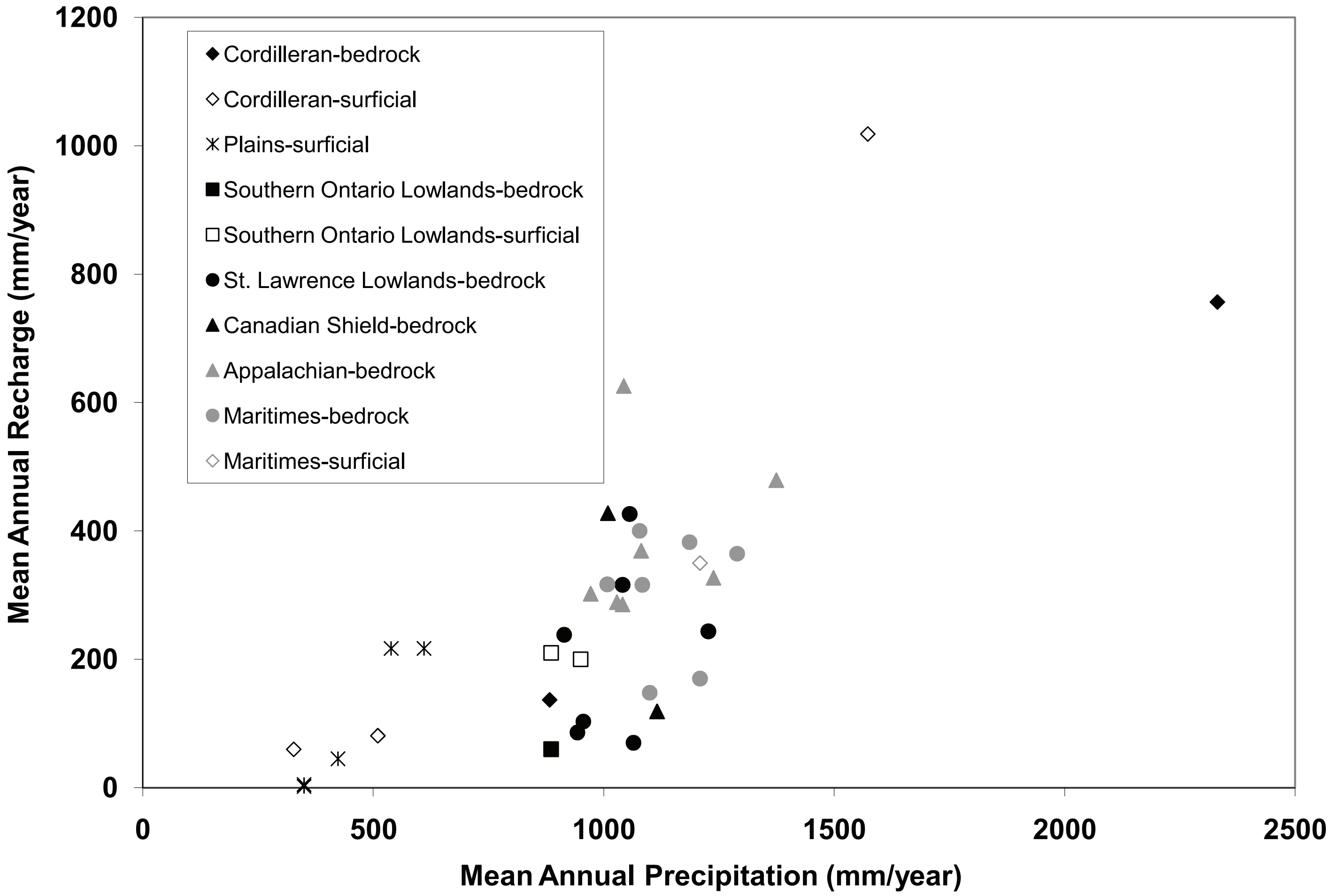


Figure 4.11 Graph showing mean annual recharge and mean annual precipitation obtained at different locations within the country's hydrogeological regions. A variety of methods were used to obtain these recharge estimates.

mountains to less than 300 mm in some intermontane valleys. Coastal regions experience highest precipitation during the winter months. Much of this precipitation falls as rain (temperatures are above freezing), except at high elevation, where it generally falls as snow (temperatures below freezing). In these coastal regions, groundwater recharge tends to occur during winter when evaporation and transpiration rates are at their lowest. Consequently, natural groundwater levels in coastal aquifers show a seasonal high during winter or early spring, and generally decline from spring to late fall (see Figure 4.9). By contrast, interior region records highest precipitation during summer (mostly as rain). Much of this precipitation is not available for recharge, however, due to high evaporation and transpiration. As the mean daily air temperature climbs, no excess water is available to infiltrate past the root zone for aquifer recharge. In the interior region and at higher elevations, snow accumulation during the winter months contributes to recharge during spring and summer as snowmelt (e.g., Okanagan Valley). Natural groundwater levels in aquifers located in the interior generally are at a seasonal high in late spring or early summer, and decline over summer and early fall. The groundwater level usually reaches a seasonal low during winter, when precipitation at the land surface is frozen and not available for recharge. Groundwater discharge, however, continues to maintain streamflows.

4.8.2 Plains

The climate of the Plains is a cool continental regime, dominated by semiarid conditions, but ranging from sub-humid to semiarid. Regional climate is zoned from south to north and from west to east as a result of Pacific or Arctic air masses combined with variations in solar radiation. Summers are short and warm, whereas winters are very cold. The western prairies have the lowest precipitation, and the highest evapotranspiration. Precipitation increases from 250 mm in southwestern Alberta to about 700 mm eastward in Manitoba. The region's basin-edge topography influences regional flow systems by introducing fresh meteoric water as recharge from isolated uplands. Local scale flow systems are driven by minor topographic variations, given the low topography of the region as a whole, its flat-lying stratigraphy, and the high bedrock heterogeneity. Depression-focused recharge tends to occur predominantly during spring snowmelt (Box 4-2). Annual recharge rates range from almost zero to about 50 mm in the prairies and up to about 200 mm in the northern forested portion of the Plains. The geochemical composition of groundwater has been found to reflect the overlying till composition (Grasby et al., 2010). Groundwater throughout the Plains region was recharged during the Pleistocene; this "fossil" groundwater can still be found at depth (Grasby and Chen, 2005).

4.8.3 Precambrian Shield

The Precambrian Shield is characterized by a wide range of precipitation, from some 1,400 mm in the south to about 400 mm at the northern tip of the Ungava Peninsula. The percentage of total precipitation falling as snow varies from about 25% in the south to more than 50% in northern parts of Quebec. Evapotranspiration also decreases with latitude, even more notably than precipitation, and the ratio of runoff to precipitation is often higher in the northern Shield. One characteristic of the Precambrian Shield Region is that roughly half of its northern domain is underlain by permafrost. The presence of a perennial or seasonal frozen layer reduces water infiltration and groundwater recharge by a considerable margin, both in surficial deposits and in bedrock. Canadian Shield bedrock is covered (for the most part) by a thin layer of Quaternary deposits, which can exceed 100 m in thickness in some bedrock valleys. Estimates of groundwater recharge within the permafrost terrain is reflected by a one order of magnitude decrease in stream baseflow with increasing latitude, from about 157 mm/year in the southern part of discontinuous permafrost, to about 15.7 mm/year and approaching zero in continuous permafrost areas (Lapointe, 1977; van Everdingen, 1987) (see Chapters 11 and 15).

4.8.4 Hudson Bay Lowlands

Climate of the Hudson Bay Lowland region is continental and strongly influenced by cold, moisture-laden Hudson Bay and polar air masses. It is characterized by short cool summers and cold winters. Mean annual temperature ranges from -4 to -2°C, although it is closer to -7°C in Manitoba. Annual precipitation averages from 400 to 800 mm, increasing from northwest to southeast. Up to 75% of the area is underlain by wetlands. There is little hydrogeological data for this region because it contains few water wells, and little development has occurred. Therefore, we know very little about groundwater recharge. Nevertheless, recharge is expected to be enhanced in those areas where solution features are well developed within carbonate-evaporite rocks insofar as Holocene karst locally enhances groundwater recharge via sinkholes. Lower recharge can be anticipated in the more massive, fine-crystalline carbonate rocks.

4.8.5 Southern Ontario Lowlands

Southern Ontario has a temperate climate with warm summers and mild winters. Mean temperature ranges from 5ºC to 8°C. Mean annual precipitation ranges from 720 to 1,000 mm, plus extremes due to major storms. Precipitation is higher east of major lakes and lowest away from these lakes. Longer, frost-free growing seasons (2,550 degree-days) near Lake Erie lead to higher evapotranspiration (about 600 mm/year) compared to the cooler (1,750 degree-days) northern interior areas (about 500 mm/year). Available moisture surplus for direct runoff to streams or groundwater infiltration varies from about 200 to 400 mm/year with local variation.

4.8.6 St. Lawrence Lowlands

Climate within the central St. Lawrence Lowlands ranges from continental in the west to maritime in the east. Northeastern areas are notably cooler due to effects of the Labrador Current. Mean annual temperatures range from 2.5°C to 5°C, while mean annual precipitation ranges from 800 to 1,100 mm. Spring arrives in April in the western areas of the region, while in the east snow may linger into May. The St. Lawrence Lowlands has generally flat-lying topography, which rarely

rises above 150 m elevation. Recharge occurs predominantly during snowmelt, and results in peak groundwater levels during late spring. Recharge may be enhanced along faults and within the karst openings of carbonate rocks, most notably where sediment cover is thin, or along major rivers or escarpments.

4.8.7 Appalachians

The Appalachian Region is one of the wettest areas in Canada. On average, it receives 1,150 mm/year of precipitation (except in Nova Scotia where the average is around 1,400 mm/year), of which 20% to 25% falls as snow. The climate is humid continental, with long, cold winters, and warm summers. Large seasonal temperature variance (up to 35°C) is common. Due to the region's relatively low relief, the major influence on weather is lands' distance to the sea. Coastal areas are cooled in the summer and warmed in the winter by the ocean, causing sudden temperature changes and frequent freeze-thaw cycles during the winter. Snowfalls are often heavy. The glacial till, the most common surficial deposit in this region, allows a fair amount of the precipitation water to infiltrate. Therefore, it is often assumed, as a first estimate that evapotranspiration, surface runoff, and infiltration each account for one third of total precipitation. However, the net recharge is often less than that, except where permeable deposits overlie permeable rocks. Average recharge rates range from 115 to 250 mm/year over large regions (representing 10% to 22% of precipitation), although these rates can reach 300 to 350 mm/year in some areas like Prince Edward Island. Usually the aquifers in eastern Canada supply streams on a regular basis, even during the summer.

4.8.8 Maritimes Basin

Climate of the Maritimes Basin is humid continental with long winters and warm summers. This region is one of the wettest of Canada, some 25% of precipitation occurs as snowfall. Because of low basin relief, distance to the sea is the major influence on weather. Northumberland's coastal strait areas are cooled in summer and warmed in winter by the ocean. Daily average air temperature varies between 17°C and 24°C in summer and between -12°C and -4°C during winter. Average precipitation is between 900 and 1,500 mm/year; highest values occur along the Bay of Fundy. Mean annual evapotranspiration varies from 345 to 440 mm/year and results in a large water surplus. The relief is commonly less than 150 m asl, although locally it can rise to 300 m asl in New Brunswick and Nova Scotia. Recharge through the sedimentary and volcanic rocks is enhanced locally by fracturing or, where terrain is overlain by sand and gravel deposits, associated with major streams and glaciofluvial corridors. Till is thin but widespread, and adequately transmissive to permit significant recharge to bedrock aquifer systems. Bedrock outcrops are rare. Potential recharge rates are between 100 and 400 mm/year.

4.8.9 Northern Canada

The permafrost region covers Canada's north, and is characterized by rock and/or soil temperatures that remain at or below 0°C through the summer, with the result that pore water is normally frozen. The southern margin of the region is irregular because secondary features, such as type of vegetation cover or snow depth, exercise some control as to where permafrost occurs. Climate is dominated by continental and polar maritime (influenced by the ocean) subtypes, and is additionally affected by the extreme solar radiation conditions of high latitudes. Mean annual temperature ranges from -20°C on Ellesmere Island to -6°C along the southern boundary. Mean annual precipitation varies from 100 mm in the north to 600 mm in the southeast. Precipitation of the central arctic is the lowest in Canada and, consequently, this area is often referred to as a polar desert. The primary hydrogeological function of permafrost is to act as a barrier to groundwater flow. Therefore, recharge is generally limited to areas where the active layer is thawed, or beneath lakes where thick taliks may form, resulting in only local groundwater occurrences.

4.9 CLIMATE VARIABILITY AND CLIMATE CHANGE

Canada's climate has varied historically over many time scales. The last of the great ice sheets began to melt 15 thousand years ago, creating significant runoff and likely significant groundwater recharge. Prior to that time, when the Canadian landmass was largely covered by ice, there was likely little groundwater recharge, although glacial meltwater may have generated recharge in some areas. Thus, climate change and climate variability play important roles in groundwater recharge variability. Whereas climate variability is generally observed on short time scales (few years to decades), climate change is manifested as a longer-term, more persistent change (decades and longer).

Because groundwater moves at very low rates through the ground, old groundwater still remains in some of the deeper aquifers, for example, within the Precambrian Shield. In such environments, the low frequency record of climate change is preserved. Shallow groundwater systems, by contrast, tend to be replenished by groundwater at faster

rates, and thus respond much more quickly to climate variations. Shallow groundwater systems often record higher frequency climate variations.

4.9.1 Climate variability and recharge

Climate variability impacts groundwater recharge over relatively short time scales. In Canada precipitation responses are associated with two extreme phases of the El Niño Southern Oscillation (ENSO), namely, El Niño and La Niña (Shabbar et al., 1997). Using the best available precipitation data from 1911 to 1994, these authors demonstrated that precipitation extending from British Columbia, through the Prairies, and into the Great Lakes region, is significantly influenced by ENSO phenomena. This variability decreases towards the pole, and is greatest in the central prairies. The pattern among the mountains and valleys of British Columbia is irregular.

Zheng et al. (2001) examined the spatial and temporal characteristics of heavy precipitation events over Canada (excluding the high Arctic) for the period 1900-1998, and discovered that about 71% of total precipitation in southern Canada comes from rainfall events. In northern Canada, more than 50% of total precipitation comes from snowfall events. Heavy rainfall and snowfall events were defined for each season and station separately by identifying a threshold value that was exceeded by an average of three events per year. Annual and seasonal time series of heavy event frequency were then obtained by counting the number of annual

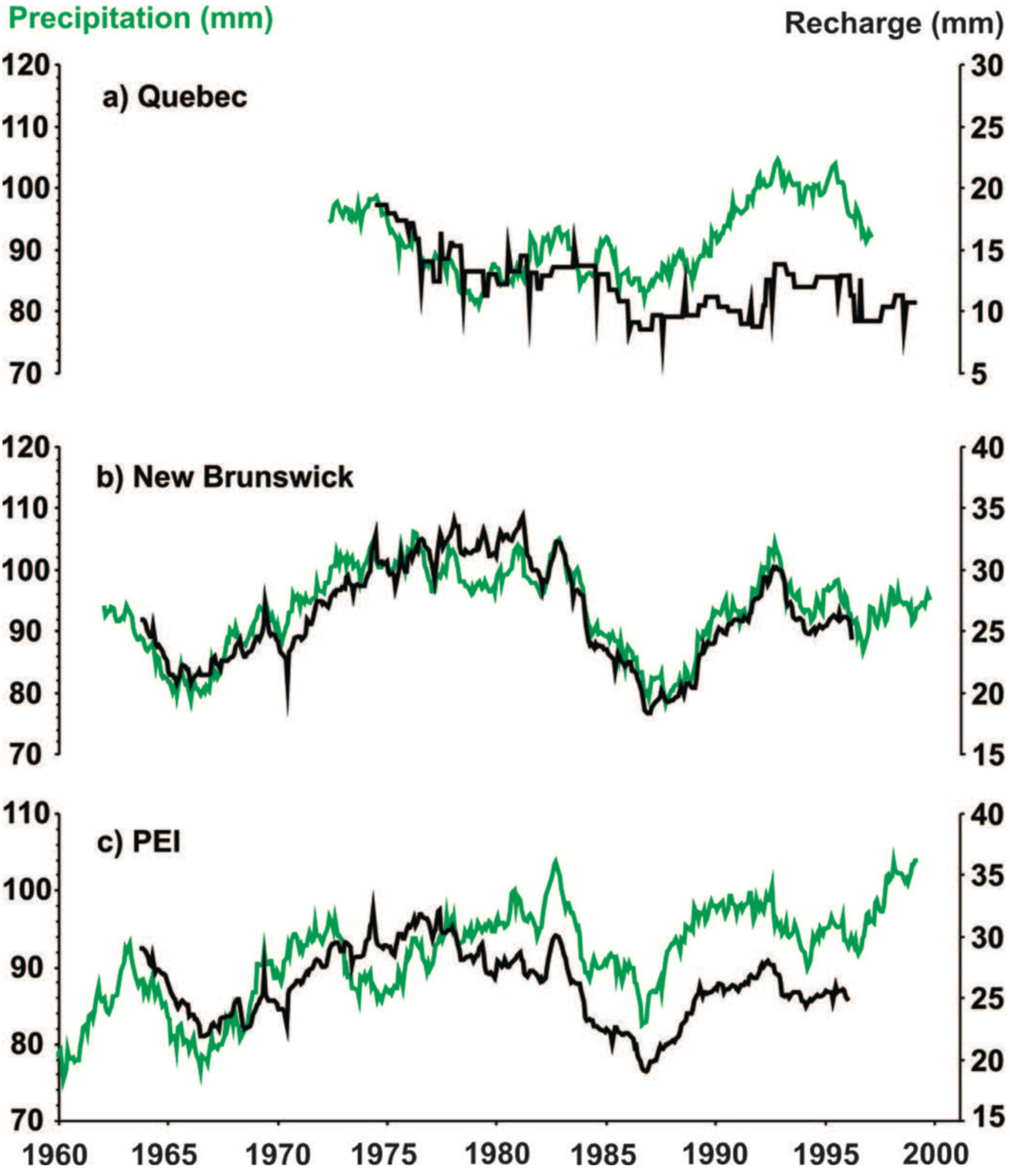


Figure 4.12 Precipitation and recharge variations in three aquifers in eastern Canada.

exceedances. Characteristics of the intensity of heavy precipitation events were investigated by examining the 90th percentiles of daily precipitation, the annual maximum daily value, and the 20-year return values.

Decadal variability is the dominant feature in both frequency and intensity of extreme precipitation events across the country, although for Canada as a whole, there appeared to be no identifiable trends in extreme precipitation (either frequency or intensity) during the last century. The observed increase in precipitation totals during the twentieth century was attributed largely to the increase in the number of small to moderate events. Stations with coherent temporal variability in the frequency of heavy precipitation events were grouped by cluster analysis and examined on a regional basis. Results show stations belonging to the same group are generally located in a continuous region, indicating that the temporal distribution of the number of precipitation events is spatially coherent. It was also found that heavy snowfall events are more spatially coherent than heavy rainfall events. Indices representing temporal variations of regional heavy precipitation display strong interdecadal variability with limited evidence of long-term trends, and vary markedly depending on the precipitation type, season, and region. Heavy spring rainfall events over eastern Canada have shown an increasing trend superimposed on the strong decadal variability. However, heavy rainfall events in other seasons or regions are generally not associated with any such trends. The number of heavy snowfall events in southern Canada reveals an upward trend from the beginning of the 20th century until the late 1950s–1970s, followed by a downward trend continuing to present day. Heavy snowfall events in northern Canada have been increasing with marked decadal variation over the last 50 years. The majority of stations have a significant positive correlation between the total amount of snowfall contributed by heavy events versus that contributed by non-heavy events. This relationship is strongest over western Canada. On the other hand, relatively few (<20%) stations had a significant correlation between total rainfall in heavy events and non-heavy events. These results suggest that the amount of precipitation falling in heavy and non-heavy events increases or decreases coherently for snow, but not for rain.

Recent studies in southern Manitoba reveal that short-term precipitation trends (wet-dry cycles) have good correlations with groundwater level variations (Chen et al., 2002, 2004). The calculated average correlation coefficient between a three-year moving average precipitation and annual groundwater levels is 0.85. 85% of the wells have a coefficient greater than 0.8. Statistically, a 0.85 coefficient means that more than 70% of the variations in the groundwater levels can be explained by the variations in annual precipitation. Annual mean air temperature displays a significant negative correlation with the annual groundwater levels. The mean value of the correlation coefficients between temperature and groundwater level from 72 monitoring wells is 0.72 (Chen et al., 2004).

The potential impact of increasing annual mean temperature on the groundwater levels in Manitoba was examined by studying the correlation coefficients between groundwater levels and temperatures in different time periods, in which the annual mean temperature had about 1.5°C difference. Calculations showed that the correlation coefficients between temperatures and groundwater levels increased about 15% from the cooler period to the hotter period, while the correlation coefficients between precipitation and groundwater levels in these two time periods changed little (<5%) (Chen et al., 2004).

Average growing season precipitation values in the Canadian Prairies range from over 300 mm in west-central Alberta and eastern Manitoba, to less than 200 mm in southern Alberta and into southwestern Saskatchewan (Bonsal et al. 1999). This precipitation is critical to several environmental processes and economic activities and, most notably, to agriculture. Also important is the temporal distribution of precipitation within the growing season. Over the agricultural region of the Plains, maximum rainfall normally occurs from mid-June to early July. Variations in this temporal distribution can also have severe effects.

In eastern Canada, variability in precipitation and recharge occurs on decadal time scales. Precipitation curves for representative climate stations in Quebec, New Brunswick and Prince Edward Island are illustrated in Figure 4.12. Interannual and longer-term (several decades) variability is evident. Groundwater recharge is found to vary similarly to precipitation, particularly at the New Brunswick site, although recharge diverges from precipitation at the Quebec and PEI sites.

4.9.2 Climate change impacts on recharge

It is expected that global changes in temperature and precipitation will alter groundwater recharge to aquifers (Zektser and Loaiciga, 1993). As a first response, climate change will cause shifts in water table levels in unconfined aquifers (Changnon et al., 1988).

Studies that examine historical precipitation and groundwater level variability lend insight into the physical processes that control groundwater recharge, and help scientists make predictions for future climate change conditions. Detection of the effects of long-term climate change remains in its early stages, and, as a result, many of the approaches used for predicting the responses of aquifers to climate change are largely modelling-based (e.g., Scibek and Allen, 2006a; Jyearkama and Sykes, 2007; Toews and Allen, 2009). The approach employed in some predictive studies (e.g., Box 4-1) utilizes future climate data generated from global climate models (GCMs) as input to recharge models. Representative climate data for specific time periods, such as the 2050s or 2070s, for example, is generated, rather than using a continuous data series spanning several decades. The resultant modelling results are limited in that they do not illustrate the progressive changes in groundwater recharge, but rather provide snapshot views of recharge for different periods in the future.

Cumulative effects of climate change are not fully accounted for in these models. Long lasting severe dry weather conditions, for example, may change an aquifer's hydraulic properties (Larocque et al., 1998), significantly altering recharge rates for major aquifer systems and affecting the sustainable yield of groundwater in certain regions. Another limitation lies in the recharge models themselves, because they commonly use daily, rather than hourly, climate data as input and, therefore, may miss capturing those extreme precipitation events which occur at time scales of less than one day. Although high intensity rainfall events, contribute, on average, to greater precipitation for any particular day or month, these events can also ultimately lead to less recharge because most of the precipitation generated turns into runoff and does not infiltrate the ground.

Much more research on the effects of extreme events on groundwater recharge is needed, particularly given the premise that future climate change will probably result in more extreme precipitation events.

4.10 CONCLUSIONS

Although we may know much about the science of groundwater recharge in general, only a few groundwater studies have been conducted across the country to provide estimates of recharge. As a result, we lack a comprehensive nation-wide groundwater recharge assessment, although a preliminary compilation of information was undertaken in the writing of this chapter. The authors compiled recharge estimates for different regions across the country as shown in Figure 4.11; these estimates were based on field measurements or modelling. In addition, the authors constructed a map detailing potential annual recharge (Figure 4.5), based on annual precipitation and potential evapotranspiration. Such compilations should be expanded as more data becomes available.

Recharge varies considerably across Canada, ranging from 0 to over 1,000 mm/year. The magnitude and timing of this recharge are strongly dependent on the region's climate, as well as the physical properties of the soil and aquifers, topography, and the nature of the land cover. Both short-term and long-term precipitation and temperature trends, as well as changes in land use and land cover, can be expected to impact on the magnitude and timing of recharge in most regions across the country. Except for a small sampling of aquifers, long term effects of climate change on groundwater recharge across Canada are not well studied.

BOX 4-1 DIRECT AND INDIRECT GROUNDWATER RECHARGE AND IMPACTS OF FUTURE CLIMATE CHANGE

The Grand Forks aquifer in south-central British Columbia (Figure 4.13) is contained within the mountainous valley of the Kettle River along the Washington State border. At Grand Forks, the climate is semiarid and most precipitation occurs in the summer months during convective activity. In the winter, much of the precipitation at high elevation is as snow: the observing sites at valley bottom record less snowfall. The valley fill consists of glaciolacustrine and glaciofluvial sediments. The top-most sediments, forming the unconfined aquifer, are comprised of Holocene age gravels and sands. Groundwater in the valley is used extensively for irrigation and domestic use (Wei et al., 1994).

Within the Grand Forks valley, the Kettle River is a meandering gravel-bed river incised into glacial outwash sediments. Recent research has demonstrated that the aquifer water levels are highly sensitive to water levels in the Kettle River (Allen et al., 2004; Scibek et al., 2007). Figure 4.14 shows a conceptual model of the interaction between the Kettle River and the aquifer. At peak flow, during the spring freshet (regional snowmelt), the rise in river stage causes water to move laterally away from the channel, resulting in groundwater levels rising over a broad area. The rate of inflow to groundwater from the river along the floodplain zone follows very closely the river hydrograph during the rise in river stage. Water is stored in the aquifer during this time. Within approximately 10 days following peak discharge, river levels begin to fall, and the groundwater flow direction is reversed. At this time, the rate of inflow from the aquifer to the river increases, and this

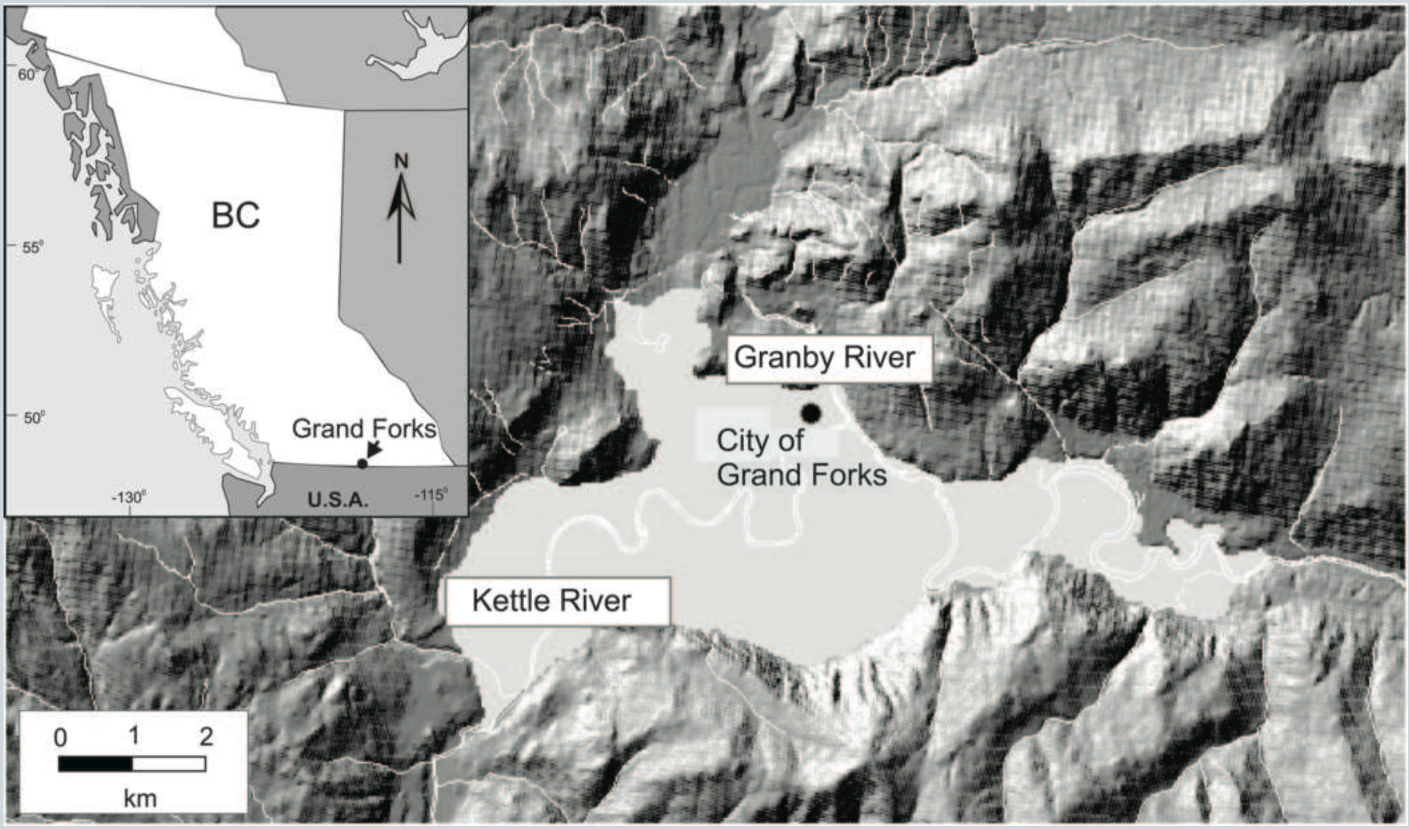


Figure 4.13 Location map of the Grand Forks aquifer in south-central British Columbia. The unconfined aquifer is hydraulically connected to the Kettle and Granby Rivers, receiving both direct recharge from precipitation and indirect recharge from streamflow.

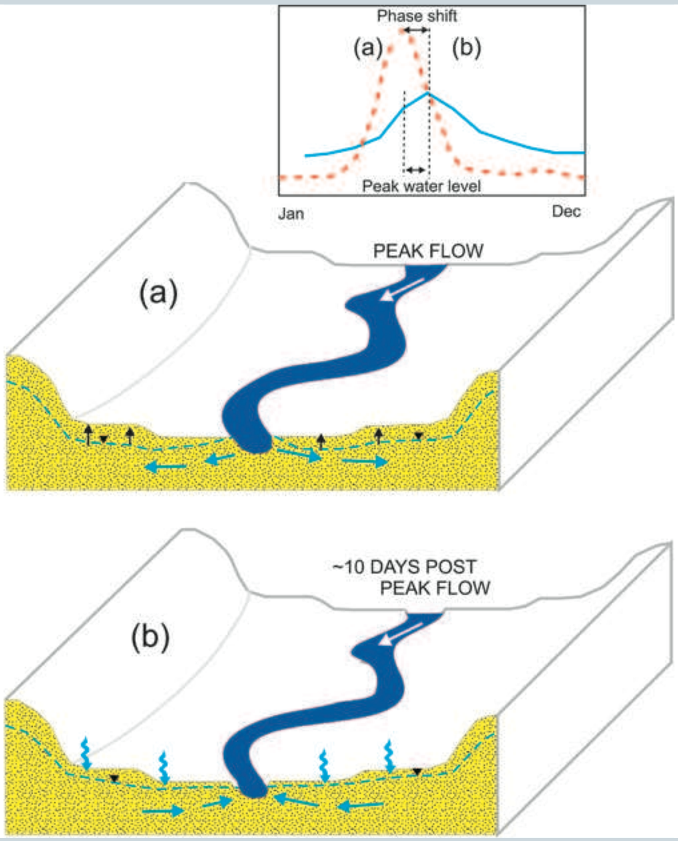


Figure 4.14 This schematic drawing illustrates the interaction between the Kettle River and the Grand Forks aquifer. (a) At peak flow, river water recharges the aquifer and moves laterally away from the channel, causing groundwater levels to rise over a broad area. (b) Within a relatively short period of time (about 10 days) following the peak streamflow, when river levels begin to fall, the groundwater flow direction is reversed and groundwater contributes to baseflow (adapted from Scibek et al., 2007).

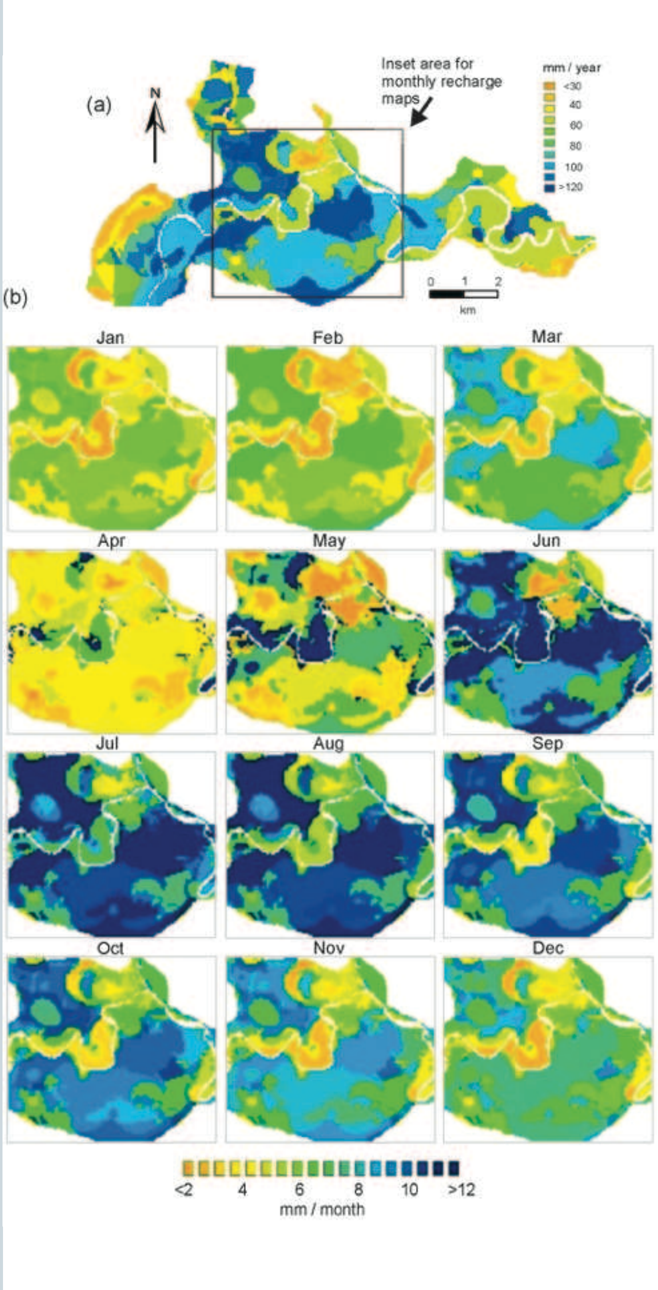


Figure 4.15 (a) Mean annual recharge to the Grand Forks aquifer. **(b)** Mean monthly recharge maps for inset area (central portion of valley). From Scibek and Allen, 2006a.

condition prevails for the rest of the year, as water previously stored in aquifer drains back to the river as baseflow seepage. Modelling results indicate that river puts about 15% of its spring freshet flow into storage in Grand Forks valley aquifer, and most of that water is released back to the river as baseflow, within 30 to 60 days. Under natural conditions, the net exchange is roughly zero over the year. When pumping wells are included in the model, however, there is a small reduction in the baseflow component to the Kettle River.

Estimates of direct recharge to the shallow aquifer were obtained by modelling. Mean annual recharge, determined spatially using the HELP infiltration model (Schroeder et al., 1994) varies considerably across the aquifer (Figure 4.15), ranging from slightly less than 30 mm/year to over 120 mm/year (corresponding to 6% and 24% of mean annual precipitation, respectively). Mean monthly recharge (to the inset area shown) follows the annual distribution of precipitation. The ground is frozen in winter, and snowmelt infiltration does

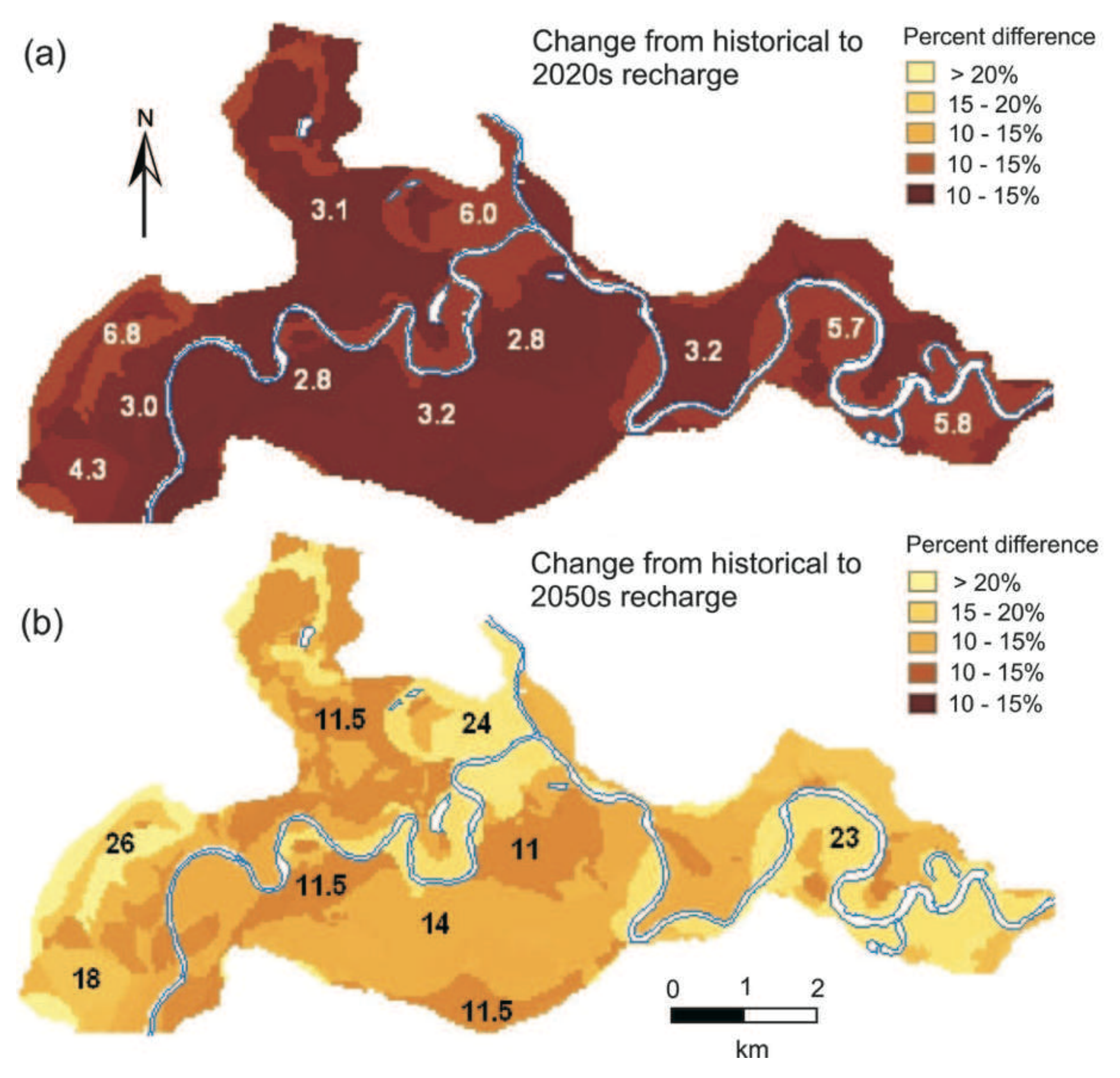


Figure 4.16 Percent change in mean annual recharge for (a) the 2020s, and (b) the 2050s, relative to historical recharge. From Scibek and Allen, 2006a.

not occur. Most of the recharge is received in late spring and summer through snowmelt and summer rainstorm events. Autumn has moderate recharge, less than in early summer. Monthly recharge varies from less than 2 mm/month to over 12 mm/month. The range in percentages (i.e., 6% to 24%) of mean annual precipitation is smaller than the range in percentages (10% to 80%) of monthly precipitation, due to seasonal variation in precipitation and averaging on annual time scales. Should a high intensity event, such as a thunderstorm, occur during the late summer most of the water will infiltrate the aquifer. When it rains more slowly, and over a longer time, much more water is lost through evaporation. This relationship may be very different in other climate regions, and in other aquifers, as high intensity rainfall events may lead to increased runoff and less infiltration. The overall effects of direct recharge in the Grand Forks aquifer are very small in comparison to indirect recharge from the Kettle River, except in those areas, such as the terraces along the valley sides, removed from the river influence.

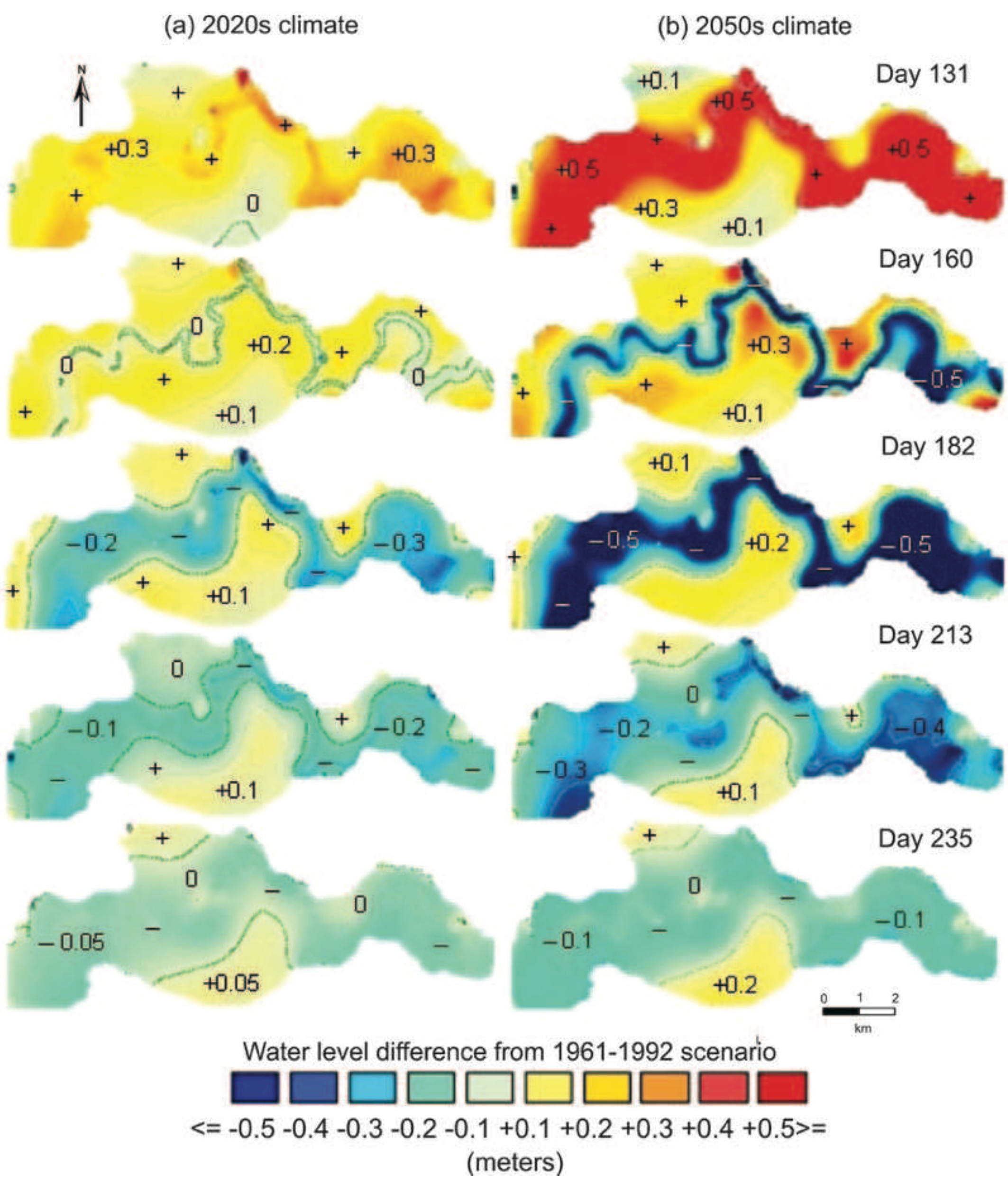


Figure 4.17 Water level differences between (a) future (2020s) and historical climate, and (b) future (2050s) and historical climate under pumping conditions. Maps represent different Julian Days. Darkest blue colours indicate values less than -0.5 m (along rivers only). From Scibek and Allen, 2006a.

The impact of predicted future climate change on groundwater in this aquifer has also been estimated. Three year-long climate scenarios were run, each representing one typical year in the present, and in future (2020s and 2050s), through the perturbation of historical weather according to downscaled CGCM1 global climate model results. Results projected for the 2050s showed that the largest increase in recharge relative to present would occur in late spring, by a factor of three or more. Recharge throughout most areas of the aquifer would evidence a 50% increase in summer months; a 10% to 25% increase in autumn, and a reduction during winter (Figure 4.16). CGCM1 downscaling was also used to predict basin-scale runoff for the river. Future climate scenarios suggest a shift in the hydrograph peak to an earlier date. Although the peak flow would remain the same, the baseflow level would be lower and of longer duration. Groundwater levels near the river floodplain are predicted to be higher earlier in the year due to an earlier onset of peak flow, but considerably lower during the summer months (Figure 4.17.). Away from rivers, groundwater levels increase slightly due to the predicted increase in recharge.

BOX 4-2 DEPRESSION-FOCUSED GROUNDWATER RECHARGE

Depression-focused recharge is commonly observed in arid and semiarid regions around the world including the Southern High Plains of Texas (Scanlon and Goldsmith, 1997), the La Plata region of Argentina (Logan and Rudolph, 1997), and the Sahel region of Niger (Desconnets et al., 1997).

Several decades of studies in the Canadian prairies (e.g., Meyboom, 1966; Zebarth et al., 1989; Hayashi et al., 2003) have established a reasonably good understanding of the recharge processes at least at the scale of individual depressions, as presented below in a summary of detailed field studies conducted at the St. Denis National Wildlife Area near Saskatoon.

The climate of the Canadian prairies is characterized by high moisture deficit and cold winters with temperatures frequently below -30°C. Annual precipitation in Saskatoon is only 360 mm, which is greatly exceeded by potential evaporation of 700 mm (Hayashi et al., 1998a). As a result, annual runoff in the prairies is typically less than 25 mm (CNC/IHD, 1978), of which a large portion is generated during snowmelt, when the rapid depletion of snowpack over frozen, relatively impermeable soil generates a relatively large amount of runoff over a period of a few weeks (van der Kamp et al., 2003). Storm runoff rarely occurs in summer and fall, and the base flow in first-order streams originating within the prairies is primarily sustained by groundwater discharge.

The continental ice sheet covered much of the prairies during the last glaciation, depositing a thick (up to 200 m) blanket of poorly sorted material referred to as glacial till. Glacial till has relatively high clay content (20%–40% by weight): the hydraulic conductivity of unweathered till is in the order of 10^{-9}–10^{-11} m/s (Keller et al., 1989). Conductivity of the weathered till in the shallow zone is usually much higher owing to the presence of fracture network and macropores (Hayashi et al., 1998a; Parsons et al., 2004). Glaciated terrains generally have undulating or hummocky topography with numerous depressions. Ephemeral ponds and wetlands form in these depressions (Figures 4.18a and 4.18b), resulting in depression-focused infiltration and groundwater recharge.

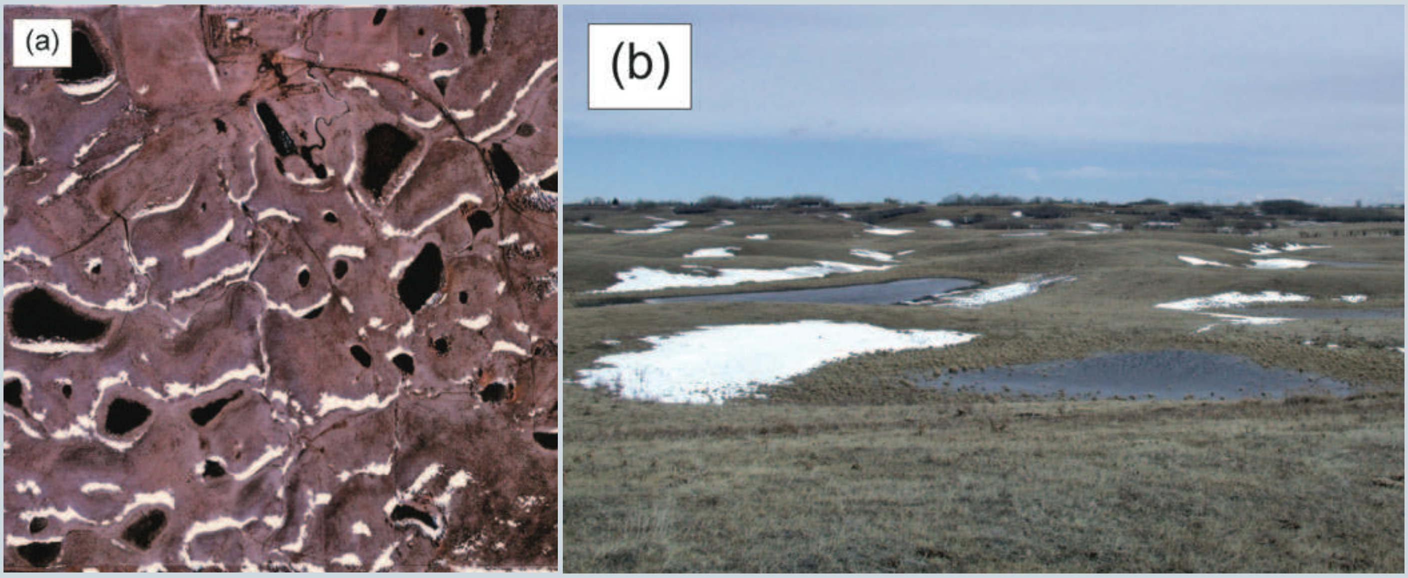


Figure 4.18 (a) An infrared (IR) aerial photograph. **(b)** A ground-based colour photograph of a pasture in the West Nose Creek watershed, located 20-km north of Calgary, Alberta. The photograph, taken on March 25, 2003, shows numerous depressions filled by snowmelt water. The water remains in depressions for a few weeks while the underlying soil thaws.

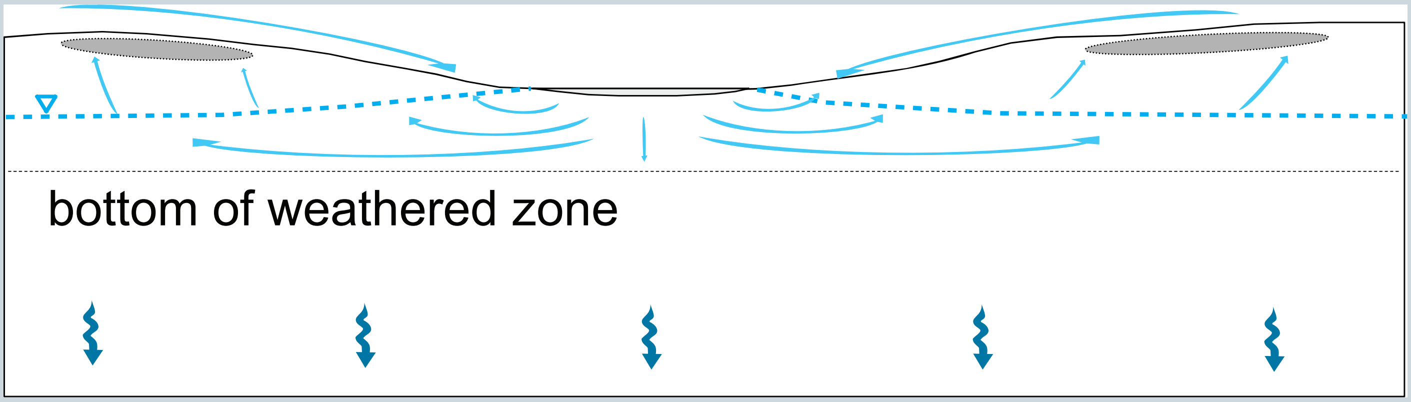


Figure 4.19 Conceptual model of snowmelt runoff, groundwater flow, and solute transport under a seasonal wetland. Arrows indicate the surface and subsurface pathways of water and dissolved salts, and the shaded areas on uplands indicate the occurrence of high soil salinity (modified from Hayashi et al., 1998b).

By definition, infiltration under depressions is regarded as shallow groundwater recharge although the recharge rate of deeper aquifers is much lower than the infiltration rate. Hayashi et al. (1998b) estimated a recharge rate of 1–3 mm/year for a sand aquifer located 25 m below the surface. This is because plants growing around depressions take up shallow groundwater to sustain relatively high transpiration rates during summer months, thereby inducing lateral groundwater flow towards the uplands (Figure 4.19). The flow usually occurs in the weathered zone, which has relatively high hydraulic conductivity. Evapotranspiration on the uplands concentrates dissolved salts in soil water, resulting in the formation of "saline ring" around depressions (Mills and Zwarich, 1986; Berthold et al., 2004). Grasses and agricultural crops growing on uplands can consume most infiltrated water during the growing season, allowing very little downward flux below the root zone. The presence of saline rings (Figure 4.19) implies that the downward flux under uplands is essentially zero averaged over a long period.

These studies suggest that the dominant mode of recharge is depression-focused. However, it is also clear that much of the shallow groundwater recharge under the depression flows laterally, to be consumed by evapotranspiration without recharging deeper aquifers. Water-holding depressions typically occupy 10%–20 % of the land within their respective watersheds (Hayashi et al., 1998b). When expressed as the recharge rate over an entire watershed, depression-focused recharge represents 1–45 mm/year of water input to deep aquifers in several zones under study in Canada and the United States (Hayashi et al., 1998b). The range of recharge rates is consistent with published values of groundwater recharge for prairie aquifers (van der Kamp and Hayashi, 1998), suggesting that depression-focused recharge may account for the majority of aquifer recharge. However, the amount of snowmelt infiltration and runoff on uplands is strongly dependent on land use (van der Kamp et al., 2003), and the effects of land use change on groundwater recharge are still not well understood. Future research is required before we can explain how land use change and climate change may affect the hydrologic cycle in the prairies, and depression-focused groundwater recharge.

BOX 4-3 MODELLING GROUNDWATER RECHARGE AND WATER BUDGETS

The spatial and temporal distribution of recharge rate has been estimated for the Chateauguay River watershed (Croteau, 2006). This regional aquifer system consists of fractured sedimentary rocks covered by heterogeneous Quaternary sediments of various thicknesses (For details on the watershed see Box 6-1, Chapter 6). Recharge was defined as the amount of precipitation water percolating through unconsolidated sediments to reach regional aquifer units. Water budget components (see Equation 4.1 in main text) were estimated with the physically based HELP infiltration model (Schroeder et al., 1994). Collected input data (climate, vertical Quaternary stratigraphy with corresponding physical properties, drainage properties, land use and vegetation cover) were integrated over a 250 × 250 m grid (47,616 cells). The model was calibrated against the runoff, and baseflow components of the hydrographs recorded over the considered period 1963–2001. The Champan (1999) baseflow separation technique was used.

Results indicate an average regional recharge rate of 86 mm/year or 9% of the mean total precipitation of 943 mm. Evapotranspiration was the most important water budget component accounting for 52% of precipitation, whereas combined surface and subsurface runoff accounted for 39% of precipitation. The average recharge varied from zero, along streams and other surface waters considered as gaining streams, up to 404 mm/year at rock outcrops and rock covered with a shallow sandy layer (Figure 4.20).

The daily evolution of water budget components averaged over the basin is shown in Figure 4.21. The year 1985 was selected as representing typical climate conditions for the region. Temperature has

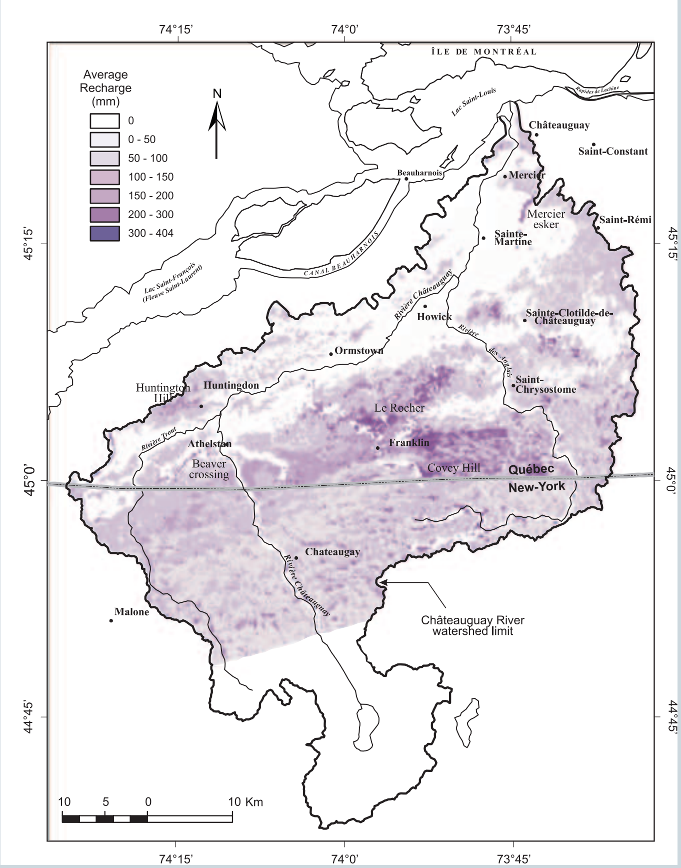


Figure 4.20 Spatial distribution of the average annual recharge rate.

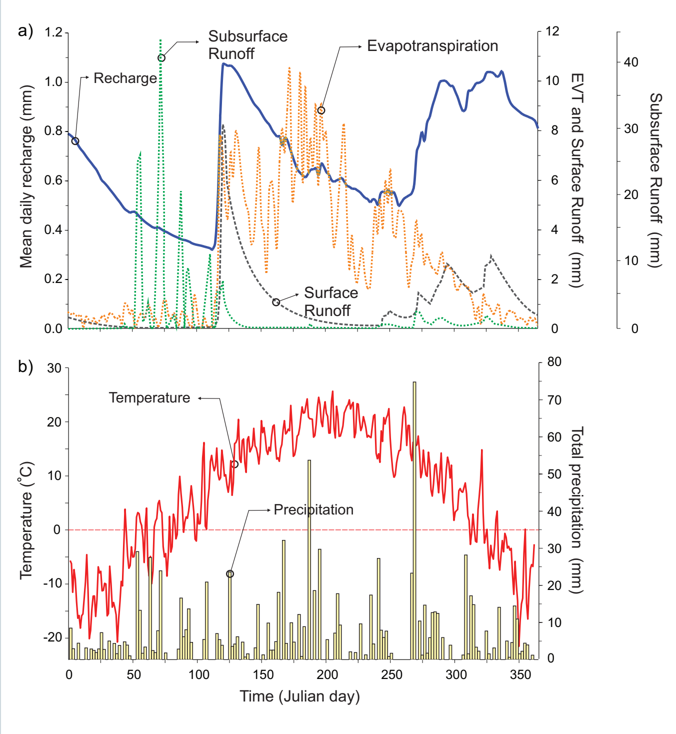


Figure 4.21 (a) Daily evolution of the recharge, surface runoff, subsurface runoff, and evapotranspiration rates compared with **(b)** daily variations in climate conditions for the year 1985.

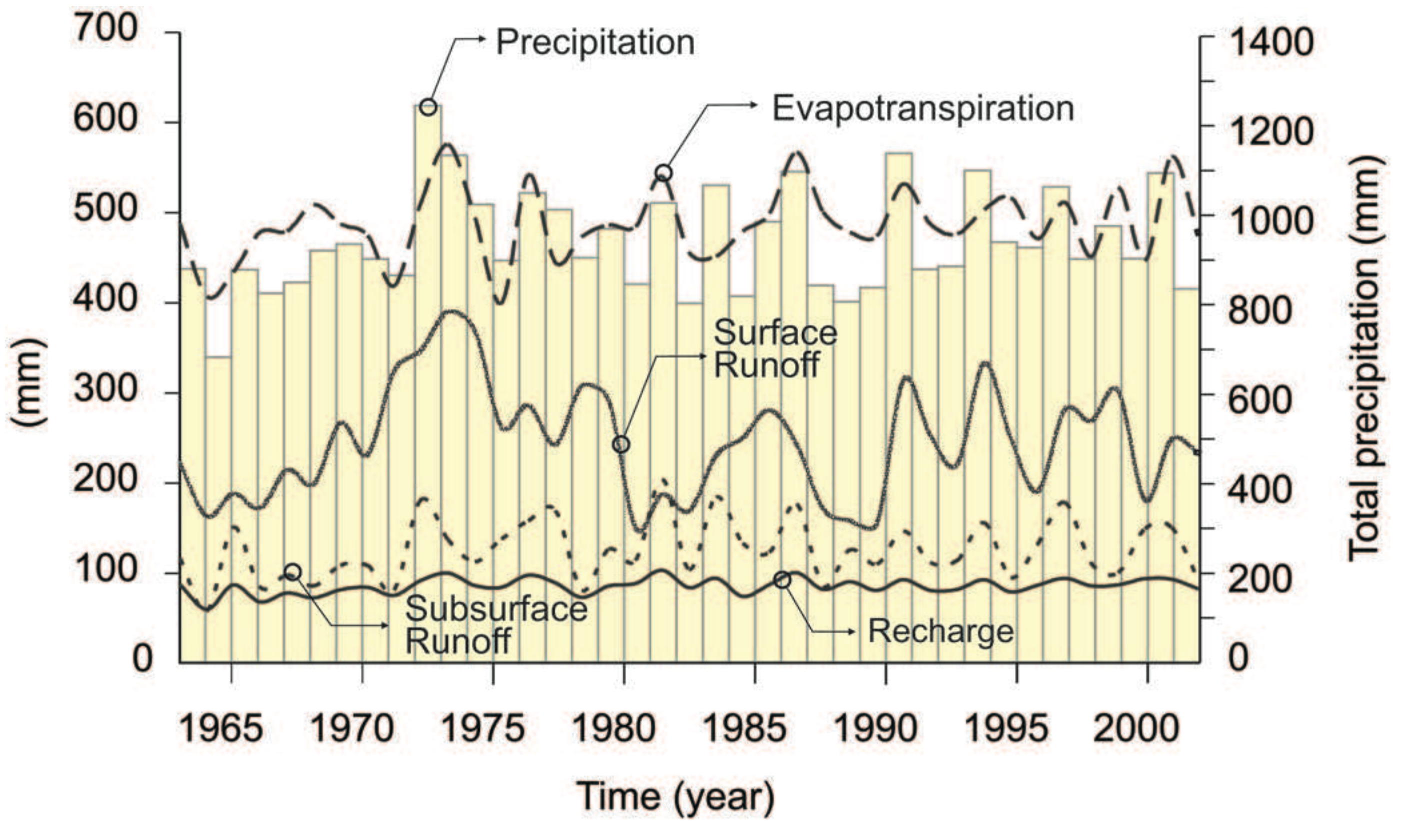


Figure 4.22 Annual variations in the water budget components.

a stronger influence on the daily values of the water budget components than precipitation. Two major recharge periods can be observed. In spring, when the temperatures rise above zero, the snowmelt contributes to a rapid increase of the recharge, subsurface runoff, and the evapotranspiration rates. In late winter, prior to this increase, surface runoff rate peaks as melted water runs off the still frozen soil. The second recharge peak occurs during the fall, as increased air humidity and decreased temperatures contribute to a reduced evapotranspiration rate which, in turn, increases the recharge rate. During this period, the vegetation cover decreases water uptake by vegetative roots and evaporation are minimal and more water becomes available for runoff and percolation.

Annual variations of the average water budget components for the considered period are illustrated in Figure 4.22. Evapotranspiration and surface runoff variations show direct correlation to precipitation fluctuations. The groundwater recharge rates are relatively constant and vary in a narrow range, with a standard deviation s = ± 9 mm/year. Recharge indicates a subdued response to precipitation fluctuations. The storage capacity of soil media overlying the regional aquifer units acts as a reservoir that releases water during the dry years and stores water surplus during the wetter years. The mean annual temperature remains fairly constant over the computed period, i.e., 6.3°C, in opposition to the daily variations of the water budget components where it assumes a major role, whereas in Figure 4.23, it is considered to have negligible impact on the total annual values.

The calibrated recharge model has been used to simulate water budget components under those extreme climate conditions considered

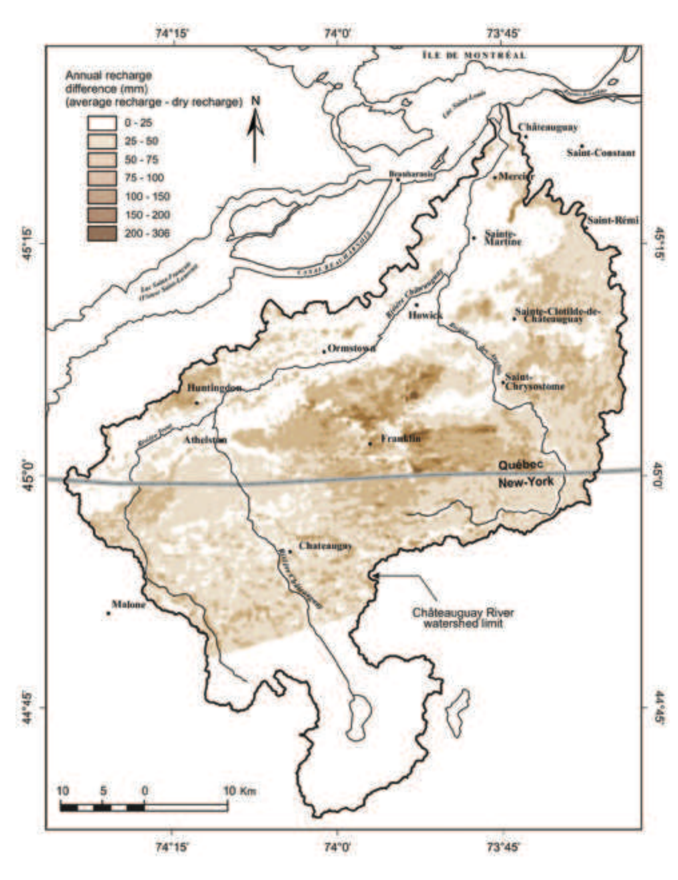
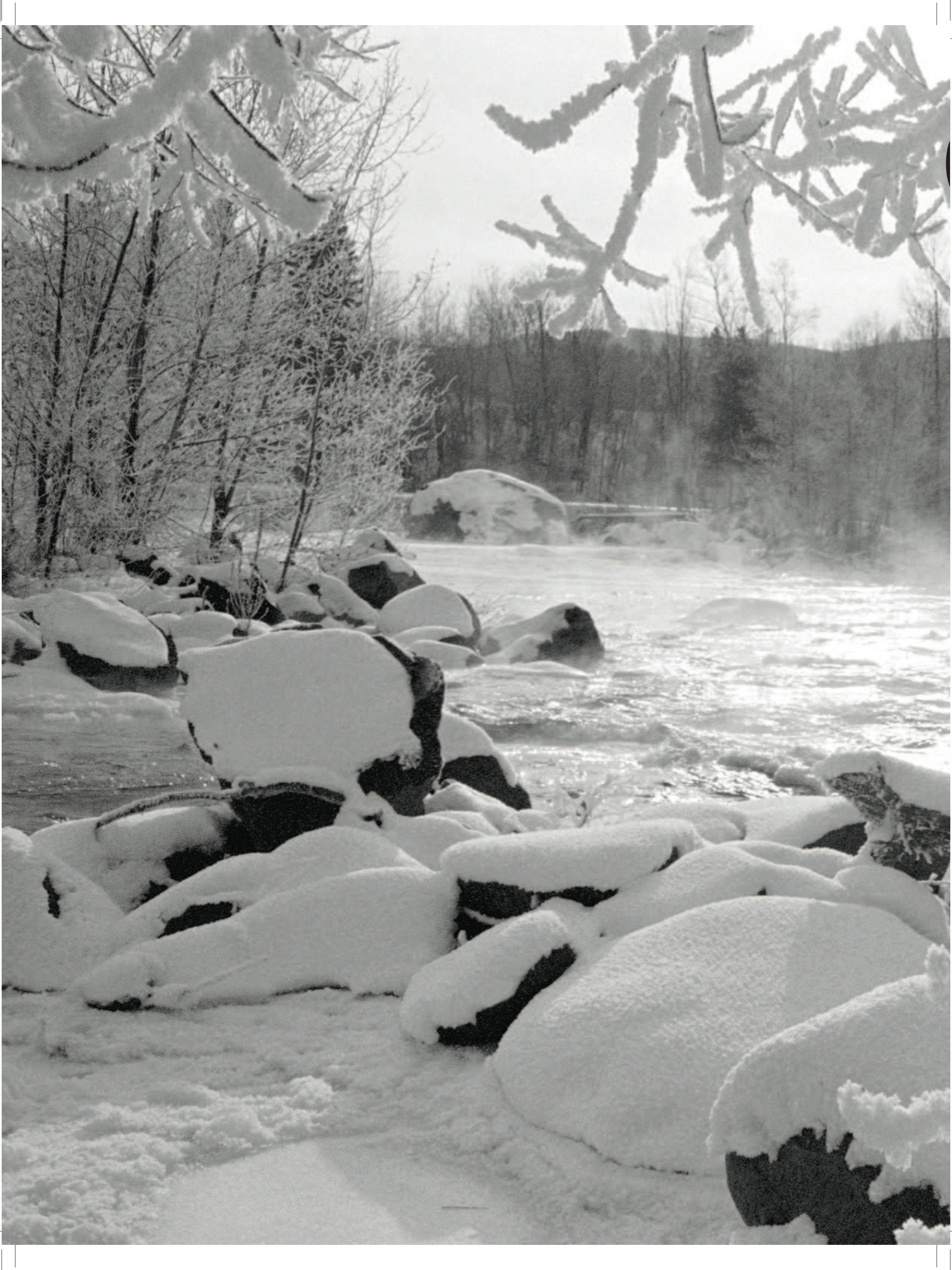


Figure 4.23 Spatial variation between average and dry recharge rates. Those areas with the greatest difference are thought to be sensitive to future dry climate conditions.

as representative for possible climate changes. Two scenarios, drought and prolonged humid conditions, were considered. Real climate data was used for these scenarios because recorded climate conditions varied considerably over the considered period, 1963–2001. Extreme conditions were defined by imposing climate data recorded for the driest (1964, precipitation=683 mm) and the wettest (1972, precipitation=1245 mm) year to the model (see Figure 4.22). The model was then run with the same input data repetitively over a period of six years, which allowed for stabilization of the soil saturation and output parameters. The results for the sixth year were those used for the analysis. These indicated a mean annual recharge rate of 51 mm/year for the drought and 99 mm/year for the humid scenario. In both cases, the spatial distribution of the recharge rate corresponded to that of the mean recharge rate shown in Figure 4.20. In other words, those areas that yielded the highest recharge rates under average climate conditions also did so under other climate conditions. A comparison to the average recharge rate for the basin (86 mm/year, mean annual precipitation=943 mm) revealed the fact that that the regional aquifers have an upper limit of how much groundwater can be replenished on an annual basis. A 32% precipitation increase yields a 15% increase in recharge rate. Further increase in precipitation would result in only limited recharge increase, and the current humid climate conditions yielded recharge rates close to this threshold. Conversely, recharge rate decreases more rapidly with precipitation decrease as a 37% decrease of precipitation yields a 67% decrease in the recharge rate.

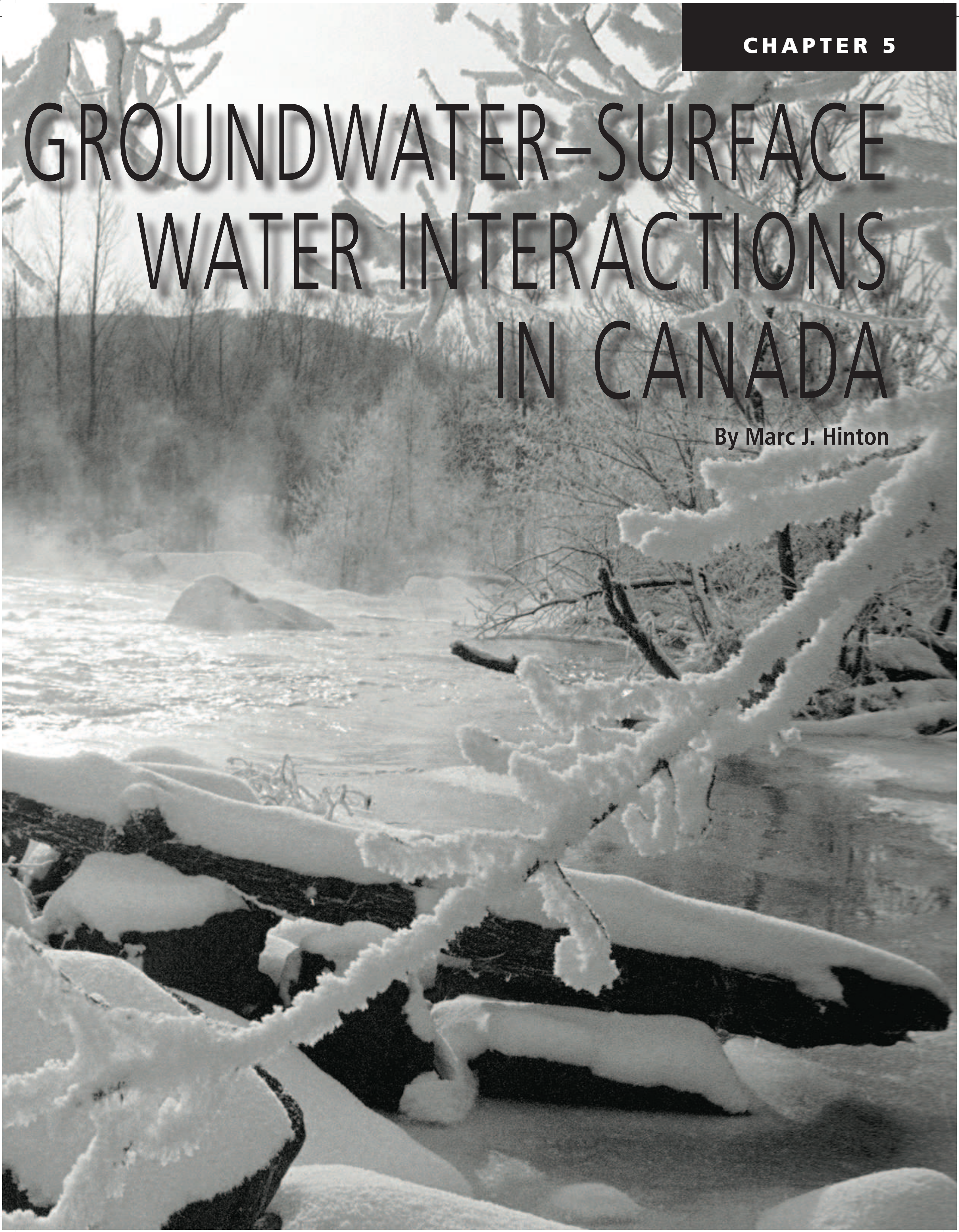
Figure 4.23 shows the spatial difference between the average and the dry recharge rates computed for each grid cell. This map actually indicates those areas where, in absolute terms, the maximum decrease in recharge rate will occur in the case where dry climate conditions prevail. These areas coincide generally, but not necessarily, with those where highest recharge rate occurs under average climate conditions. The recharge map and the recharge sensitivity map define and confirm spatial distribution of those regions where most attention must be paid to the environment protection and its groundwater resource.



CHAPTER 5

GROUNDWATER–SURFACE WATER INTERACTIONS IN CANADA

By Marc J. Hinton



5.1 INTRODUCTION

The dominant processes for returning water back to the ocean from land surfaces are: surface water flow, groundwater flow, and transport of atmospheric vapour from evaporation or transpiration (Figure 5.1). Storage and exchange of water among these surface, subsurface and atmospheric reservoirs is spatially and temporally variable and, as a result, is important for aquatic and terrestrial ecosystems, management and protection of water resources and, ultimately, land use management and planning.

This chapter focuses on the interactions of two of these reservoirs: groundwater and surface water, and on summarizing key concepts of groundwater-surface water (GW-SW) interactions. Canadian research and data about GW-SW interactions are considered, in addition to examples of GW-SW interactions in specific Canadian settings. The chapter concludes with future challenges for scientists and decision makers.

5.2 KEY CONCEPTS OF GROUNDWATER–SURFACE WATER INTERACTIONS

To make informed decisions that protect water and aquatic resources, we must understand how groundwater and surface water interact. This section summarizes several key concepts by drawing upon recent research, overviews and reviews of several aspects of GW-SW interactions (e.g., Winter, 1995; Brunke and Gonser, 1997; Boulton et al., 1998; Winter et al., 1998; Winter, 1999; Jones

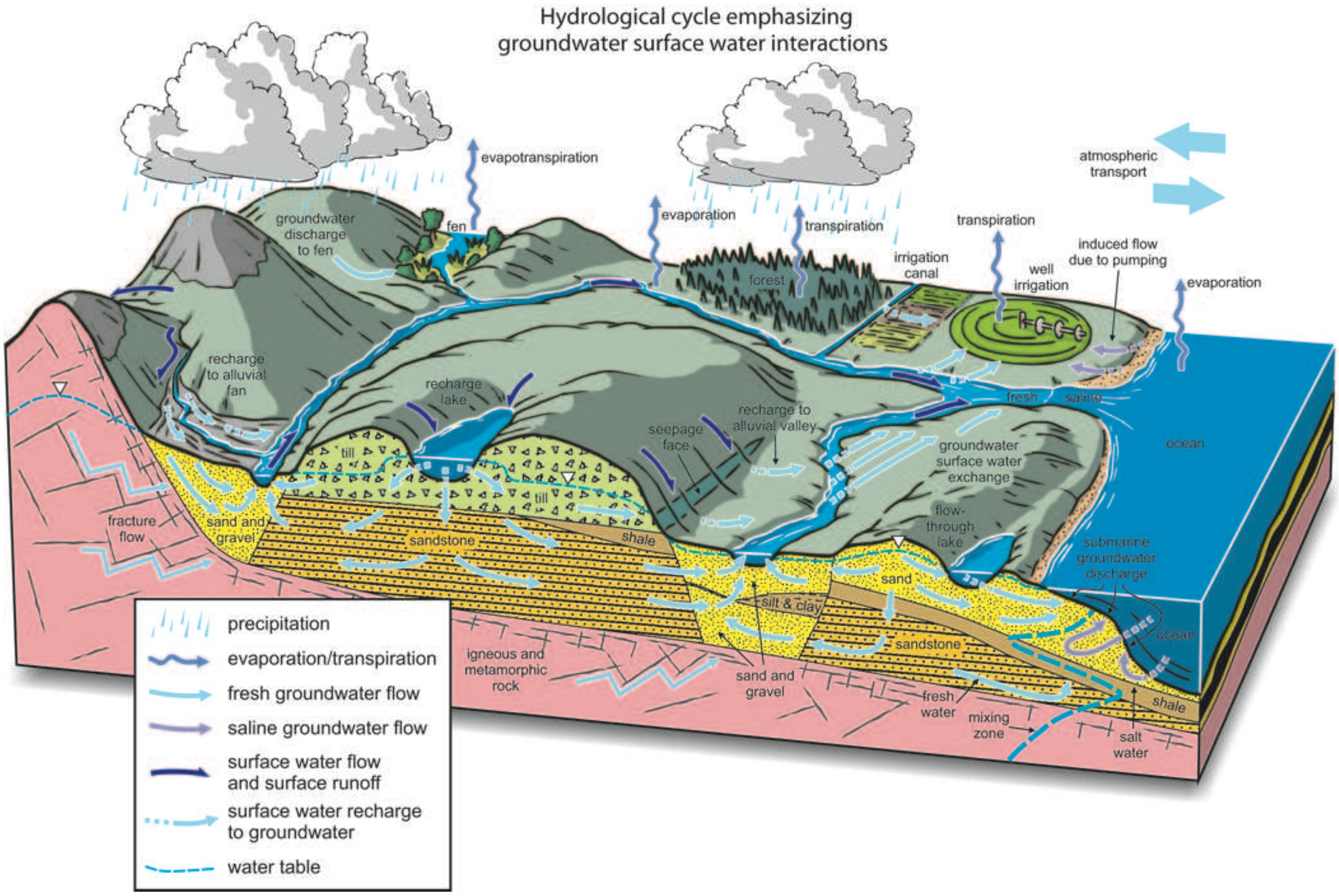


Figure 5.1 Hydrological cycle emphasizing groundwater-surface water interactions.

and Mulholland, 2000; Hayashi and Rosenberry, 2002; Sophocleous, 2002; Smith, 2005; Kalbus et al., 2006).

5.2.1 GW-SW interactions, an element of the hydrological cycle

Groundwater and surface water have markedly different flowpaths and residence times through the landscape (Figure 5.1) and, consequently, different physical and chemical characteristics that affect their ecological roles. GW-SW interactions generally refer to the processes associated with the transfer or mixing of water between groundwater and surface water reservoirs. Traditionally, surface water and groundwater have been investigated separately with subsequent consideration of GW-SW interactions only at the interfaces where they meet. However, an important conclusion of this chapter is that understanding the issues of GW-SW interactions should also include greater consideration of the processes that influence groundwater and surface water throughout the watershed. Furthermore, groundwater and streams should be considered as integrated components of a hydrological continuum (Brunke and Gonser, 1997).

5.2.2 Importance of GW-SW interactions

Groundwater and surface water interactions are often most recognizable where large localized flows exist between these two reservoirs, for example, at springs where water flows out of the ground to form headwaters of streams or, less commonly, where streams disappear into the ground in karstic terrain. GW-SW interactions, however, are far more

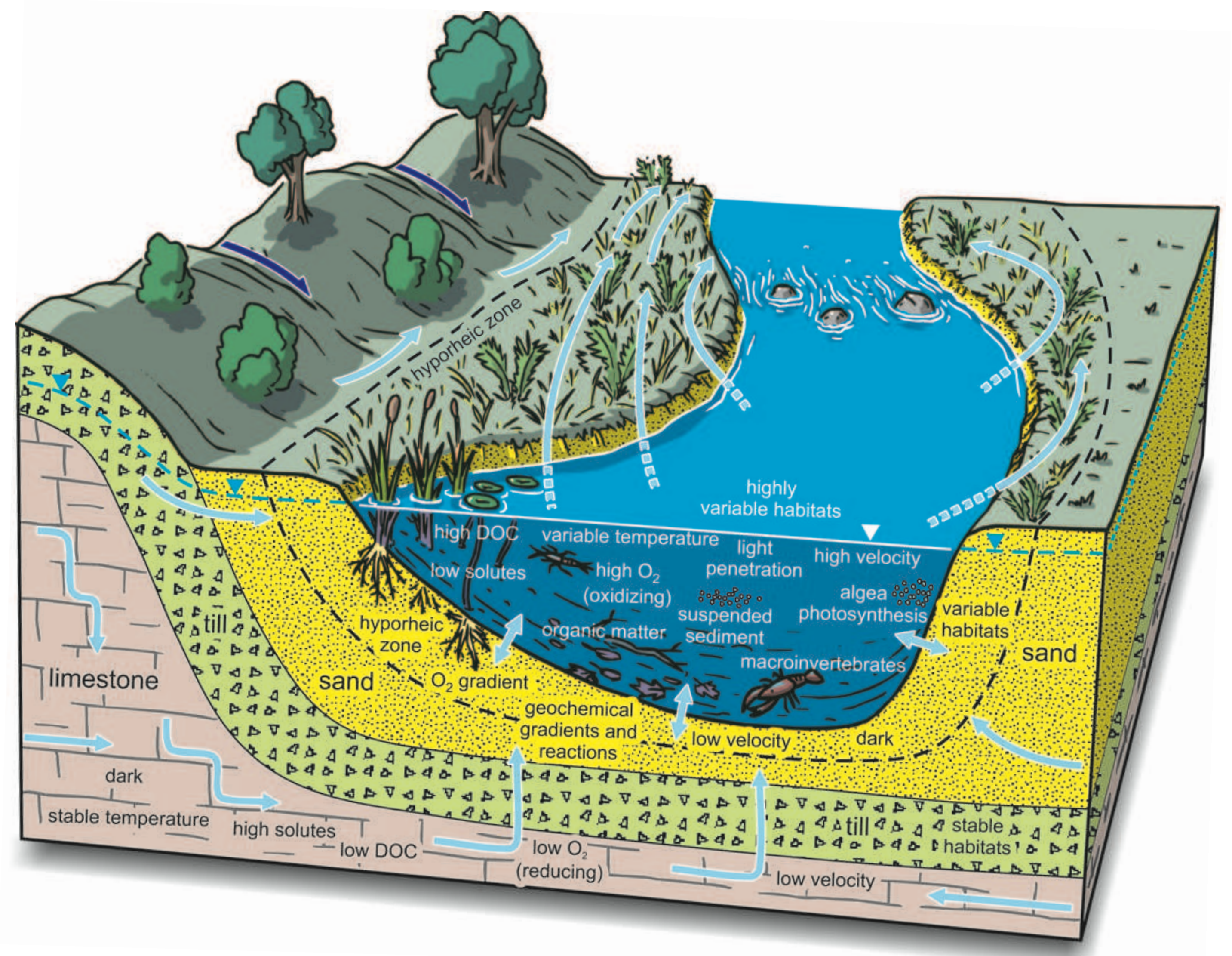


Figure 5.2 Characteristics and processes of groundwater, surface water and the hyporheic zone.

widespread, particularly in the form of groundwater discharge to streams, rivers, lakes, wetlands, reservoirs, estuaries and oceans. Groundwater is often the main source of dry weather flow in streams and rivers. Conversely, in some areas, surface water recharges aquifers to form a significant proportion of the groundwater resource. The fact that many surface water and groundwater systems are hydraulically interconnected has such obvious implications for the management of water resources that some advocated treatment of groundwater and surface water as a single resource (Winter et al., 1998).

Another consequence of hydraulic GW-SW interactions is the effect on aquatic and riparian habitats and their ecosystems. Chemical and physical characteristics of groundwater and surface water often differ greatly due to differences in the nature, rates and duration of their processes (Table 5.1). Groundwater usually displays higher solute content, lower dissolved oxygen, and more stable temperature, whereas surface water is generally characterized by lower solute content, high dissolved oxygen, high detrital organic matter and more variable temperature. Large physiochemical gradients between groundwater and surface water result in an ecotone (boundary between ecosystems) called the hyporheic zone which is a

TABLE 5.1 GENERALIZED COMPARISON OF PHYSICAL, CHEMICAL AND ECOLOGICAL CHARACTERISTICS AND PROCESSES BETWEEN SURFACE WATER (PRIMARILY STREAMS AND RIVERS) AND GROUNDWATER (ECOLOGICAL CONCEPTS FROM GIBERT ET AL., 1994)

PROCESSES		CHARACTERISTICS	
Groundwater	Surface water	Groundwater	Surface water
greater depth of flow	water flow at surface	high solutes	low solutes
low flow velocity	high flow velocity, variable	particle movement limited to colloids	variable sediment load, erosion, sedimentation
long residence time	short residence time	wide range of ages	“young” water
extensive contact with mineral surfaces	greater contact with organic matter and organisms	low organic matter	high organic matter
contact with soil gases	contact with the atmosphere	low dissolved oxygen, reducing conditions common	high dissolved oxygen, oxidizing conditions common
no exposure to solar radiation	exposure to solar radiation	stable temperature	variable temperature
heterotrophy(energy from carbohydrates and other organic materials)	photosynthesis, autotrophy (synthesize organic substances from inorganic compounds)	short and simple food webs	complex food webs
low productivity	high productivity	low richness, diversity and density of organisms in ecological communities	high richness, diversity and density of organisms in ecological communities

transition between groundwater and surface water systems (Figure 5.2, see Gooseff (2010) for various definitions of hyporheic zone). The hyporheic zone performs many important functions, such as water transfer, storage and transformation of nutrients and contaminants, buffering of acidity and redox (reduction-oxidation) gradients, metabolism of organic matter, and habitat for distinct biota (Boulton et al., 1998).

GW-SW interactions can influence water quantity and quality, aquatic and riparian ecosystems and, by extension, societal activities that depend on these resources and their functions. The reverse situation, however, is more common when societal activities influence one or more of these resources and have an effect on the state or function of the linked systems. For example, changes in land use and land management practices (e.g., land development, application of fertilizers) can influence both diffuse and focused groundwater recharge (see Chapter 4), water use, water quality, water fluxes and flowpaths, sedimentation and erosion, sediment clogging, and terrestrial and aquatic ecosystems. Minimizing potential impacts of land use changes requires a holistic understanding of the interactions among these systems in which GW-SW interactions are sometimes of particular importance. Furthermore, consideration of the interactions between groundwater and surface water systems should extend beyond their interface to the entire watershed. Consideration of the interchange between groundwater, surface

water and aquatic and riparian ecosystems extends beyond scientists, water managers and conservation officers to encompass policy makers, planners and the general public whose activities directly and indirectly affect these resources.

5.2.3 Hydraulic connection

GW-SW interactions are only possible because of hydraulic connections between the two systems. The degree of interaction depends on the amount of water flowing between the systems. As in Darcy's Law (see Chapter 2), volumetric flow is directly proportional to three factors: hydraulic conductivity, hydraulic gradient, and area perpendicular to flow. Hydraulic conductivity is generally the most important factor determining the intensity (or fluxes) of GW-SW interactions. Low hydraulic conductivity can limit the groundwater flow to values much less than available climatically (see Chapter 4). Since most groundwater flows along the path of least resistance, intense GW-SW interactions are often associated with high hydraulic conductivity. Due to the considerable heterogeneity of most sediments and bedrock, large spatial variability in GW-SW interactions is common at many scales. Therefore, it is necessary to consider the hydraulic conductivity of both the groundwater system and the GW-SW interface.

Surface water bodies often deposit sediment that originates from primary productivity or erosion; their deposits differ from those of the groundwater system in hydraulic conductivity, geochemical characteristics and ecological function. Fine-grained lake sediments, for example, can form a low conductivity layer above a high conductivity aquifer that would limit fluxes between the aquifer and the lake, whereas coarser sediments in a nearby streambed would allow groundwater and surface water to exchange more freely. While the hydraulic conductivity of a groundwater system influences the magnitude and patterns of flow in the entire flow system, the hydraulic conductivity of the interface often influences the magnitudes and smaller-scale patterns of flow near surface water bodies (Conant Jr., 2004). Several physical, chemical, biological and microbiological processes can result in the clogging of the surface interface sediments, thereby reducing hydrological exchanges (Brunke and Gonser, 1997; Brunke, 1999; Rehg et al., 2005). In contrast, bioturbation by benthic invertebrates can reduce clogging of sediment and increase GW-SW exchange (Nogaro et al., 2006).

The gradient of hydraulic potentials is the driving force of water flow and direction. Temporal changes in hydraulic gradients provide insight on the fluctuations in GW-SW interactions over time. Spatial patterns of groundwater potentials and hydraulic gradients at a watershed scale are usually fairly constant under natural conditions; therefore, the general patterns and magnitudes of groundwater flow are often stable. The dynamic nature of GW-SW interactions is most apparent near surface waters and is frequently the result of changes in surface water elevations (e.g., due to precipitation, runoff or damming) or fluctuations in shallow water tables (usually adjacent to surface water) in response to precipitation. An exception to this generalization is the large change in hydraulic gradients that can result from groundwater pumping.

The area of the interface between groundwater and surface water systems can also be important, particularly for groundwater systems with low hydraulic conductivity; if the area is large, substantial flows (volume/time) can occur even when fluxes (volume/area/time) are small. In geological units with high conductivity, large volumes of flow may occur within small areas (e.g., large springs).

Important exceptions are karst environments where Darcy's Law does not necessarily apply as high flows between surface water and groundwater may occur in conduits or fractures even under low hydraulic gradients (Ford and Williams, 2007; Worthington and Ford, 2009).

5.2.4 Types of GW-SW interactions

There are three basic types of GW-SW interactions based on the direction of flow at the interface: groundwater discharge, groundwater recharge, and GW-SW exchange. Groundwater discharges to surface water when groundwater levels are higher than adjacent surface water levels. Surface water recharges groundwater when surface water levels are higher than groundwater levels. GW-SW exchange occurs where surface water flows into the adjacent groundwater and then back into the surface water, usually when the direction of groundwater flow is sub-parallel to surface water bodies (Figure 5.1).

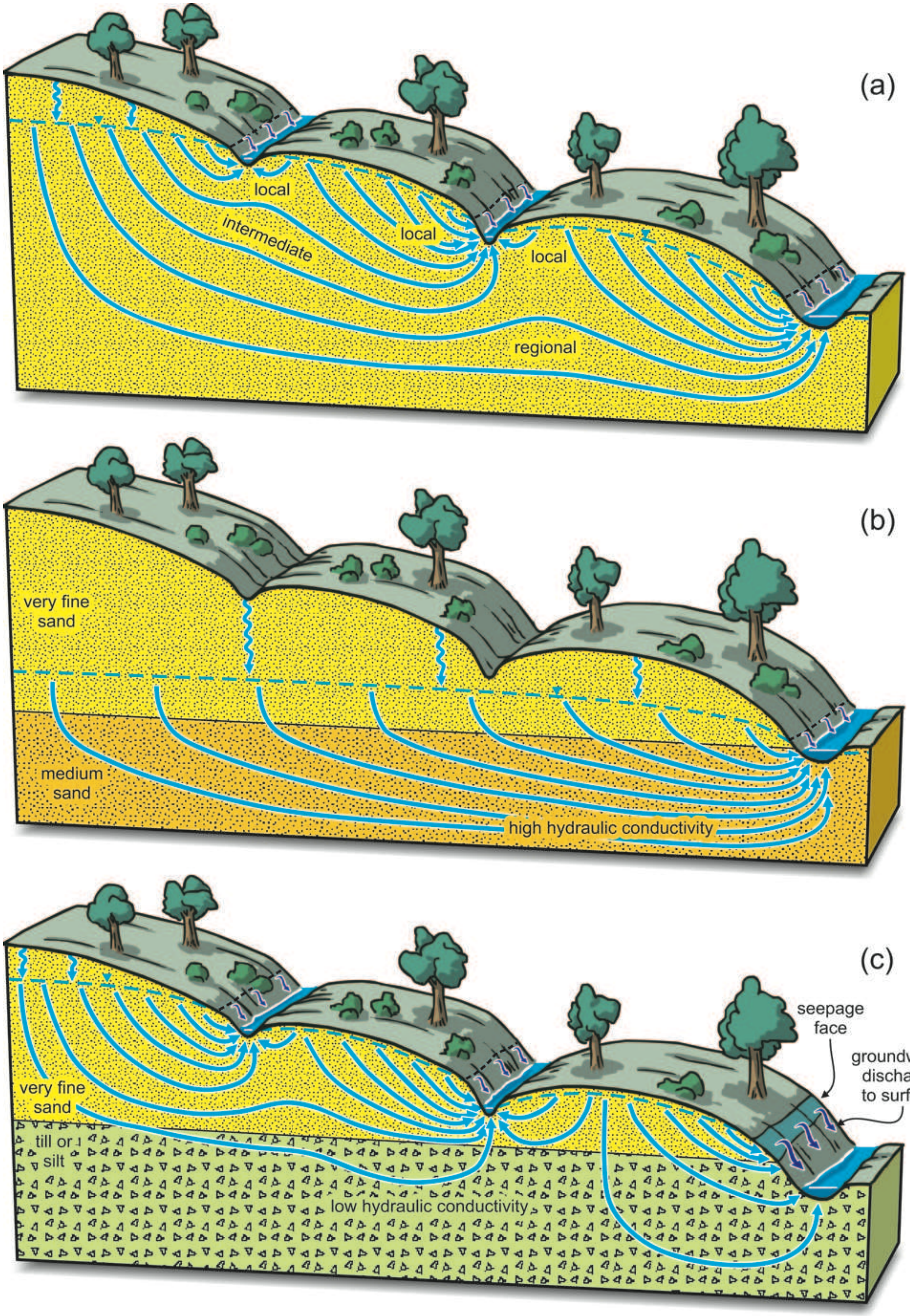


Figure 5.3 Groundwater flow systems. **(a)**in a homogeneous aquifer, **(b)** with a high hydraulic conductivity underdrain, **(c)** with a low hydraulic conductivity barrier (note same surface topography but different flow patterns).

5.2.4.1 Groundwater discharge to surface water

Because recharging groundwater ultimately returns to the ground surface within the overall flow system, groundwater discharge is a widespread form of GW-SW interactions. Although groundwater discharge is most commonly recognized as groundwater springs (see Springer and Stevens, 2009 for descriptions, sketches and photographs of spring types), it occurs more commonly as flow directly into surface water bodies.

Since groundwater flows from high potential (high water elevation) to low potential, groundwater systems produce discharge at lower elevations than at their recharge sites. One important challenge is to quantify the distribution of groundwater discharge. As discussed in Chapter 2, groundwater flow systems develop in a nested, hierarchical structure at local, intermediate and regional scales (Figures 2.17, 5.3a). The creation of these flow and discharge patterns is largely a function of the flow systems' capacity to transmit water along different flowpaths under the existing hydraulic gradients. Figure 5.3 illustrates how the subsurface geology can influence the distribution and fluxes of groundwater discharge along three flow systems with identical surface topography. In panel (a), the uppermost stream has a small recharge area contributing to its flow, whereas the middle and lower streams have much larger contributing areas which include discharge from intermediate and regional flow systems. Panel (b) shows that a more permeable underlying aquifer connected to a surface water body at low elevation can function as an effective drain for the entire flow system, resulting in dry conditions in the upper two valleys with all flow directed to the lowermost stream. In contrast, the underlying aquitard in panel (c) becomes a hydraulic barrier that limits the development of deeper intermediate and regional flow systems and results in the predominance of shallow local flow systems. The upslope recharge area contributing to the upper stream is much larger than in panel (a) and a larger seepage face develops just above the aquitard contact along the lower stream valley.

5.2.4.2 Surface water recharge to groundwater

Although less common, surface water recharge to groundwater can be a significant source of groundwater recharge, particularly where direct recharge is low or where there is a highly permeable hydraulic connection with surface water.

The required condition for surface water recharge to groundwater is a surface water level higher than underlying groundwater levels. If the ground is fully saturated beneath the surface water body, the system is considered to be fully connected and the rate of recharge will increase proportionally with the depth of the groundwater level (Brunner et al., 2009a; Brunner et al., 2009b). When the water table has dropped sufficiently to allow the development of an unsaturated zone between the surface water body and the water table (a condition that requires a "clogging" layer of lower hydraulic conductivity sediment below the surface water body), the system is considered to be disconnected and the surface water body will infiltrate the ground at the maximum rate irrespective of additional changes in groundwater levels (Brunner et al., 2009a; Brunner et al., 2009b). At intermediate groundwater levels, the system is considered to be transitional and the rate of recharge increases slowly towards its maximum value as groundwater levels decline. Therefore, knowledge about the state of

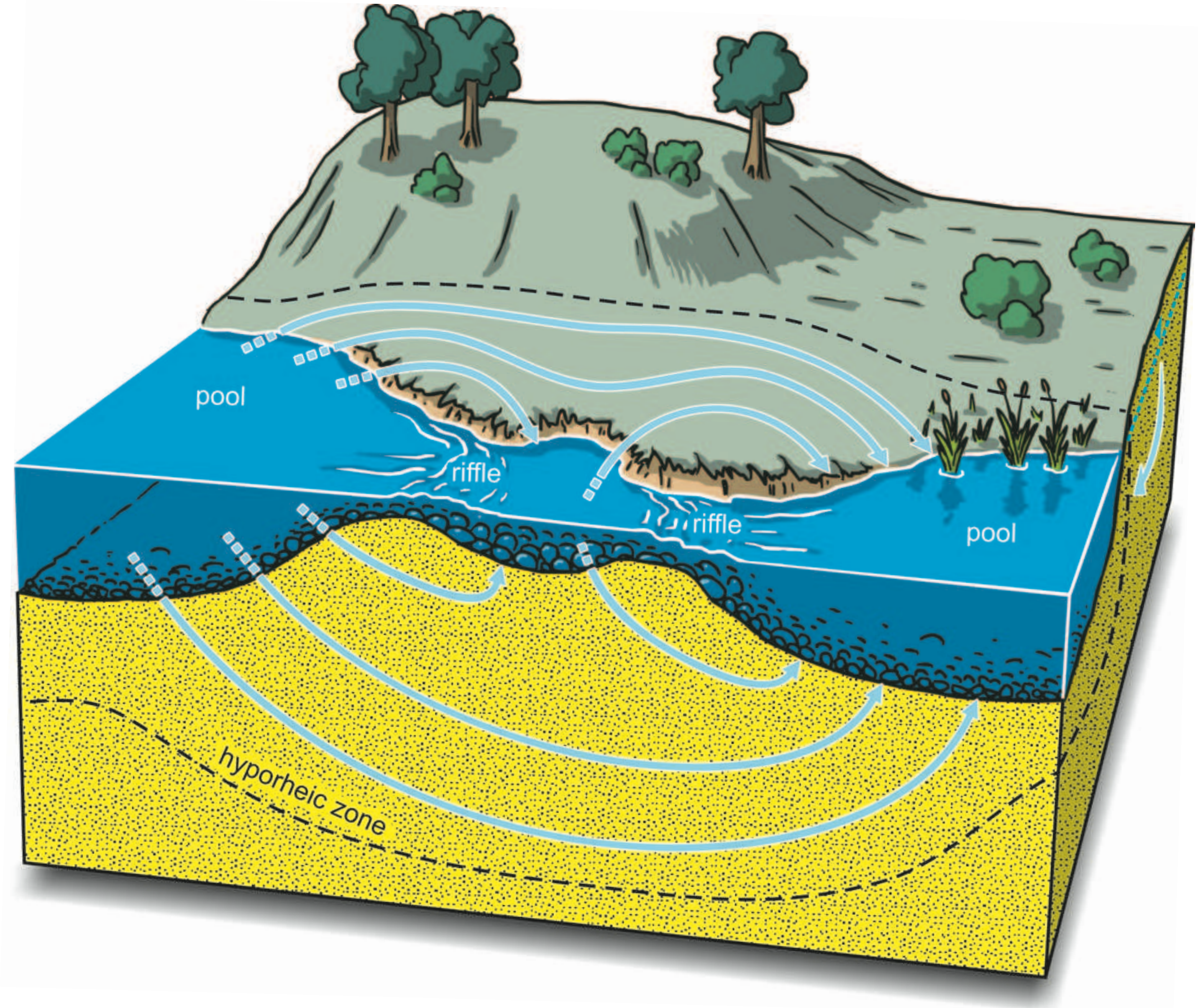


Figure 5.4 GW-SW interactions along a pool and riffle reach of a stream. The block diagram shows a longitudinal section along a pool-riffle sequence; the top of the block illustrates lateral GW-SW exchanges through the stream bank whereas the front of the block demonstrates the vertical GW-SW exchanges beneath the stream bed.

connection between a surface water body and the underlying groundwater can be useful to assess the potential effects of changes in groundwater levels (for example, due to pumping) on surface water fluxes and recharge.

Surface water recharge to groundwater often occurs in topographic depressions fed by surface runoff over low-permeability or frozen soils (Hayashi et al., 1998; Hayashi et al., 2003). These depressions serve as temporary surface water storage areas that slowly recharge the groundwater beneath and surrounding them. This depression-focussed recharge may be a significant source of recharge, particularly in arid or semi-arid regions (Box 4-2) where diffuse recharge may be small. It can occur in small (10-1,000 m^2) or larger depressions such as prairie potholes, kettles lakes, ponds, and wetlands which may be either temporarily or permanently flooded.

Settings where surface runoff, streams or rivers cross into unconfined aquifers with lower groundwater levels can be among the highest intensity

GW-SW interactions, particularly in aquifers with high permeability. These interactions can occur at a variety of scales. For example, at the hillslope scale, surface runoff along a steep bedrock outcrop can infiltrate the colluvium at the base of the slope and recharge its water table. At the watershed scale, upland streams may flow onto permeable alluvial fans, terraces or coarse fluvial deposits and transmit much of the flow through the subsurface (Box 4-1, Kontis et al., 2004). Because these interactions rely on variable surface water supply, recharge will also vary significantly with time.

Surface water may also recharge groundwater as a result of human activities. These may be intentional through structures designed to increase groundwater resources or unintentional through leakage of reservoirs, unlined canals or irrigation (Bouwer, 2002, Figure 5.1). Such recharge can result in significant groundwater increase but may require treatment to minimize impairment of native groundwater quality (National Research Council (U.S.). Committee on Ground Water Recharge, 1994).

5.2.4.3 GW-SW exchange

Surface water and groundwater systems are hydraulically connected so water naturally flows back and forth between these systems in response to spatial and temporal changes in surface water and groundwater levels. In these exchanges, surface water enters the subsurface, flows as groundwater along or beneath the stream or river, mixing with existing groundwater before discharging back to the surface water at a lower elevation (Figure 5.4). These exchanges can occur across a wide range of scales. When there is a small obstruction along a streambed, currents can produce small scale pressure gradients that induce flow through sediment (Thibodeaux and Boyle, 1987). Small scale GW-SW exchange, commonly referred to as hyporheic exchange (Harvey and Wagner, 2000), can result from streambed topography, sediment heterogeneity, and is often associated with stream features, such as riffle-pool sequences or debris dams (Harvey and Bencala, 1993; Kasahara and Hill, 2006; Hester and Doyle, 2008; Käser et al., 2009). The physical break in slope at the transition between the pool-riffle boundary increases hydraulic gradients and permits more subsurface flow which, in turn, causes increased flow of surface water to the subsurface (Figure 5.4). This water flows roughly parallel to the stream along the riffle and may mix with surrounding groundwater to varying degrees. At the riffle-pool boundary, horizontal hydraulic gradients decrease to the extent that the subsurface can no longer accommodate the flow and the water is hydraulically forced to discharge back to the stream (Figure 5.4).

GW-SW exchange can also occur at a larger-scale such as surface water flowing through alluvial aquifers (Figure 5.1, Larkin and Sharp Jr, 1992; Woessner, 2000), or bank storage in response to fluctuating surface water levels (Jung et al., 2004). An important distinction between small- and large-scale GW-SW exchanges is that the large-scale GW-SW exchange may extend beyond the influence of some biological, microbiological and geochemical processes associated with the hyporheic zone. Therefore, it is sometimes important to consider the temporal and spatial scales of GW-SW exchange in the conceptualization of GW-SW interactions (Gooseff, 2010). It is also possible, in some instances, that surface water which recharges groundwater does not discharge back to surface waters but exits the groundwater flow system through evaporation or

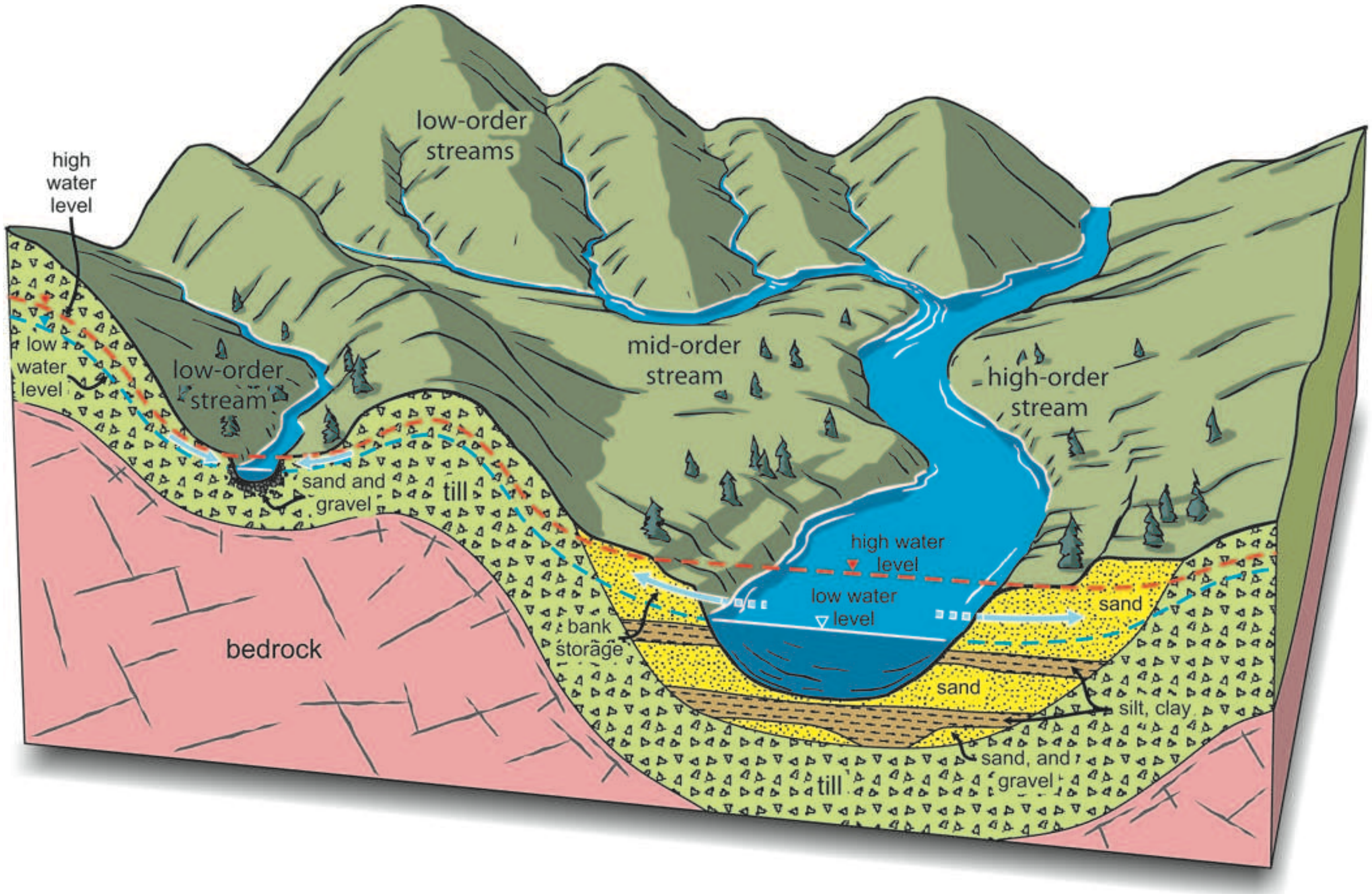


Figure 5.5 GW-SW interactions during storm in low- and high-order streams.

pumping from a well (Gooseff, 2010).

The importance of GW-SW exchange to larger-scale watershed processes may not be apparent since it generally involves a small portion of the watershed area adjacent to surface waters. However, GW-SW exchange provides a mechanism to transport organic matter, nutrients and oxygen from the stream into the hyporheic zone and enhances physiochemical and ecological processes such as nitrogen transformations and organic matter retention and metabolism that perform important watershed functions (Brunke and Gonser, 1997; Jones and Mulholland, 2000). In this manner, microscopic processes that accompany these hydrological exchanges can play key roles in macroscopic behaviour at the watershed or landscape scales (Pringle and Triska, 2000).

5.2.5 Interactions with different SW systems

The nature and significance of GW-SW interactions vary with the types of surface water bodies such as streams, rivers, ponds, lakes, reservoirs, wetlands, estuaries and oceans. Such differences are related to variability in surface water levels, groundwater flow, water chemistry, mixing and ecological dependence on groundwater.

5.2.5.1 Streams and rivers

Groundwater discharge to the surface is responsible for the existence and permanence of many streams, particularly in regions with humid climates and permeable, porous substrates. However, the role of groundwater is not limited to sustaining stream flow during periods of dry weather. Numerous studies have shown the dynamic nature of GW-SW interactions during periods of storm runoff wherein shallow groundwater near the stream can make significant (and often dominant) contributions to headwater and medium sized streams (see references in Gibson et al., 2005). Rapid rises of groundwater levels adjacent to surface waters can result in rapid displacement of soil water and groundwater into adjacent surface water bodies. Such contributions have significant implications for the biogeochemical characteristics of streams. For example, the input of groundwater helps to neutralize acidic deposition in surface water and reduce its ecological impacts (Bottomley et al., 1984).

Groundwater interactions with streams and rivers are likely the most widespread and significant. They usually have the largest GW-SW fluxes among all surface water bodies due to the higher permeability of many streambeds. They have also been the primary focus of most studies on hyporheic processes (cf. Brunke and Gonser, 1997; Jones and Mulholland, 2000). Important biogeochemical processes occur in the riparian zones of stream and rivers. A notable example is the removal of nitrates derived from fertilizers or waste in riparian areas where biological processes such as denitrification and plant uptake reduce the nitrate loads to streams (Hill, 1996; Cey et al., 1999; Devito et al., 2000; Maître et al., 2003).

An important concept that is discussed more frequently in the ecological rather than hydrological scientific literature is the significance of stream order on GW-SW interactions. The river continuum concept (Vannote et al., 1980), the flood pulse concept (Junk et al., 1989) and the riverine ecosystem synthesis (Thorp et al., 2006) are a few of the models that discuss how the geomorphic, hydrological, biogeochemical and ecological roles of streams and rivers change significantly from low-order headwater streams to high-order river systems. Low-order streams usually comprise much of the watershed area and are often characterized by large cumulative inputs of nutrients, organic matter and water from terrestrial areas, higher relief, and small, discontinuous coarse fluvial deposits. High-order streams are often characterized by lower terrestrial inputs of nutrients and water, higher in-stream photosynthetic production, lower relief, and broader, thicker, finer and more continuous fluvial sediments (Figure 5.5).

Although the differences in hydrological and geomorphic processes adjacent to low- and high-order streams are recognized, there has been little attempt to synthesize the resulting variable nature of GW-SW interactions across scales. These differences are particularly evident during storms. For example, the rapid displacement of groundwater into streams during storms occurs predominantly in low-order streams (Figure 5.5) where GW-SW exchanges may remain relatively close to the stream channels. In mid- and high-order streams, rapid displacement of groundwater during storms is progressively less important. However, GW-SW exchange becomes more significant when wider and flatter valleys coupled with greater increases in surface water levels cause surface water to flow into the stream bank, known as bank storage (Figure 5.5). Although the patterns of GW-SW interactions with stream order may differ from watershed to watershed, large variability in GW-SW interactions (and their hydrological and ecological significance) is expected as water flows from headwater streams to high-order outlets. Smith and Lerner (2008) demonstrated the impact and significance of variability in geomorphic and geochemical processes occurring along a river where thicker, finer, and more organic-rich riverbed sediments of lowland

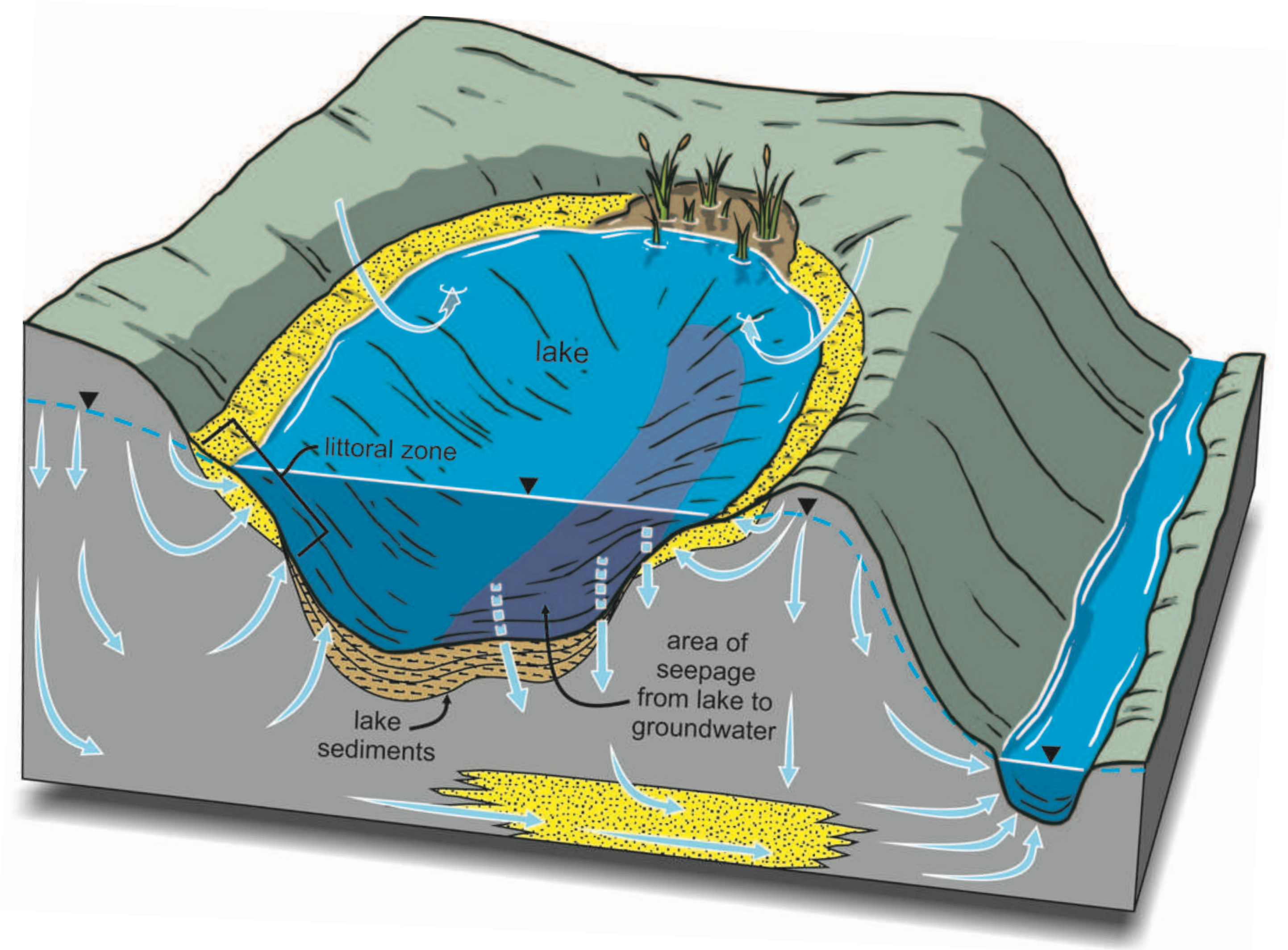


Figure 5.6 GW-SW interactions around a lake. Groundwater discharge within lakes is usually greatest near the lake perimeter and decreases rapidly with distance from the shoreline (McBride and Pfannkuch, 1975). This pattern is observed because the lake water surface is flat and the hydraulic gradient between the lake and underlying groundwater decreases with distance from shore. The distribution of groundwater discharge to lakes can also be influenced by the hydraulic conductivities of the bottom sediments in the lake basin. Lacustrine sedimentation is often composed of low-permeability, fine, inorganic and organic materials (Wetzel, 2001) that act as a physical barrier to reduce GW-SW interactions.

rivers significantly increased pollutant retardation potential as compared to upland river sediments and underlying aquitards.

5.2.5.2 Lakes and ponds

Interactions between lakes and groundwater include groundwater discharge into lakes, lake seepage into groundwater, and flow-through lakes that both receive discharge and supply groundwater systems in different areas within the same basin (Winter, 1999) (Figures 5.1 and 5.6). Groundwater inputs to lakes or ponds can occur directly through the shore or lake sediments, or indirectly as groundwater discharge to streams and/or rivers that subsequently flow into lakes. Direct groundwater discharge into lakes occurs where the adjacent water table is higher than the lake water level. Conversely, lake seepage to groundwater occurs at shorelines where the water table is lower than the lake surface (Figure 5.1). In some lake settings underlain by more permeable units, Winter (1976; 1978; 1999) demonstrated that groundwater can discharge to a lake throughout the entire shoreline, yet lake seepage to groundwater may occur

through the lake bottom (Figure 5.6).

Time scales of influent and effluent groundwater fluxes within a lake can change rapidly, within minutes, and seasonally (Sebestyen and Schneider, 2001; Rosenberry and Morin, 2004). This variability in extent and intensity of groundwater flow occurs in response to fluctuating water levels along the lake edge caused by recharge of shallow water tables or evapotranspiration from shoreline vegetation. Longer-term changes in GW-SW interactions can also result from regional changes in groundwater or lake water levels caused by climatic influences, such as drought or prolonged wet periods (Winter, 1999).

The hydrological significance of GW-SW interactions for lakes and ponds is variable due, in part, to the large range of climatic, topographic, geologic and hydrogeological settings of lake basins. In general, the intensity of groundwater-lake interactions is expected to be less than groundwater-stream interactions because of the lower permeability of lake bottom sediments and the more gentle topographic and hydraulic gradients adjacent to lakes. In most lakes, streamflow dominates water inflows and outflows; precipitation and/or evaporation may also produce significant fluxes for many lake water balances. Although direct groundwater fluxes into or out of lakes are minor in most instances, they can be significant in some settings such as prairie potholes or depressions (Box 4-2, Hayashi et al., 1998; Hayashi et al., 2003), alpine lakes (Hood et al., 2006; Roy and Hayashi, 2007; Roy and Hayashi, 2008), dunes (Winter, 1986), karst seepage lakes (Lee and Swancar, 1997) and flow-through lakes (LaBaugh et al., 1997; Smerdon et al., 2005a). In these cases, groundwater fluxes are hydrologically significant either because lake sediments are permeable and/or stream inflows and outflows are minor or ephemeral.

Even where direct groundwater flux is a small component of a lake or pond hydrological budget, GW-SW interactions may still be significant to the hydrology, ecology or geochemistry of lakes, ponds or the surrounding groundwater systems. In the case of the lower peninsula of Michigan, only approximately 5% of the groundwater discharge occurs directly to the Great Lakes whereas the remaining 95% discharges to streams before reaching the lakes (Hoaglund III et al., 2002). The indirect component of groundwater discharge to the Great Lakes via streams accounts for approximately 22%-42% of the water inputs (Holtschlag and Nicholas, 1998).

The positions of lakes with respect to local and regional groundwater flowpaths can influence lake chemistry because of differences in groundwater chemistry as it evolves along different flowpaths before discharging to surface waters (Birks and Remenda, 1999; Winter, 1999). As with groundwater discharge to streams, the fate of groundwater nutrients and contaminants flowing through lake sediments is expected to be altered particularly because of the higher organic matter content of lake sediments. Therefore, there is often a need to consider the nature of GW-SW interactions even in lakes where other hydrological fluxes dominate.

5.2.5.3 Reservoirs (impoundments)

Reservoirs are frequently constructed by damming rivers; their geomorphological characteristics are intermediate between rivers and lakes (Wetzel, 2001). The shallower upstream portion of the reservoir is typically akin to the riverine zone. The deeper downstream portion of the reservoir forms the lacustrine zone. The intermediate portion in between the riverine and lacustrine zones is classified as a transitional zone (Wetzel, 2001). GW-SW interactions are also likely intermediate between rivers and lakes with more similarity to lakes due to the large area of uniform hydraulic head imposed by reservoir and lake water surfaces.

Despite many similarities between reservoirs and lakes, some differences are worth noting. Firstly, increasing water levels in the reservoir will change the spatial distribution of hydraulic gradients in the local groundwater flow system. Groundwater gradients into the reservoir will decrease or reverse, whereas hydraulic gradients between the reservoir and the downstream outlet (or aquifer) will increase, often substantially. Controlling seepage is an important design consideration, not only to reduce water losses from the reservoir, but also to prevent hazards associated with erosion of the dam or abutment by groundwater flow (Cedergren, 1989). Secondly, variations in the reservoir level are often large and can result in significant GW-SW interactions due to temporal changes in hydraulic gradients between groundwater and the reservoir. Reservoir storage and release will also influence the flow and level of the downstream river with resulting effects on the geomorphology, GW-SW interactions and ecology of the downstream river (Sawyer et al., 2009). Thirdly, dams completely change sedimentation and erosion patterns in both upstream reservoirs and downstream rivers (Collier et al., 1996) with resulting changes to sediment distribution and hydraulic conductivity patterns. In some cases, rising water levels in reservoirs can saturate permeable formations that were previously unsaturated. For instance, Smerdon et al. (2005b) gives an example of a permeable window providing a hydraulic connection between a reservoir and a buried valley aquifer in Alberta. Finally, impoundments, even small ones, through their changes to sedimentation and hydraulic exchanges can influence biogeochemical cycling in streams (Fanelli and Lautz, 2008).

5.2.5.4 Wetlands

Wetlands cover approximately 14% of Canada's land surface (National Wetlands Working Group, 1997), and occur within every hydrogeological region of Canada. There are five wetland classes — bogs, fens, marshes, swamps and shallow water — distinguished by their genetic origin and properties such as vegetation, morphology, soils, water levels, hydrology and hydrochemistry. Groundwater is an integral component of wetlands and frequently has an important role in their formation, evolution and function (National Wetlands Working Group, 1997; Winter et al., 1998; Winter, 1999; Glaser et al., 2004). A critical variable in wetlands is water level; it is a major control on hydrological, biogeochemical and ecological processes. Wetland water levels are regulated by GW-SW-atmosphere interactions both within wetlands and with their surrounding uplands, wherever present.

Wetlands occur in a wide range of hydrogeological settings which promote saturation near ground surface (Winter et al., 1998). Wetlands in groundwater discharge zones rely on inflow from local and regional groundwater systems to sustain wetland water levels. The stability of inflow depends on the extent, hydraulic characteristics and position within the flow system. Wetlands also occur in surface depressions underlain or filled with low-permeability units such as crystalline bedrock of the Canadian Shield, or clayey till in the Canadian Prairies. In these areas, surface runoff from the surrounding uplands and direct precipitation are typically the main water sources, and are therefore more variable. The role of low-permeability units is usually to limit subsurface outflow from the wetland. Although the low permeability may limit the subsurface fluxes, these fluxes may be hydrologically or geochemically important to the wetland or the surrounding upland (Berthold et al., 2004). Wetlands also develop in areas of low topographic gradient such as the Hudson Bay Lowlands where local groundwater flow systems develop within the raised bogs, and all the water is derived from atmospheric sources (Glaser et al., 2004). These wetlands are susceptible to climatic variability and fluctuating water levels (Reeve et al., 2006).

Some considerations that are relevant for GW-SW interactions in wetlands include organic soils, vegetation, geochemical processes and vulnerability to climate. GW-SW interactions often occur within wetland organic soils which influence their hydraulic and geochemical functions. The hydraulic conductivity of peat varies as a function of depth with higher permeability in the upper, poorly decomposed material and lower permeability in the deeper, decomposed peat (Letts et al., 2000). The presence of macropores formed by roots can further enhance shallow hydraulic conductivity. As a result, the dominant groundwater fluxes are often lateral exchanges near the wetland surface. The high moisture storage of organic soils is also a significant characteristic that helps stabilize water level fluctuations and increases moisture availability to vegetation.

Vegetation can have a significant influence on GW-SW interactions in wetlands. Several examples in prairie wetlands and ponds show that transpiration from surrounding upland vegetation constitutes a major water loss during dry periods and leads to groundwater flow towards transpiring vegetation (Hayashi et al., 1998; Winter, 1999).

Evapotranspiration from wetland vegetation can also influence wetland hydrology as exemplified by the rise in water table after clear-cutting forested wetlands (Dube et al., 1995). The interdependence of climate, vegetation and the water table has important ecological, hydrological and geochemical consequences for wetlands. Water table depth, its fluctuations, and geochemistry influence the vegetation that can grow; likewise, vegetation can influence the water table elevation through evapotranspiration. Many interrelated factors influence the long-term evolution of wetlands and their hydrological and biogeochemical roles. The complexity of interactions in wetland systems illustrates the difficulty in predicting effects of wetland disturbance and highlights the value of site specific assessment of GW-SW-atmosphere interactions prior to wetland alterations.

Humans rely on both natural and constructed wetlands for water quality benefits such as sediment, nutrient and pollutant removal (Johnston, 1991). Wetlands can be short and long-term sinks for various chemical elements. GW-SW-atmosphere interactions can influence the geochemical function of wetlands by their control on water levels and hydrological flowpaths, and on the biogeochemical processes related to oxidized or reduced conditions. For example, low water levels can lead to oxidation of reduced sulphur compounds stored in wetlands; these are then flushed

into surface waters when the water tables rise again (Eimers et al., 2007). As a result, increasing drought in a warming climate can cause wetlands to contribute acidity to lakes and slow their recovery from decreased atmospheric sulphur deposition (Aherne et al., 2008).

GW-SW-atmosphere interactions in wetlands are affected by climate change and may also indirectly influence climate. Wetlands are a major carbon reservoir and form the largest natural source of methane (CH4), an important greenhouse gas (Denman et al., 2007). Changes in temperature and water table depths can alter carbon cycling dynamics in several ways and result in increased or decreased carbon dioxide (CO2) and CH4 emissions from wetlands (Waddington et al., 1998; Rosenberry et al., 2006; Denman et al., 2007). Winter (2000) suggests that wetland vulnerability to climate change is variable and depends on GW-SW-atmosphere interactions. Wetlands are vulnerable to the extent that they derive their water supply from precipitation; in contrast, wetlands that obtain water from regional groundwater flow systems are least vulnerable (Winter, 2000). Consequently, bogs that receive their water supply from precipitation would be more vulnerable to climate change than fens which are sustained by groundwater. Studies of GW-SW-atmosphere dynamics in wetlands during dry and wet periods (e.g., Winter and Rosenberry, 1998) may prove useful for quantifying the effects of climate change on wetlands and the role of wetlands on carbon cycling.

5.2.5.5 Oceans and coastal areas

Research on GW-SW interactions in coastal areas has traditionally focused on assessing fresh water resources with emphasis on fresh groundwater discharge to the ocean or the impacts of groundwater pumping on salt water intrusion into freshwater aquifers (e.g., Segol and Pinder, 1976; Merritt, 1996). A more holistic perspective is emerging for which the term "submarine groundwater discharge" (SGD) is used to describe any flow of water across the sea floor, including both fresh groundwater and re-circulated sea water (Figure 5.1, Burnett et al., 2003; 2006). SGD is a unique form of GW-SW interactions that includes not only topography-driven groundwater flow, but also additional processes leading to groundwater flow and mixing, such as ocean dynamics (tides, waves, currents, storms), density gradients and geothermal gradients (Burnett et al., 2003; Wilson, 2005).

Freshwater SGD, like GW-SW interactions with lakes, is generally concentrated in the nearshore area and decreases with distance from shore (Taniguchi et al., 2002; Burnett et al., 2003; 2006; Martin et al., 2007). However, instances of large offshore freshwater SGD have been reported in springs and deep confined aquifers (Burnett et al., 2003). SGD also varies temporally due to hydraulic gradients on land and additional variations can result from tide, storm, wind, and current-induced gradients. Compared to lakes, coastal zones often have more permeable sediments so that nearshore SGD fluxes are expected to be higher than for lakes. Estimates of fresh SGD to the oceans have large uncertainties but range from approximately 0.3% to 16% of global river flow (Burnett et al., 2003). Significant human influences on SGD can result from activities such as groundwater pumping, construction of shoreline structures and dredging. Another concern is global sea level rise due to climate change (Meehl et al., 2007) and its impact on salinization of coastal freshwater resources.

Just as the processes and characteristics of groundwater and surface water contrast in freshwater systems (Table 5.1, Figure 5.2), the biogeochemical processes and characteristics of groundwater and seawater differ. Consequently, GW-SW interactions within coastal aquifers enhance mixing and can influence flow and water quality in fresh, brackish and salt water environments, which can be important for geological, geochemical and biological processes (Moore, 1999).

Freshwater resources and ecosystems are vulnerable to salt water intrusion. Estuaries, coastal lagoons and coastal marine ecosystems are vulnerable to variations in salinity and to inputs of pollutants, inorganic and organic carbon, but they are particularly sensitive to nutrients. Nitrogen input from groundwater appears to be a significant contributor to coastal eutrophication because concentrations in coastal groundwaters may be several orders of magnitude greater than those of receiving coastal waters (Valiela et al., 1990; Paerl, 1998; Bowen et al., 2007). One study illustrates the profound effects of nitrogen transport to coastal waters via groundwater in transforming the coastal ecosystem (Valiela, 1992). Nitrogen from groundwater increased primary production by phytoplankton and macroalgal biomass which dominated the ecosystem, increased the frequency of anoxic events, and decreased the extent of native sea grasses.

5.2.6 Interactions with different GW systems

GW-SW interactions also vary according to the nature of porosity and the dynamics of groundwater flow systems. Groundwater flow systems respond differently to spatially and temporally variable climatic, hydrological and human factors. How a groundwater flow system stores and transmits water will influence GW-SW interactions.

Because the unsaturated zone influences the storage and redistribution of infiltrating precipitation, it also has an indirect role on GW-SW interactions. The variable nature of water storage and transmission among porous, fractured and karst groundwater flow systems will generate variable GW-SW interactions.

5.2.6.1 Porous media flow systems

Groundwater flow through porous media (flow occurs through inter-granular pores) is critical in many geologic settings in Canada because much of the land surface is covered by porous sediment. Even where the sediment is thin, it often has a significant effect on water storage and transmission within a watershed. Furthermore, sediment is often present in the valleys of streams and rivers even when upland areas are predominantly bedrock. As a result, most studies of GW-SW interactions have focused on flow in porous sediments.

The dominant factor influencing GW-SW interactions in porous media settings is the grain size distribution which controls the hydraulic conductivity and can also be significant for geochemical, biological and filtration processes in hyporheic zones. The large specific yield (or storage capacity) of unsaturated porous sediments also allows for greater bank storage of surface water adjacent to rivers during floods than would a comparable stream bank composed of karst or fractured crystalline bedrock.

Two larger scale factors in porous flow systems that influence GW-SW interactions are the depth of the water table and whether the aquifer is confined or unconfined. In unconfined aquifer systems where the water table fluctuates within approximately two metres of land surface, and storage in the unsaturated zone is limited, groundwater levels increase rapidly in response to infiltration events; groundwater discharge to surface water can also respond rapidly. In this setting, most of the groundwater typically flows in local flow systems and discharges to the nearest surface water body (Figure 5.3c). In unconfined aquifer systems with deep water tables, the unsaturated zone stores most infiltration; the water table responds to large snowmelt or rainfall events and seasonal patterns of evapotranspiration and precipitation. Deep unconfined aquifer systems also tend to have longer flowpaths to surface water bodies (e.g., Figure 5.3b) and often produce groundwater levels, water chemistry and discharge fluxes that are more stable than shallow unconfined systems. Groundwater flow through confined aquifer systems is generally regulated by the flow through the confining aquitard. Consequently, discharge from these systems is expected to be sustained and more stable.

5.2.6.2 Fractured media flow systems

The nature of flow and, therefore, of GW-SW interactions in fractured geological materials can be quite variable depending on both the fracture system and the porosity of the matrix. It may vary from discrete fractures in non-porous crystalline rocks to networks of interconnected fractures in porous rocks or sediments. Whereas the latter may behave similarly in many ways to the porous flow systems described above, due to the available storage within the porous matrix, non-porous fractured rocks have little available storage and respond more rapidly to a greater depth than porous flow systems. For example, unconfined aquifers in non-porous fractured bedrock would generally have much lower available storage than a comparable unconfined granular (e.g., sand, gravel) aquifer. Consequently, groundwater levels, chemistry and discharge from a fractured bedrock aquifer would likely be more variable and the flow system would have less capacity to sustain discharge during periods of low recharge.

Although differences in near-stream GW-SW exchanges between fractured and porous media may be expected, there have been relatively few studies that investigate these exchanges and their implications specifically for fractured flow (Oxtobee and Novakowski, 2002; 2003; Praamsma et al., 2009). Fracture flow settings may have received comparatively less scrutiny due to the greater difficulty and cost of instrumentation (Praamsma et al., 2009).

5.2.6.3 Karst terrain flow systems

Karst terrain occurs in various regions across Canada (Ford, 1983) with distinctive landforms, hydrogeology and hydrology that result from the dissolution of soluble rocks to form fissures and conduits (Ford and Williams, 2007). Karst features can range widely from small fissures to extensive cave systems. Because karst systems develop as highly-interconnected subsurface drainage networks (Worthington and Ford, 2009), their hydrological and hydrogeological systems function quite differently than fractured or porous media aquifers. Although recharge, discharge and GW-SW exchange can occur in karst terrain, their rates and

processes may differ substantially. For example, groundwater discharge to surface water in karst terrain often occurs as discrete springs that result from the convergence of groundwater into subsurface conduits which function as high-permeability drains. In contrast to springs in porous media, which generally have stable flow, temperature and water chemistry, these parameters can fluctuate greatly in springs of karst terrain (Ford and Williams, 2007). Despite considerable study of surface water and groundwater systems in karst terrain (see Ford and Williams, 2007), GW-SW interactions concepts such as hyporheic zone and exchange have received little attention (Cardenas and Gooseff, 2008). Given the widespread distribution of karst terrain, the differences in hydrological and geochemical processes between karst and porous media, and the unique ecological habitats afforded by many springs, more focused study on GW-SW interactions in karst terrain appears warranted.

5.2.7 Natural and human influences

In light of the wide range of hydrological, ecological and societal issues and processes relevant to GW-SW interactions (section 5.2.2), both natural and human influences may need to be considered depending on the purpose of a given investigation. Natural factors that influence GW-SW interactions include climate, topography, hydrology, geology, hydrogeology, geochemistry, ecology, wildlife, vegetation, and permafrost. Human activities can disrupt natural factors and, either directly or indirectly, influence GW-SW interactions. Examples include groundwater and surface water withdrawal, artificial recharge, land drainage, surface water impoundment, irrigation (and irrigation canals), land use change, nutrient application, and waste water discharge. Studies of GW-SW interactions, by their nature, need to consider complex interactions and cumulative effects. General knowledge of GW-SW interactions and processes may be suitable for qualitative analysis, but dedicated study is likely necessary for quantitative analysis and assessment.

5.2.8 Spatial and temporal scales

GW-SW interactions occur at scales varying from the thickness of sediment beds (sub-millimetre to metre) to that of watersheds (> 5 km) (Hancock et al., 2005; Dahl et al., 2007). Recognition of temporal and spatial patterns and variability are important elements of any GW-SW investigation. Quantifying water fluxes, chemical fluxes and transformations, or microbiological processes involved in GW-SW interactions can be inherently difficult due to the spatial and temporal variability of natural systems even at small spatial scales such as a stream segment. For example, groundwater fluxes to a stream can vary by more than one order of magnitude on the scale of tens of centimetres due to variations in stream bed hydraulic conductivity (Conant Jr., 2004). Patterns that emerge at successively larger scales may not simply represent the cumulative effects of small-scale processes because hydrological, hydrogeological and ecological processes change across a watershed (e.g., river continuum concept and Tóth's scales of groundwater flow systems, Figure 2.17). Consequently, understanding GW-SW interactions at a watershed scale may require integration of data at various scales.

Similarly, the temporal scales of GW-SW interactions may change across a watershed as water table dynamics and storage vary. To consider the possible impacts of landscape changes on GW-SW interactions, it is important to recognize that changes to hydrological systems, particularly groundwater systems, propagate at different rates. For example, impacts from a change in recharge water quality would depend on water velocity, whereas impacts from a change in recharge or pumping rate would depend on water level changes. Therefore, the water quality and quantity impacts from a change in land use could manifest itself over different time scales.

When groundwater is removed from the flow system, either through pumping or decreased recharge, water that is captured will ultimately affect surface water (Sophocleous, 2000; Bredehoeft, 2002; Devlin and Sophocleous, 2005). This process may take many years, even centuries, depending on several parameters, including hydraulic properties, flow system change in storage and distance to surface water. Where water capture is more distal to surface water, impacts will be delayed, and occur gradually. The time required to reach a new groundwater equilibrium will also be longer (Bredehoeft, 2002). This delayed and gradual response becomes a problem for assessing potential impacts of groundwater changes on GW-SW interactions. The problem is compounded in urban areas where the cumulative effects of multiple withdrawals (or sources) that occur at different times and locations are difficult to assess. Consequently, long-term effects are often disregarded or identified as being insignificant.

5.2.9 Methods of investigation

Traditional field hydrological and hydrogeological methods to study GW-SW interactions include the use of piezometers, seepage metres, natural or artificial chemical tracers, water chemistry, water temperatures, stream hydrographs, and incremental stream discharge measurements (Harvey and Wagner, 2000; Kalbus et al., 2006). Methods used in ecological and microbiological studies include various approaches to identify and enumerate macro- and micro-organisms including the use of DNA, microcosm, mesocosm or solute injection experiments that quantify microbial activity or nutrient retention (e.g., Barton, 2006; Griebler and Lueders, 2009; Ibisch et al., 2009). The scale of measurement varies from point values to the entire watershed. Given the spatial variability in GW-SW interactions (section 5.2.8), methods must be selected for the appropriate scale of processes being studied.

Another approach to investigating GW-SW interactions is to develop models that use mathematical formulations of processes to simulate several components of the groundwater, surface water or biogeochemical systems. Models vary widely in the issues they address, in processes stimulated, in the assumptions required, in the way GW-SW interactions are represented, and in the numerical approaches used to solve the mathematical equations (Tellam and Lerner, 2009). Models help address the problem of integrating spatially variable processes and properties (Gauthier et al., 2009); they can also provide insight into regional, long-term and/or cumulative effects on GW-SW interactions (e.g., Sulis et al., 2011). Models, however, generally have relatively high data requirements to allow appropriate calibration.

A significant advance has been the development of physically-based models that fully integrate subsurface and surface flow (VanderKwaak, 1999; Panday and Huyakorn, 2004; Therrien et al., 2005; Jones et al., 2008; Brunner and Simmons, 2010). In these models, the GW-SW interfaces are not boundary conditions and the GW-SW interactions are controlled by the models' representations of the processes and parameters. One application of such a model to a watershed revealed the importance of better characterizing evapotranspiration to improve transient stream simulations (Li et al., 2008). Another model implementation incorporated thermal transport modelling to consider GW-SW-atmosphere interactions on temperature distributions (Brookfield et al., 2009). Although these integrated models will likely provide significant insight into GW-SW-atmosphere interactions, they require extensive data sets that are not widely available. The cost, effort and difficulty of collecting sufficient site-specific data may limit the application of such sophisticated GW-SW models in most watersheds.

5.3 GW-SW INTERACTIONS IN CANADA

5.3.1 Research and data

An extensive amount of research has contributed to an increased understanding of GW-SW interactions from studies both in Canada and worldwide. Much of the knowledge about GW-SW processes has accumulated gradually from independent studies from a number of different disciplines addressing a broad range of issues. Better understanding of GW-SW interactions has seldom been the main goal of research studies, yet has been required to improve the grasp of the issue of interest. For example, understanding nitrogen dynamics from uplands through riparian zones and into streams has required a better understanding of the hydrological and biogeochemical interactions between surface water and groundwater (Hill, 1996; 2000). One ongoing challenge is to integrate fragmentary knowledge of GW-SW interactions from many disciplines into a more holistic understanding of interrelated processes.

One research approach that has fostered better multi-disciplinary understanding of GW-SW interactions has arisen from long-term research catchments where hydrological and geochemical mass balances and ecological monitoring are combined with process-oriented research. In Canada, long-term catchment-scale research has addressed issues such as lake eutrophication and acidification (e.g., Dillon et al., 1987; Jeffries et al., 2003; Schindler et al., 2008; Yan et al., 2008), land or forest management practices (Foster et al., 2005; Mallik and Teichert, 2009), climate change (Schindler, 2001; Eimers et al., 2004) and the cycling of toxic contaminants (Hall et al., 2005). By design, these research programs have contributed towards a multidisciplinary understanding of interacting natural processes in which GW-SW interactions are often significant.

Although much has been learned about GW-SW interactions from independent studies and catchment-scale research, additional insight has been gained more recently by specifically targeting GW-SW exchanges and related processes (Harvey and Wagner, 2000). The number of studies of this nature is increasing in Canada, and many have been focused at relatively small spatial scales (e.g., Conant Jr., 2004; Kasahara and Hill, 2006; see Hayashi and Van Der Kamp, 2009). At larger-scales, integrated or coupled groundwater and surface water models are being used to incorporate the effects of GW-SW interactions when considering issues such as climate change (Scibek et al., 2007; Gauthier et al., 2009; Sulis et al., 2011). More studies specifically focussed on GW-SW exchanges are needed across a wider range of geographic scales (e.g., pool-riffle to river basin scales): these studies would benefit greatly from an approach that combines field research and modelling. The concept of classifying and mapping GW-SW interactions across multiple scales is also relatively recent (Dahl et al., 2007). Additional investigations in the development of classification, mapping and field techniques can provide key data on the nature of GW-SW interactions to support scientific analysis and decision making.

To date, there has been no detailed examination of data available regarding GW-SW interactions in Canada. With respect to water-related data for sustainable groundwater management, however, an expert panel found that data collection has failed to keep pace with demands over the past 20 years (Expert Panel on Groundwater, 2009). This report also indicated large discrepancies in groundwater monitoring data collected countrywide. A survey of Canadian groundwater professionals revealed insufficient groundwater data and the need for integrated groundwater and surface water monitoring data (CCME, 2010). A recent evaluation of the Canadian surface water hydrometric network concluded that almost all Canadian main watersheds do not have adequate hydrometric networks (Mishra and Coulibaly, 2010). Therefore, it is expected that the type, amount and distribution of surface water, groundwater and ecological data available for watersheds across Canada varies considerably and is usually inadequate for assessment of GW-SW interactions. Watershed- and site-specific data of GW-SW interactions is often insufficient to make informed decisions about land and water use on the watershed scale. Even in watersheds, where surface water and groundwater dynamics are reasonably well characterized, data specifically on GW-SW interactions is usually sparse. Most existing groundwater flow models have insufficient data to validate GW-SW fluxes and their distributions. To manage surface and groundwater resources in an integrated manner will require a greater effort in systematic and integrated data collection of groundwater, surface water, and GW-SW interactions, in addition to better data analysis, interpretation and reporting.

5.3.2 Conceptual models in Canadian settings

Despite the scarcity of data and interpretations on GW-SW interactions in Canada, there is the need to consider these interactions in numerous applications such as assessment of environmental impacts of development, predictions of climate change impacts or water resource development planning. Consequently, as part of the overall study area conceptualization, it is often necessary to develop a conceptual model of GW-SW interaction (either explicitly or implicitly) based on available data. Conceptualization of these interactions can be critical to establishment of boundary conditions for surface water and groundwater models. A key element of conceptual model development is the application of useful generalizations (LeGrand and Rosen, 2000). Few conceptual models of GW-SW interaction have been developed explicitly; more detailed generalizations and conceptual models applicable to specific settings are needed (e.g., Woessner, 2000 for a fluvial plain setting). Development and testing of such generalizations and conceptual models will advance current understanding of processes where specific data on GW-SW interactions is limited. In effect, the proposed solution to the problem of large variability in GW-SW interactions and insufficient data is to build conceptual models of type environments that can be applied to site specific situations. This approach is commonly used by geologists in the form of facies models (Walker, 1992) and is finding increased application by hydrogeologists (LeGrand, 1970; Anderson, 1989).

In Canada, the large number of variables influencing GW-SW interactions (e.g., geology, topography, hydrology and climate) and their variability may influence applicability and usefulness of such generalizations and conceptual models. For example, some generalizations about GW-SW interactions in permafrost environments may be broadly applicable across northern Canada; by contrast, a conceptual model of GW-SW interaction for an alluvial fan would only be applicable to that specific setting.

Much has been learned about GW-SW interactions from a wide range of studies in various disciplines. Various elements of the results can be integrated to begin development of generalizations about GW-SW interactions in regions where little data exists specifically on GW-SW interactions.

Following are three brief examples where integrating the existing literature allows for consideration of the nature and key controlling factors of GW-SW interactions in specific Canadian settings.

5.3.2.1 Permafrost

The presence of permafrost, seasonally frozen ground (otherwise known as the active layer), and a low-precipitation regime dominated by snow accumulation distinguishes both surface water and groundwater flow regimes in the permafrost hydrogeological region. As a result, the nature and some of the key factors controlling GW-SW interactions in northern Canada are expected not only to differ when compared to areas with similar physiography farther south, but also to be more complex because of the additional interactions between the hydrological and thermal regimes.

Permafrost or perennially frozen ground is a key factor controlling GW-SW interactions because frozen ground has very low permeability, and behaves hydraulically as an effective aquitard (Sloan and van Everdingen, 1988). Permafrost continuity and thickness control development of groundwater flow systems and appear to affect the nature and intensity of GW-SW interactions. One useful classification of groundwater in permafrost regions is based on its position relative to the permafrost (see Chapter 15, Tolstikhin and Tolstikhin, 1977; Sloan and van Everdingen, 1988): a) suprapermafrost water above permafrost in the active layer and taliks (perennially unfrozen ground), b) intrapermafrost water within the permafrost, and c) subpermafrost water beneath the permafrost (see also Figure 15.6). Interactions between subpermafrost groundwater and surface water in the continuous permafrost zone are limited to areas where open taliks allow a hydraulic connection across permafrost (e.g., beneath large lakes). These settings are not well studied yet, therefore their significance is not fully known. As a first approximation, it is assumed that these fluxes are generally small since even large rivers in continuous permafrost can cease to flow after freeze-up (Woo, 1986). Interactions between suprapermafrost groundwater and surface water are more widespread but occur during the period of active layer development and are limited to shallow depths. In areas of discontinuous permafrost, there is more opportunity for GW-SW interactions caused by hydraulic connections between subpermafrost aquifers and surface waters. Discharge sites are sometimes indicated by the presence of springs, open water in the winter, and icings (aufeis) formed by the freezing of groundwater discharge (van Everdingen, 1974). Significant differences in winter baseflow yield between rivers in continuous (approaching 0 mm/year) and discontinuous (30–160 mm/year) permafrost highlight the significant role of permafrost continuity (Williams and van Everdingen, 1973; Sloan and van Everdingen, 1988).

Another key factor controlling GW-SW interactions in the permafrost hydrogeological region is the seasonal dynamics of the active layer. Seasonal ground freezing and thawing results in seasonal variations in groundwater recharge, flow, storage and flowpaths in suprapermafrost groundwater. The varying frost depths and water tables significantly influence subsurface flowpaths and rates (Quinton and Marsh, 1999). Understanding the thermal regime is crucial because it can affect GW-SW interactions differently than in non-permafrost areas. Thermal regimes differ based on slope aspect and position, moisture content, surface vegetation and thermal properties, leading to both spatial and temporal differences in suprapermafrost groundwater flow and overall water balances (Carey and Woo, 1999; Quinton and Carey, 2008).

Similarly, thermal regime of surface waters and their hyporheic zones are important factors affecting GW-SW interactions. Both the depth of permafrost and the seasonal freeze and thaw cycles influence hydraulic and geochemical functions within the hyporheic zone. Whereas some surface waters can maintain taliks and perennial flow beneath them, others will freeze and effectively shut off hyporheic flow. Usually, larger and deeper water bodies, such as lakes, are more likely to maintain unfrozen hyporheic zones. By contrast, the hyporheic zones of small streams or peatlands are more frequently

within the active layer, and contract and expand seasonally as they freeze and thaw. Consequently, the depth of thaw and hyporheic flow will be quite uneven along streams due to variable thermal conditions or GW-SW exchange (Zarnetske et al., 2008; Brosten et al., 2009). However, groundwater flow modelling predicts that a deepening subsurface thaw under warming climatic conditions only affects hyporheic exchange to a threshold depth (Zarnetske et al., 2008).

Despite increased research in the Arctic to assess the multiple impacts of climate change and geotechnical problems on infrastructure, Woo et al. (2008) note the dearth of groundwater research on intrapermafrost and subpermafrost aquifers within the last decade, and have identified the need for well-integrated process studies of ground and surface water hydrology. Only recently have studies specifically considered GW-SW exchanges in the hyporheic zones of Arctic rivers (Edwardson et al., 2003; Greenwald et al., 2008; Zarnetske et al., 2008). These studies have found that biogeochemical processes in the hyporheic zone of Arctic streams transform nutrients, such as N and P, and may be as important as similar processes in temperate zones (Edwardson et al., 2003; Greenwald et al., 2008).

The permafrost hydrogeological region is currently undergoing significant changes in permafrost and hydrological conditions (White et al., 2007; Woo et al., 2008). Both Walvoord and Striegl (2007) and St. Jacques and Sauchyn (2009) detected long-term (>30 years) increases in winter discharge from streamflow records in the Northwest Territories, Yukon and Alaska . They propose that these changes could be attributed to increased groundwater contributions from permafrost thaw. Such changes are intimately linked to permafrost degradation via various interrelated processes (Chapter 15, White et al., 2007; Woo et al., 2008). Climate impacts on permafrost to alter groundwater flow systems and their interactions with surface water (Michel and Van Everdingen, 1994; Bense et al., 2009). GW-SW interactions can also have a role in the degradation of permafrost and the hydrological impacts of climate change due to heat transport by recharging groundwater or GW-SW exchange. Despite the significant potential impacts of climate change and GW-SW interactions to northern hydrology, there is little research on groundwater flow systems and GW-SW interactions in the permafrost hydrogeological region of Canada.

Thermal regime is a key element of the conceptualization of GW-SW interactions in permafrost settings, and this conceptualization is more complex because it must consider both the hydrological and thermal regimes. For example, thermal modelling can be used to estimate the dimensions of lakes that might have open taliks in the zone of continuous permafrost (e.g., Cumberland Resources Limited, 2005) and thus predict where deep subpermafrost groundwater may interact with surface water. Suprapermafrost groundwater fluxes and flowpaths are closely linked to the seasonal freezing and thawing of the active layer and are highly variable both spatially and temporally. Subpermafrost groundwater contributions are expected to be more constant on a seasonal basis, but may increase in the long term as a result of permafrost degradation.

5.3.2.2 Permeable glacial sediment

Many areas of high groundwater discharge are associated with permeable glacial deposits such as eskers, kames and kame terraces, interlobate moraines, subaqueous fans, ice marginal deltas and outwash. These landforms occur in all hydrogeological regions of Canada and have the potential for significant GW-SW interactions. Groundwater discharge is commonly the dominant and most extensive type of GW-SW interaction in these settings although GW-SW exchange can also be significant at a local scale. Even though conceptualization of GW-SW interactions may differ according to landform, some generalizations are possible.

First, permeable glacial landforms often have a positive topographic expression that includes elevated areas of groundwater recharge such that a groundwater flow system develops on the scale of the landform. Typically, groundwater discharge is concentrated at the edges of landforms where there is a rapid change in slope that reduces hydraulic gradients. Sometimes where there is a decrease in sediment thickness or permeability that forces groundwater to discharge (e.g., Gerber and Howard, 2002).

Second, higher recharge rates in these settings sustain higher groundwater discharge and baseflow to perennial surface waters which maintain more constant flow, water levels and geochemical conditions than ephemeral surface waters. Due to the permeable nature of glaciofluvial sediment, headwater streams with perennial flow can develop even in watersheds of only a few square kilometres.

Third, GW-SW interactions are more intense where higher-permeability units are connected hydraulically with surface waters. The wide range of permeability in glacial landscapes and the extensive

distribution of lower-permeability units such as till and fine grained glaciolacustrine or glaciomarine sediment results in preferential groundwater flow in these more permeable units. Groundwater discharge rates and fluxes per unit area in the Oak Ridges Moraine area are highest in areas where permeable sediments are in hydraulic connection with surface waters, and lowest in areas where surficial sediments are till or fine grained glaciolacustrine (Hinton, 1995; Hinton et al., 1998; Hinton, 2005). The continuity of low-permeability units can also affect GW-SW interactions at the scale of a stream reach. In an intensive study along a 60-m reach of a river, Conant (2004; Conant Jr. et al., 2004) mapped large differences in groundwater fluxes and contaminant concentrations over distances of a few metres in riverbed sediments composed of fluvial sands. Areas of highest discharge measured only a few square metres in size and corresponded to localized breaches in the underlying unit, which was formed of silt, clay and peat.

Similarly, variability in GW-SW interactions may also result from variability within permeable glacial landforms. Each type of landform has characteristic distributions of sediment facies that result in characteristic horizontal and vertical patterns of hydrostratigraphy (e.g., Anderson, 1989). For large and complex landforms such as the Oak Ridges Moraine in southern Ontario, the strata are typically deposited in a sequence beginning with proximal sands and gravels progressing into finer, more distal sediment (Barnett et al., 1998). Localized areas of high groundwater discharge within permeable portions of the Oak Ridges

Moraine are consistent with such facies variations (Hinton et al., 1998). In summary, GW-SW interactions in permeable glacial settings are expected to show significant spatial variability as a result of the depositional patterns of sediment facies, the larger scale stratigraphic sequence of high- and low-permeability units and the topographic expression of these landforms.

5.3.2.3 Mountains

Mountainous areas, such as within the Cordillera, Appalachian and portions of the Canadian Shield regions, include a particularly wide range of geologic, topographic and climatic conditions, and the nature, distribution and intensity of GW-SW interactions are highly variable. In upland mountainous areas, it appears that shallow subsurface flow may play a significant role in GW-SW interactions. A review of GW-SW interactions in alpine and subalpine watersheds draws attention to the important contributions of groundwater to surface water, primarily, as very shallow subsurface flow through soils or shallow sediment. Secondarily, as groundwater flow through shallow fractured bedrock or thicker, less permeable sediment adjacent to surface water (Roy and Hayashi, 2007). Recent studies of one alpine watershed in the Rocky Mountains demonstrated that local scale deposits of coarse unconsolidated sediments (in this case talus and moraine) along drainage pathways can result in significant GW-SW interactions which impact hydrological response and water quality (Roy and Hayashi, 2008, 2009). Similarly, limited terrace deposits in the Mirror Lake watershed of the White Mountains, New Hampshire significantly influenced water chemistry and groundwater and surface water fluxes along a mountain stream (Winter et al., 2008). These examples suggest that localized presence of permeable sediment can result in significant GW-SW interactions even within watersheds where groundwater fluxes through the bedrock are relatively minor.

Stream valleys draining upland areas are subject to intense GW-SW interactions. GW-SW exchange is enhanced at the reach scale (connecting tributaries between streams and rivers) by changes in stream topography (Figure 5.4, Harvey and Bencala, 1993). The higher permeability of alluvial deposits at the watershed scale can become a preferential groundwater flowpath of mountain watersheds, providing a significant portion of the total groundwater flow to the valley below (Smerdon et al., 2009). Topographic and geologic conditions of the valley-margin position occupied by alluvial fans are conducive to all three types of GW-SW interactions (Houston, 2002; Woods et al., 2006; Blainey and Pelletier, 2008). The apex or head of an alluvial fan is usually characterized by coarse sediment, a high hydraulic gradient, and a source of surface water (Blair and McPherson, 1994) — conditions that permit significant surface water recharge as an upland river crosses a fan (Figure 5.1). GW-SW exchange also occurs at the landform scale when recharged surface water flows as groundwater through the fan, discharging back to the surface near its base (Woods et al., 2006; Smerdon et al., 2009). Additional factors affecting the GW-SW interactions in alluvial fans are the extreme variability in flow from upstream (Houston, 2002; Smerdon et al., 2009) and the heterogeneity in geologic and hydrogeological facies (Blair and McPherson, 1994; Weissmann and Fogg, 1999; Fleckenstein et al., 2006). The heterogeneity contributes to significant variability in surface water distribution infiltration to the fan, and the resulting low flow conditions of the river (Fleckenstein et al., 2006).

Similar interactions can also occur in valley fill aquifers receiving recharge from upland streams. Water balance estimates for 12 valley-fill aquifers in the glaciated northeastern United States indicate that upland runoff provides from 31% to 93% of the total groundwater recharge (Kontis et al., 2004). Small upland tributaries will occasionally go dry on a seasonal basis in areas where they enter large valleys which absorb all the runoff. Recharge amount from larger upland streams and rivers often depends on the streambed hydraulic conductivity of the streambed and the relative water levels between surface water and groundwater. Groundwater pumping from valley-fill aquifers can also induce recharge into an aquifer when groundwater levels fall below that of the stream (Kontis et al., 2004). Surface water recharge to valley-fill aquifers ultimately discharges back to surface water at lower elevations, which is usually the main river in each valley (Kontis et al., 2004).

A key element of GW-SW interaction conceptualization in major valleys is the transient recharge of alluvial aquifers from rivers during high stages, and subsequent groundwater discharge as river stage declines (Box 4-1, Scibek et al., 2007). Although the process is analogous to bank storage, this type of GW-SW exchange can occur on a scale from hundreds of metres to several kilometres because of the down-valley component of groundwater flow. An additional control on GW-SW interactions in major valleys is aquifer continuity; aquifers are usually bounded by valley walls which can cause them to narrow or pinch off, forcing groundwater discharge into the river (SRK Consulting Inc., 2003). From these examples, it is apparent that, although permeable sediments may cover only a relatively small proportion of the area in mountainous regions, they are predominantly located in valleys adjacent to surface waters where more intensive GW-SW interactions can occur.

5.3.3 Summary of GW-SW interactions in Canada

GW-SW interactions are important in all hydrogeological regions of Canada, regardless of intensity. Better understanding of groundwater, surface water and their interactions in regions with greater reliance on groundwater is needed to manage water resources and their dependent aquatic and ecological habitats sustainably. Even in geographic areas where groundwater resources are traditionally considered of lesser importance (e.g., Canadian Shield and permafrost regions), GW-SW interactions may be significant with respect to water quality issues (e.g., lake eutrophication and acidic deposition) and climate change impacts (active layer and permafrost dynamics). Despite limited groundwater fluxes through glacial till and crystalline bedrock, the geochemical significance of these subsurface fluxes can be substantial. In the absence of carbonate minerals, weathering of silicates is the main source of alkalinity through groundwater flow and discharge (Aravena et al., 1992).

Although GW-SW interactions are not well studied in most Canadian watersheds, conceptual models could provide insight into key processes likely to be important within a specific setting. Conceptual models for GW-SW interactions are yet to be developed for most Canadian watersheds. Such models will remain fragmentary unless integrated with multidisciplinary studies of groundwater, surface water and GW-SW interactions.

5.4 CONCLUSIONS AND FUTURE CHALLENGES

Nevertheless, significant progress has been made in the study and understanding of GW-SW interactions both in Canada and globally. We have better knowledge of the hydrological exchanges between groundwater and surface water and the biogeochemical and ecological processes that occur in riparian and hyporheic zones. Canadian research has made, and continues to make, important contributions to the understanding of GW-SW interactions. However, our knowledge with regard to watershed- or site-specific GW-SW interaction processes across Canada remains limited. The Canadian landscape is vast, with many factors influencing GW-SW interactions over a wide range of spatial and temporal scales; these factors are also undergoing transformation as a result of climate change and changes in land use. Improved understanding of GW-SW interactions will be necessary if Canadians wish to make informed decisions that lead to sustainable use of our water and aquatic resources. Considerable challenges remain for both the scientific community and decision makers in Canada. These include

- improving the integration of knowledge from various disciplines to advance conceptual understanding and quantitative prediction of impacts (e.g., ecological impacts of hydrological or hydrochemical changes; Hunt and Wilcox, 2003)
- coupling of detailed field-based data and modelling at the watershed scale to test and validate conceptual and numerical GW-SW models and the processes they represent
- incorporating greater consideration of atmospheric processes in GW-SW interactions (National Research Council Committee on Hydrologic Science, 2004)
- considering the cumulative and long-term effects of climate change, water use and land use on aquatic and groundwater-dependent resources (Schindler, 2001)
- compiling and analyzing existing data to provide preliminary interpretations of GW-SW interactions at large watershed scales (Ivkovic, 2009)
- conducting more systematic investigations of GW-SW interactions in specific regions or settings where current knowledge is insufficient (e.g., permafrost areas, urban areas)
- recognizing that sustainable development of water resources is inherently linked to GW-SW interactions since sustainability limits are often defined for ecological or social impact criteria which thresholds are attained before hydrological limits for water resources are reached (Alley and Leake, 2004)
- developing policies that recognize the central role of GW-SW interactions in the protection of aquatic, riparian and wetland ecosystems (e.g., EU Water Framework Directive (see Dahl et al., 2007))
- increasing the use and accountability of adaptive management in which there is ongoing data collection and analysis to facilitate a flexible decision-making process (Maimone, 2004)
- continuing support for intensively studied watersheds across the country wherein conceptual knowledge is advanced, methodologies are developed, and the resultant knowledge is fed into integrated management of GW-SW resources. Such studies require both the dedicated effort of scientists and water managers and a long-term financial commitment from funding agencies. In effect, we need adaptive management and the integration of emerging scientific

knowledge into watershed management. This need is greatest in watersheds where land use is intensifying (e.g., urbanized or urbanizing areas and areas of agricultural or industrial intensification) so that continued monitoring and focused studies can be used to assist in this management. Such catchments will provide opportunity for all parties to become involved in administration of watershed and demonstrate to the public what can be accomplished by effectively integrating science information into local decision making

These challenges require greater interdisciplinary collaboration between scientists, closer interaction between scientists, water managers and policy makers, and wider site-specific data and analysis of those areas where decisions may influence long-term water and aquatic resources. (Tellam and Lerner, 2009, have outlined some of these issues in the context of developing management tools for the river-aquifer interface.)

Another broader, more significant challenge is raising public awareness of the interconnection between land use and its impact on water and aquatic resources. Protection of aquatic and water resources is not simply a question of protecting riparian areas; it also requires effective management of terrestrial components of the watershed. Recognition of this interconnection is necessary before the public becomes more willing to support land management policies for the protection of water resources.

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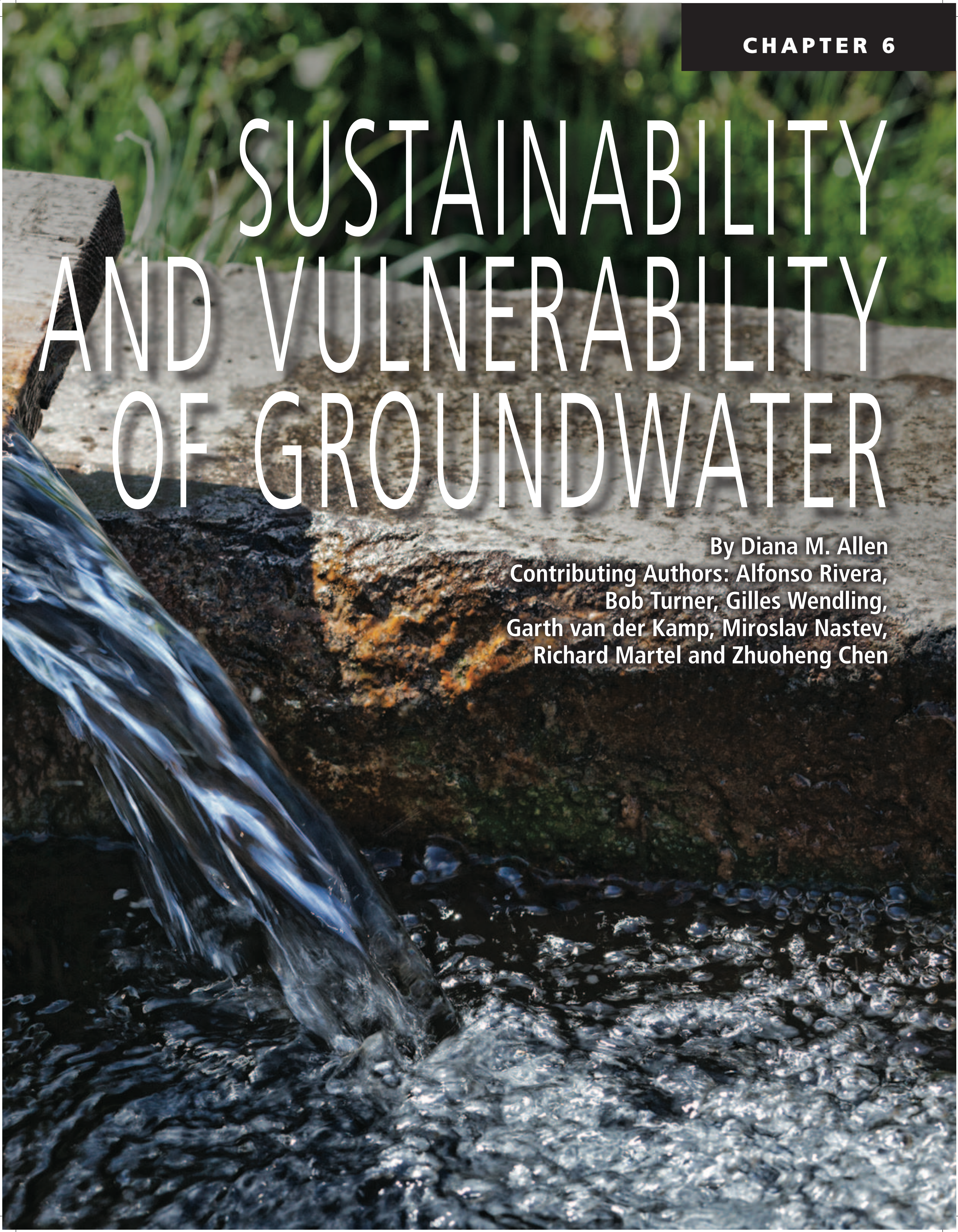

CHAPTER 6

SUSTAINABILITY AND VULNERABILITY OF GROUNDWATER

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6.1 INTRODUCTION

Ecosystems along groundwater and surface water flowpaths have established a natural balance over a long period of time, because these systems are present in streams, lakes, wetlands, estuaries and along foreshores, the main conduits and discharge areas of fresh water. Any re-routing, extraction or contamination of water at locations along its natural flow path will affect all of those ecosystems which rely on water.

It is only in relatively recent geologic history that humans have created a strong footprint on this planet's natural environment. Early Man used readily accessible water sources, such as rivers, springs and lakes. The first man-made wells were dug in Mesopotamia and China to meet needs of sedentary population centres as well as those of agriculture. Extraction rates during these early times were limited because they relied largely on human and/or animal power, or pulleys.

During the industrial revolution, humans developed the capacity to lift water continuously and to drill deeper wells to meet the exponential growth in demand for fresh water. This growth was the result of population densification due to urbanization, coupled with the industrialization of agriculture and industry.

One significant result of the industrial revolution was a dramatic increase in the production and use of chemicals (for industrial processes, fertilizers, etc.). Production of both human and animal waste also increased, creating an urgent need for more efficient waste disposal methods. Waste disposal technologies, however, still are not significantly advanced to deal with the range of waste products being produced, and there was no conception of the fact that disposal of chemical and biological waste could be potentially detrimental to the environment.

Following the industrial revolution, impacts of continued population growth, mankind's often unsustainable consumption of fresh water, and our legacy of environmental pollution have forced us to seek new insights into the need for source protection for both the quality and quantity of our surface and groundwater resources. As surface water resources become more fully mapped, developed and appropriated (in the Okanagan and Southern Alberta, for example), groundwater remains the only other available source for new and future development.

Groundwater and surface water are closely related, and in many areas, the two may be said to comprise a single resource (Winter et al., 1998). Groundwater extraction, through pumping, can result in reduced river flows, low lake levels, and reduced discharges to wetlands and springs, causing concerns about drinking water supplies, riparian zones, and critical aquatic habitats (Alley et al., 1999).

Humans contribute to and experience the causes of global change processes created by unsustainable land use and climate change. There is an underlying need for better understanding of the interaction between humans and our environment, and this need becomes more urgent as changes in land use escalate in tune with human population growth. One recent development in this regard is the increased attention now being paid to the sustainable management of groundwater (and surface water) (Downing, 1998; Sophocleous, 1998).

Herewith we present our observations and conclusions concerning groundwater sustainability and vulnerability. Within the context of this chapter, sustainability relates to the quantity of groundwater available for sustainable use, while vulnerability relates to the groundwater quality.

6.2 GROUNDWATER DEVELOPMENT AND SUSTAINABILITY

6.2.1 How much water is available?

Groundwater dynamics and its hidden nature often impede the understanding and management of this vital resource. One important initial step toward sustainable groundwater resource management involves the exploration and understanding groundwater's hydrogeologic nature and mechanics.

Water moves constantly through the ground as a flux or flow. The flux occurs because water is added at certain times of the year, essentially to "top up" the aquifer within its recharge areas, causing an increase in the hydraulic potential. As a result, the water then begins to move into areas of lower hydraulic potential and, under natural conditions, eventually discharges to springs, streams, lakes and oceans. The flux mechanism can be thought of as a water slug added to the ground, which gradually makes its way to areas of discharge.

A certain amount of water is always "stored" in the ground at any given time. Some 30% of the total groundwater existent on this earth is estimated to be stored as groundwater. (Fresh water stored in rivers, lakes and as soil moisture amounts to less than 1% of the world's fresh water total, while polar ice and glaciers account for some 69%.)

Not all aquifers, however, have the same ability

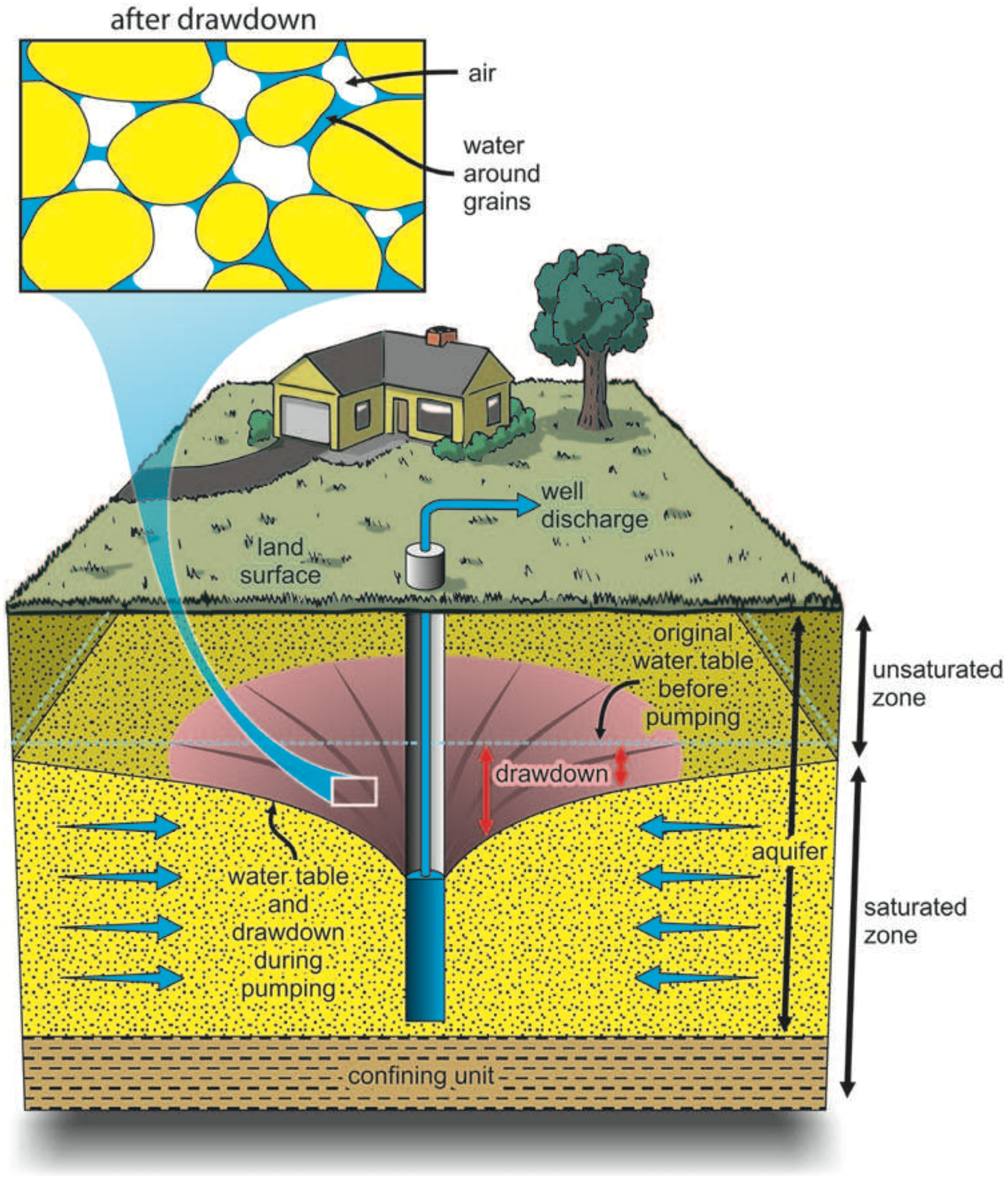

Figure 6.1 Unconfined aquifer cone of water table depression.

to store water. A general rule is the more porous the aquifer, the more void spaces exist for water storage. Sand and gravel aquifers, therefore, have a much higher storage potential than do aquifers of crystalline rock, although fractures can increase the porosity and, therefore, the overall rock aquifer storage capacity.

Whether an aquifer is confined or unconfined also plays a role in its ability to store, and relinquish, water. Figure 6.1 illustrates an unconfined aquifer and a pumping well. When an unconfined aquifer is pumped, water in storage releases from pore spaces at the water table, to be replaced with air. As a result, over time, the water table will drop, creating a cone of water table depression around the well. The pump itself acts to lower the hydraulic potential around the well screen, causing water from surrounding regions to begin travelling towards the well. As more and more water is pumped from the well, more and more outlying storage water moves in as replacement, and the cone of depression increases. In the case of confined aquifers, it is also appropriate to consider a cone of under-pressuring, which remains fully water saturated but with lower hydraulic potential closer to the well.

Pumping from a confined aquifer, one with a low permeability confining unit which overlies the aquifer, is quite different because the pore spaces never actually empty completely (i.e., no air fills the void, illustrated in Figure 6.2). Water in a confined aquifer is released from storage largely because the grains within the aquifer move closer together. In other words, the aquifer becomes more compacted as the groundwater pressure declines. The amount of movement is very small, particularly in rock aquifers, and leads to only a small release of water from storage, but, this amount can become substantial, over large areas.

An aquifer's high or low storage capacity is only one piece of the puzzle scientists use when determining how much water is available. To be capable of extracting groundwater for use, an aquifer must also be permeable enough to allow groundwater to move freely towards a well, replacing the volume of water being extracted.

Aquifers with low permeability tend to develop deeper cones of depression when compared to aquifers with high permeability. Aquifer recharge must also occur, otherwise the groundwater level continues to decline inevitably until pumping is no longer feasible. Groundwater discharge from the aquifer is also important for maintaining surface water supplies and ecosystems. Thus, it is the interplay of specific storage capabilities and the hydraulic conductivity, the nature of the aquifer, recharge and discharge, and, of course, pumping rate, that ultimately determine the groundwater amount available for use (see Chapter 2 for more details). Determining what amount can be used safely, without causing undue decline of groundwater levels and without harm to the ecosystems supported by natural groundwater discharge, offers a number of challenges to groundwater professionals and managers.

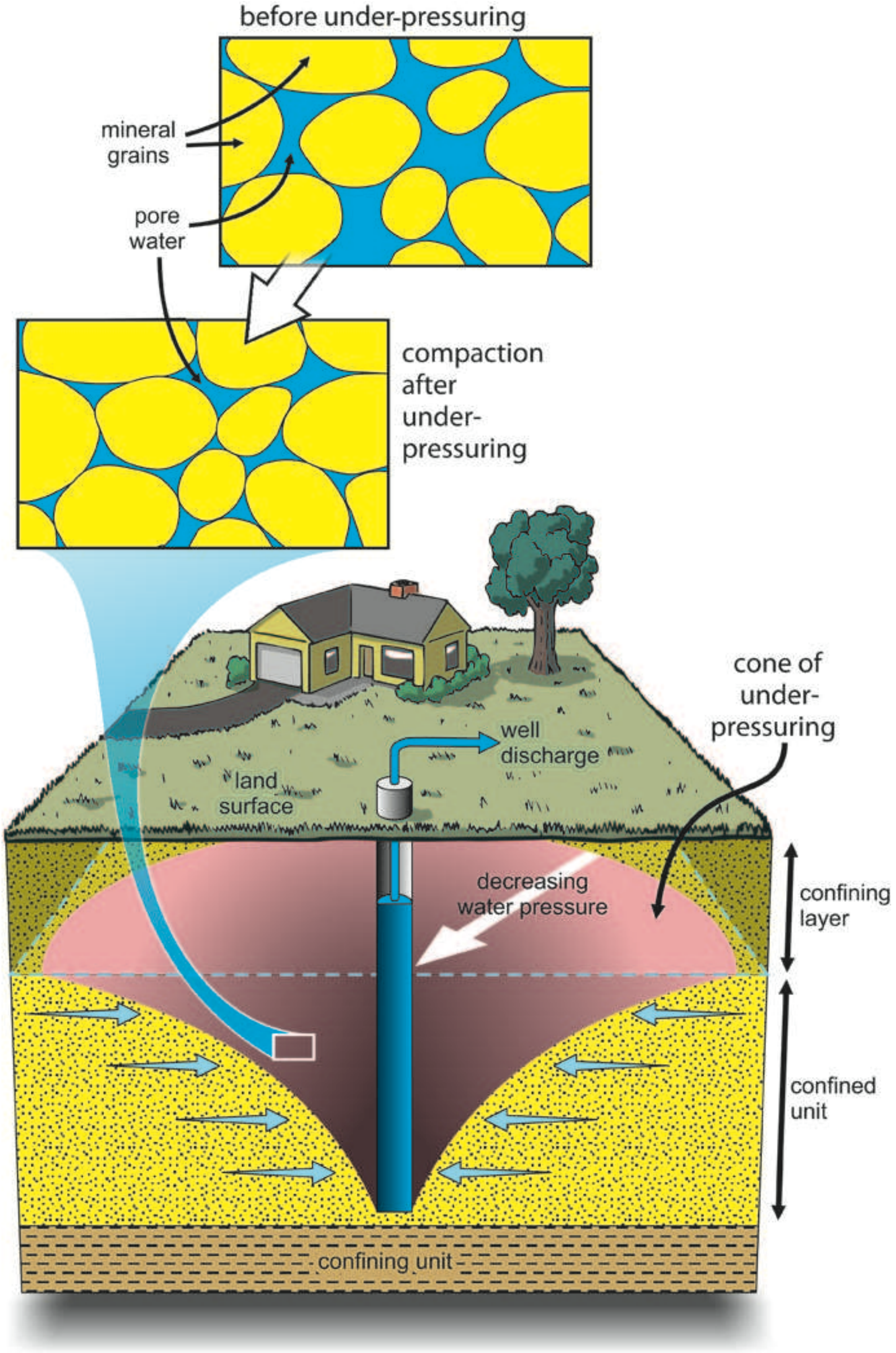

Figure 6.2 Confined aquifer: cone of under-pressuring.

6.2.2 What is sustainability?

Groundwater development can be considered sustainable when it is used in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic or social consequences (Alley et al., 1999). In practice, the process of determining "unacceptable consequences" is usually subjective, and can be narrowed down to a small number of constraints which must be satisfied: the drawdown in the pumping well should not exceed 70% of available drawdown, or baseflow in a nearby stream must be sustained during drought conditions. These constraints on groundwater development are established by regulatory agencies responsible for groundwater management, and usually in discussion with groundwater users and other stakeholders, such as wildlife agencies and watershed management groups. In the past, constraints, if any, have usually focused on the production wells themselves and, sometimes, the pumping impact on nearby groundwater users (e.g., Alberta's "Q_{20}" method; Maathuis and van der Kamp, 2006). As water resource use and land use continue to intensify, constraints on groundwater developments are beginning to be defined within the context of watershed and aquifer management plans; these adopt a much wider view, one which includes many other parameters, such as source water protection, to monitor and maintain water quality and groundwater-surface water interactions.

Groundwater sustainability must be defined within the context of the complete hydrologic system of which groundwater is a part (Alley et al., 1999). Groundwater pumping necessarily changes any pre-existing groundwater regime. As a result, most constraints are set in terms of limits on groundwater level changes and groundwater discharges to surface water. The dynamic response of the groundwater system to pumping is of over-riding importance.

Prediction of such response relies strongly on the observed behaviour of the groundwater system as a whole. The hydrogeological complexities and those of the recharge and discharge processes usually prohibit reliable prediction based solely on limited hydrogeology information. Systematic monitoring a groundwater system's response, including groundwater levels in observation wells, pumping rates, groundwater discharge to surface water (springs, baseflow of streams, lakes, etc.) is essential for informed groundwater management.

Ideally, this development should proceed in stages, guided by on-going monitoring; this process is generally referred to as an adaptive management approach. A complete assessment implies full maintenance and protection of the groundwater resource to balance ecomonic, social and environmental needs (Rivera, 2008).

One of the most important sustainability attributes is that it fosters a long-term perspective on groundwater resource management (Alley et al., 1999). A common misconception is that groundwater is renewed at the same rate each year, and that such renewals will continue to provide groundwater for use forever. Not true. Groundwater is perhaps best described as a semi-renewable resource. It is renewable in the sense that precipitation replenishes the amount of storage water annually, but non-renewable insofar as the amount replenished and time for replenishment varies yearly. As a result, groundwater stored in aquifers varies from year to year, owing to annual fluctuations in precipitation (and recharge) (Figure 6.3). Precipitation amounts and temperatures can range considerably above (e.g., large storms, snow pack)and below average[1] values.

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[1] Average precipitation is based on what has been measured at climate stations in a watershed over a certain period of time. In Canada, these are commonly referred to as 30-year climate normals, which describe the average climatic conditions of a particular location. At the completion of each decade, Environment Canada updates its climate normals for as many locations and as many climatic characteristics as possible. The climate normals and extremes are based on Canadian climate stations with at least 15 years of data. Data between 1971 and 2000 are used in this chapter (Environment Canada, 2006).

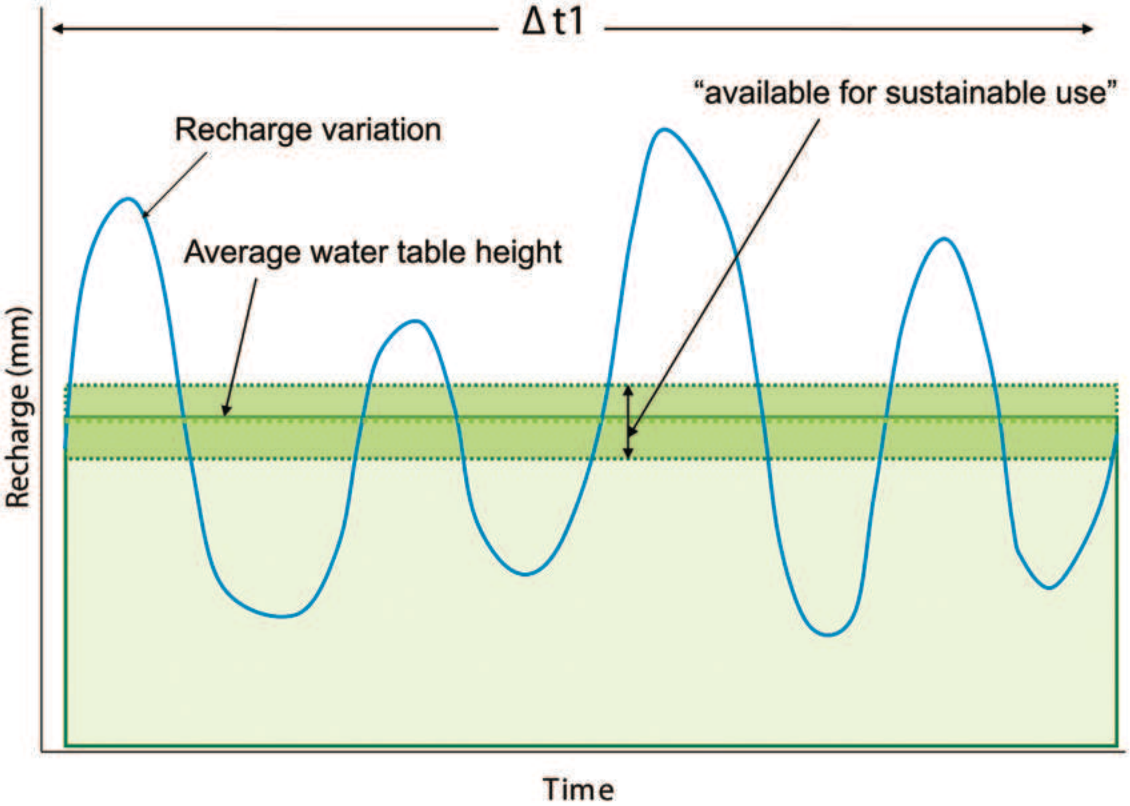

Figure 6.3 Variations in recharge over a certain time period (Δt_1), and the concept of the amount of groundwater available for sustainable use as a fraction of available recharge.

Another common misconception is that if water extraction equals recharge, there will be no impact, and extraction can continue forever. In reality, extraction is only a portion of the stored groundwater and this amount, reflects on only a small portion of the recharge added each year (Figure 6.3). When groundwater recharge is lower, so too is the water table. The effects of this lowering are evidenced throughout the entire aquifer system, ultimately resulting in decreased stream baseflow levels during the low flow season when groundwater is the dominant source of stream water. Although the contribution of groundwater to total streamflow varies widely among streams, hydrologists estimate the average contribution ranges between 40 and 50% in small and medium streams (Alley et al., 1999). During droughts, when other water sources dry up, groundwater flow to streams is especially important for maintaining aquatic ecosystems, including fish populations.

Artificially lowering the water table, through pumping for example, can reduce or even reverse groundwater flow to streams with consequent negative impacts on streamflow. But effects of groundwater pumping are often slow to manifest themselves. Because groundwater development may take place over many years, both current and future development should be taken into consideration in any water management strategy, along with information on climate variability and climate change.

When trying to determine how much groundwater is available for sustainable use, we need to consider the period for which we have collected data. Figure 6.4 shows us that information provided through the time period Δt_1 will be different from that provided for the longer time period Δt_2. Sustainability estimates based on data collected during the period Δt_1 may grossly overestimate the available groundwater. We must also

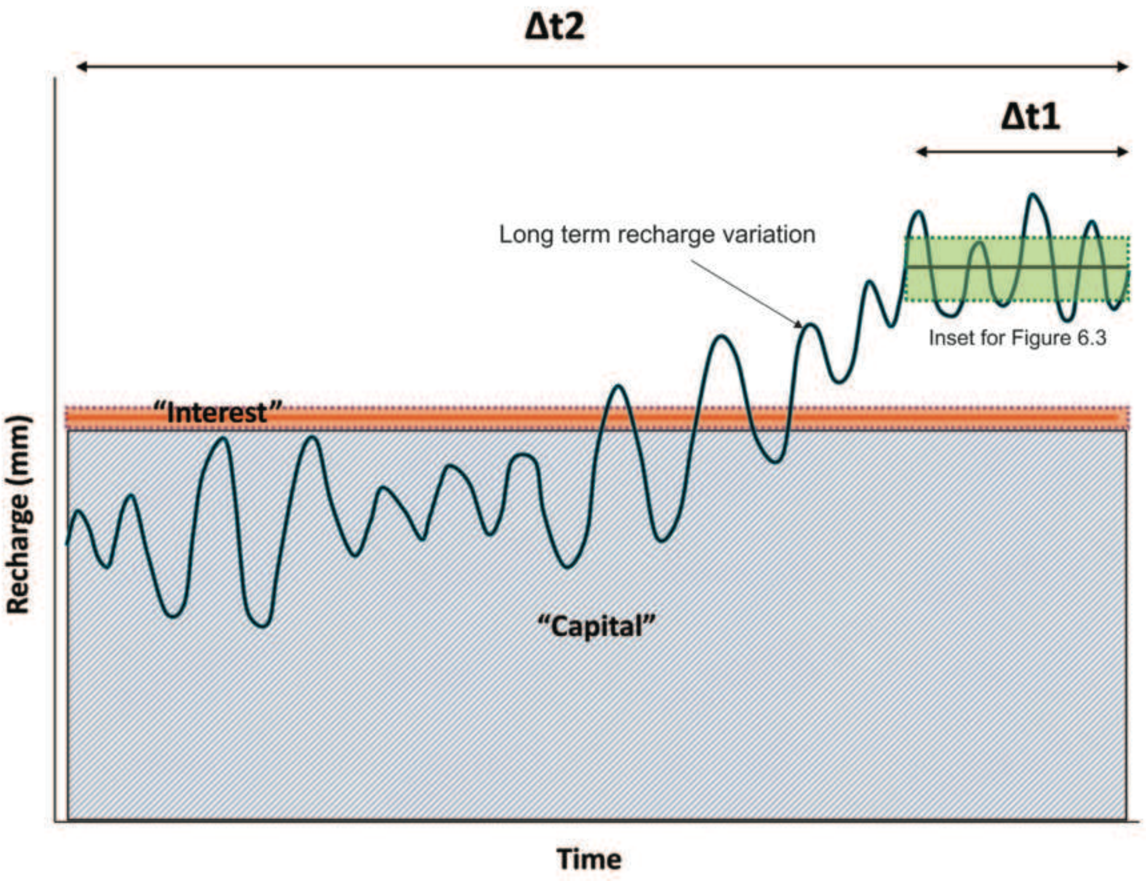

Figure 6.4 Recharge varies over short- (see Figure 6.3 corresponding to Δt_1 time period) and long-time scales (corresponding to Δt_2 time period in this figure). If the sustainability of an aquifer is determined based on a data set of limited length, this may not provide an accurate measure of available water. Removal of groundwater from an aquifer system should be viewed as using the "interest" rather that exploiting the "capital".

consider the time scale at which the groundwater moves through a specific aquifer. For a given time period (Δt_2), there will be a volume of water that corresponds to the recharge "excess", or, in other words, the volume of water for which removal will not translate into large ecosystem disturbances. Using the financial analogy of "capital" and "interest", we are then using the interest in such cases, and not the capital, although in times of temporary water scarcity (e.g., in semiarid and arid regions; Dragoni and Sukhija, 2008), it may be necessary to tap into the groundwater located in long-term storage ("capital" in Figure 6.4). This is a management decision, because the practice is not sustainable over long periods.

A number of definitions regarding groundwater sustainability have been proposed over the years. Discussions of "safe yield", "sustainable yield" and similar concepts have created considerable confusion, resulting in disagreements over definitions as well as some serious misconceptions (Devlin and Sophocleous, 2005; Alley and Leaky, 2004; Bredehoeft, 1997; Bredehoeft, 2002; Wood, 2001). Regardless of which term is used, sustainable or safe groundwater development (extraction) means there must be no unacceptable consequences. Any definition needs to define the time period involved and the specific unacceptable consequences.

A general definition of sustainable yield is often made in terms of specific constraints. These might include, for example, the fact that the withdrawal rate should not exceed some fraction of the recharge rate, or that the groundwater system must come to a new and acceptable steady-state condition. Such constraints may be useful for particular groundwater developments, but it is a mistake to accept them as generally applicable overall. Recharge rates in many cases are quite irrelevant to the setting of constraints.

Most groundwater in Canada's Prairie regions occurs in complex heterogeneous aquifer systems which have little or no relation to local surface watershed boundaries. Additionally, a large proportion of groundwater discharge occurs through evapotranspiration in diffuse areas; the recharge/discharge processes are highly variable both in time and space. Thus, groundwater monitoring relies primarily on observation well records and the reporting of withdrawal rates. With the exception of a few isolated surficial aquifers, estimates of recharge and discharge rates have high uncertainty and are of limited relevance to sustainable groundwater management for the majority of Prairie aquifers (van der Kamp and Maathuis, 2006). There is rarely a need to specify conditions wherein a new steady state must be reached, because these groundwater systems may exist in a transient state for the far foreseeable future without any observable unacceptable consequences.

Transboundary aquifers require additional constraints on groundwater development, including, principally, the need to harmonize regulatory requirements of different jurisdictions and the need to plan for an equitable usage of groundwater resources (see Chapter 16). Recently, the consequences of over-pumping have become clear in the Great Lakes region, and the U.S. Geological Survey issued a "wake-up" report. This report illustrated the fact that over-pumping on the U.S. side of the Great Lakes Basin can cause groundwater to flow away from major bodies of water rather than into them (USGS, 2005 as cited by Nowlan, 2007). No similar research results have been reported on the Canadian side.

6.2.3 Groundwater development: The risk or consequence factor

Groundwater development has potentially far-reaching consequences—beyond those of causing a decline in water level and/or pressure around a pumping well (see Figures 6.1 and 6.2).

Adjacent pumping wells have a zone of influence that represents the cumulative effects of pumping (the cones of depression coalesce (Figure 6.5a). This phenomenon not only results in a greater, and more widespread, lowering of the water table or potentiometric surface, but can also lead to issues of well interference between well users. The cumulative impacts of all nearby wells should be taken into consideration when predicting the sustainability of an aquifer or even a particular well; however, the extent to which this is done in Canada is open to question.

Maathuis and van der Kamp (2006) stated that all jurisdictions within Canada include an assessment of potential impacts on other users, and on surface water, as part of the licensing procedure. Criteria for evaluating such impacts, however, vary widely from one jurisdiction to another and are, at best, only vaguely defined. Furthermore, Maathuis and van der Kamp indicated that it is not clear how the cumulative impacts of many groundwater users are addressed, or whether they are addressed at all. In Nova Scotia, for example, withdrawals from the aquifer must be sustainable[2], new groundwater withdrawals should not cause any significant adverse effects to existing groundwater users, and groundwater allocations are based on a first-come,

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[2] In this case, sustainable is defined as not causing unacceptable environmental, economic or social consequences.

first-served[3] basis, with priority given to drinking water applications (Nova Scotia, *Environment Act*).

Ontario issues permits for groundwater withdrawals over 50,000 L/day excepting domestic or traditional agricultural use[4], and a determination of any potential interference with existing groundwater users is required (Ontario, *Water Resources Act*).

Alberta legislation takes a number of considerations into account when granting new water allocations; these include protecting the aquifer from over-development, protecting household water supplies and those of prior license holders, and protecting the environment (Alberta Environment, 2003).

Similarly, in Saskatchewan and Manitoba, a Groundwater Investigation Report (Saskatchewan Watershed Authority, 1999) and Groundwater Exploration Permit (Manitoba Water Rights Act, 1998), respectively, must be submitted for new applications, including an evaluation of the impact of any project on surrounding users.

British Columbia does not require licensing of groundwater, and well owners have no recourse when a new well is constructed and subsequently interferes with an original well. Recent amendments to the BC Water Act provide for licensing in specific areas designated as Water Management Areas. Otherwise, only private water utilities using groundwater as a water supply source require certificates of Public Convenience and Necessity, which, in turn, requires a groundwater evaluation for the well in question (British Columbia, *Water Utility Act*).

When a well is situated near a stream or lake, the lowering of groundwater levels around that well during pumping may impact surface water levels (Figure 6.5b). Situating a well near a surface water body can effectively draw water from that body, although the effects of pumping may not be as noticeable or as detrimental during high runoff periods (e.g., spring and early summer) as they are during periods of low flow (e.g., late summer). Wells located near streams or lakes may be also more prone to contamination by microbial pathogens originating in these surface waters.

The term GUDI, or Groundwater Under the Direct Influence of surface water, is used to refer to groundwater sources (wells, springs, infiltration galleries, etc.) that may lie in close connection to surface waters (e.g., AWWA, 1996, 2001; Ontario Ministry of Environment, 2001; Nova Scotia Department of Labour, 2001; U.S. EPA, 1991a; U.S. EPA, 2001). A number of criteria exist to identify GUDI sources, including whether the source is in a sensitive setting (i.e., a well in an unconfined aquifer, a spring, a well in a karst aquifer, etc.), and the source's proximity to surface water (the source must be located at a sufficient distance away from the surface water body to minimize risk of contamination). The well must be properly constructed, and available chemical and microbiological data must show the raw well water does not regularly or periodically contain bacteria. GUDI groundwater supplies pose a public health risk and must be identified and carefully managed.

Groundwater development over large areas can lead to significant regional lowering of groundwater levels (Figure 6.5c). Fortunately, unsustainable groundwater development has not been a major problem in Canada. Aquifer water levels, for the most part, appear to be relatively stable across

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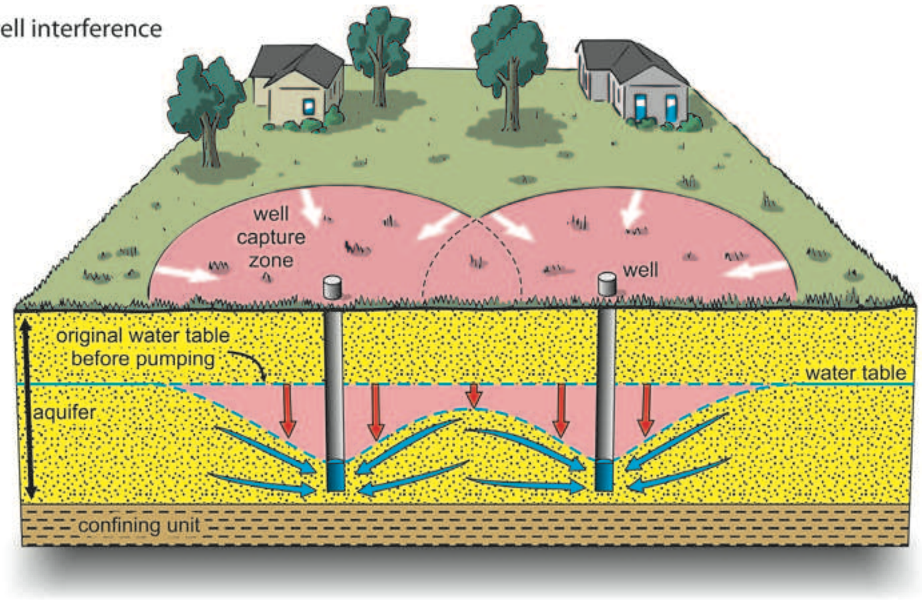
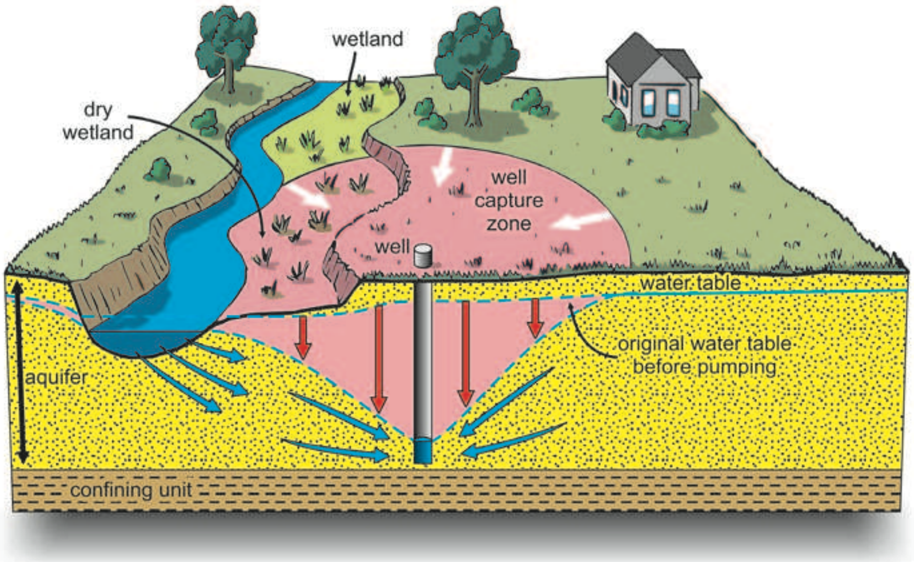
[3] The "first-in-time, first-in-right" doctrine is common to other jurisdictions across Canada (except Saskatchewan) and elsewhere around the world.

[4] Non-traditional crops are commonly thought of as low acreage, niche crops such as ethnic fruits and vegetables, culinary and medicinal herbs, and plants for industrial uses (e.g., fibre hemp). A non-traditional crop may be new to a region or simply new to the grower.

(a) well interference



(b) impact on streams and wetlands



(c) regional drawdown

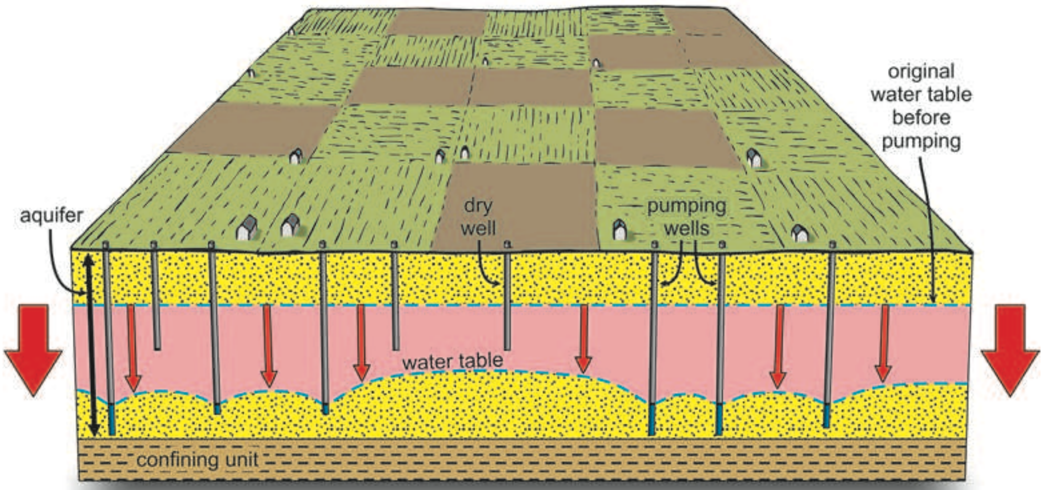


Figure 6.5 Impact of declining water levels due to: (a) well interference, (b) impact on streams and wetlands, (c) regional drawdown.

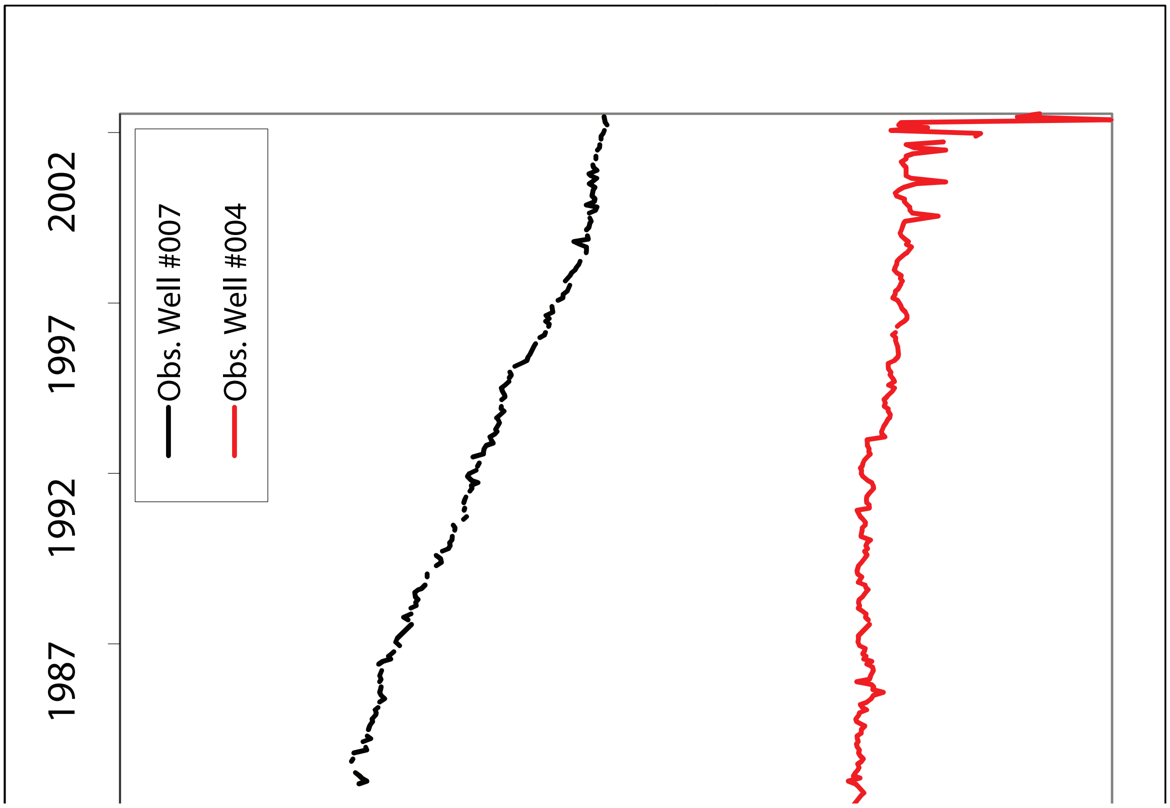


Figure 6.6 Indications from two BC provincial observation wells #004 and # 007 of a long-term declining trend in groundwater level within the Langley region of the Lower Fraser Valley.

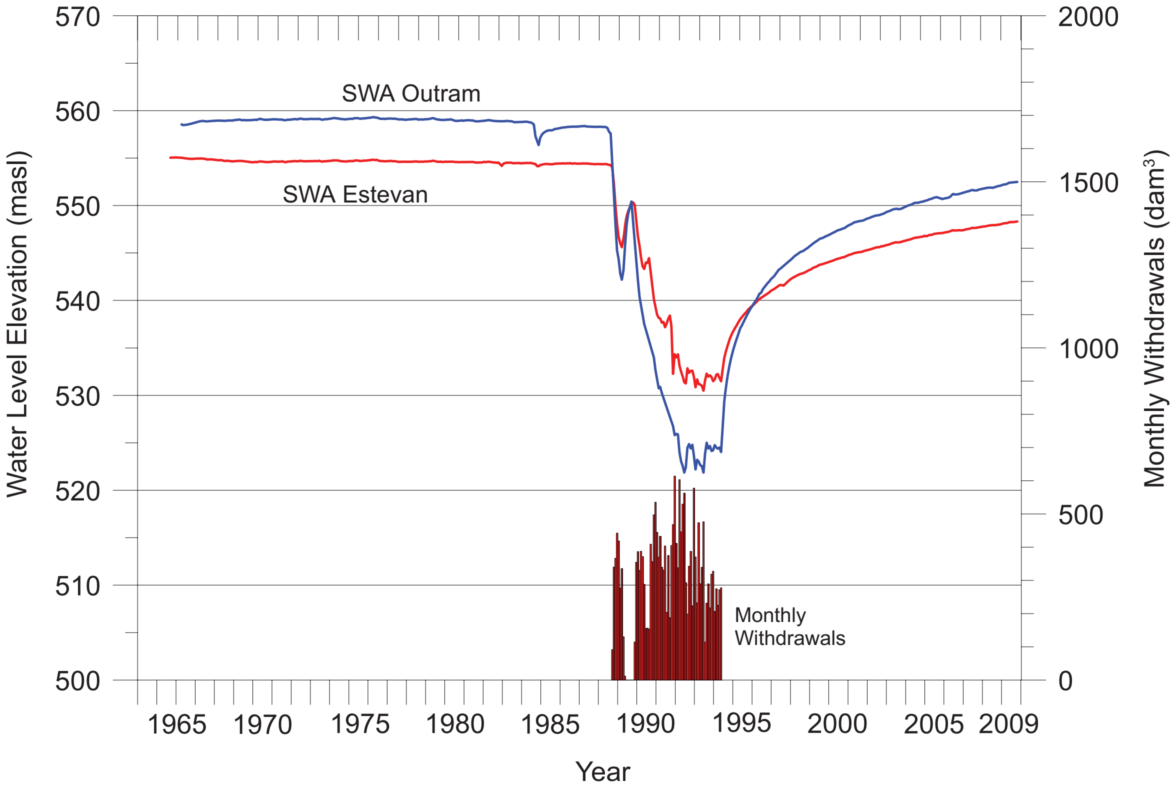


Figure 6.7 Total monthly withdrawals for the Estevan aquifer production wells and water level data for the Outram and Estevan observation wells (7.3 km and 8.6 km respectively distant from the well field). Total monthly withdrawal in cubic decametres (dam^3) (With permission from Saskatchewan Watershed Authority).

most of the country. In those areas where there has been significant development, however, scientists have discovered early signs of declining water tables. Groundwater levels in the Langley area of the Lower Fraser Valley, for example, have declined by over 1.5 metres since 1980 (Figure 6.6).

Southwestern Saskatchewan's Estevan Valley aquifer system is one of the major preglacial buried valley aquifers in that province (van der Kamp and Maathuis, 2006). The system is unique in that it has been the subject of groundwater resources evaluations since the early 1960s. Withdrawal data for production wells and water level data for two observation wells situated 7.3 and 8.6 km away from the well field (Figure 6.7), respectively, indicate that recovery of water levels due to over-pumping will take several decades. The pumping's zone of influence extends tens of kilometres, with drawdown of up to 13 m observed 35 km from the well field. At the Canada-U.S. border, 23 km from the well field, maximum drawdown was 20 m. The zone of influence extends into the U.S. portion of the aquifer, but apparently these effects did not translate into limitations on the withdrawal rate (see Box 10-2 for more details on this case).

Recently, the consequences of over-pumping have become clear in the Great Lakes region (USGS, 2005), when a computer modelling study calculated the differences in groundwater flow directions between the late 19th century and the year 2000. Under pre-development conditions, the model indicated that 1.9 million U.S. gallons per day (7,192 m^3/day) of groundwater flowed upward from the deep to the shallow part of the flow system, and into Lake Michigan, over the area of the Lake between southeastern Wisconsin and Michigan. Under year 2000 simulation, the model simulated that 1.3 million U.S. gallons per day, most of which originates as lake water, flows vertically in the opposite direction. While the loss of water from the lake is small relative to the total lake volume, model results indicate that development may have a significant impact on the hydrologic cycle.

Groundwater pumping can cause more than a decline in water levels or reductions in the discharge to streams, lakes and wetlands. As water is pumped from an aquifer, the aquifer's ambient pressure is reduced. Any water pressure reduction, whether accompanied by an increment of the overburden load or not, produces an increase in effective stress in the solid matrix. This increase results in solid matrix deformation, which manifests itself as compaction, leading, in turn, to observable land subsidence. We are lucky in Canada because widespread land subsidence has not been observed in any region to date. Several cases of significant regional land subsidence attributed to groundwater pumping have been documented around the world. These include the San Joaquin Valley and the Houston-Galveston area (U.S.), Bangkok (Thailand), Venice and Ravenna (Italy), and Mexico City (Mexico).

Groundwater quality may also be impacted by declining water levels. Usually occurrences of degraded water quality are related to salinity increases. Studies of Winnipeg's regional carbonate aquifer have revealed that fresh groundwater southwest of the city helps to prevent saline groundwater on the west side of the Red River from migrating eastward. This saline/fresh water boundary is strongly controlled by river systems (Charron, 1965; Grasby and Betcher, 2002). Charron (1965) demonstrated that this boundary was west of the Red River and south of the Assiniboine River in the early 1900s. He also

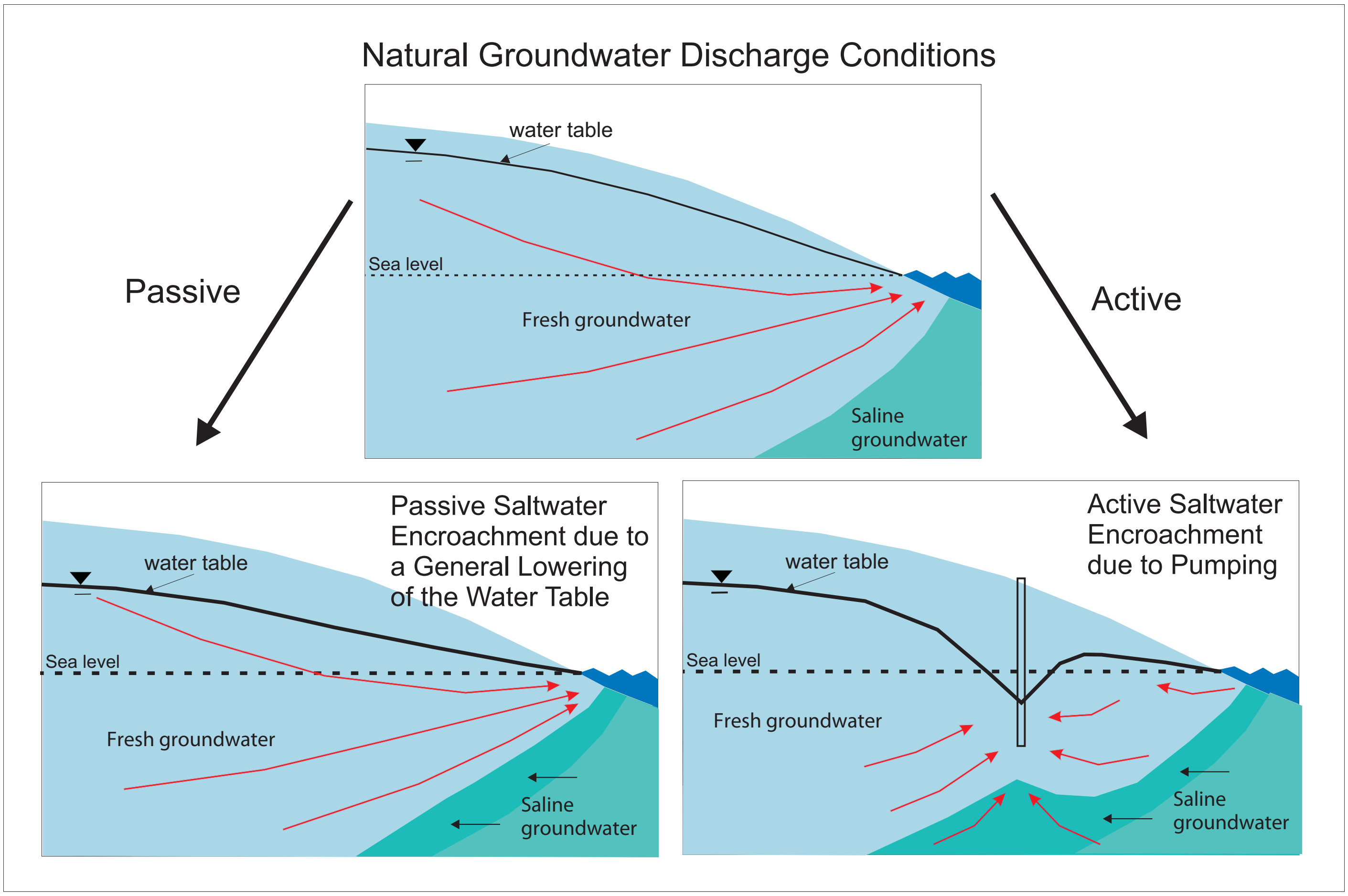


Figure 6.8 Active and passive saltwater intrusion relative to natural groundwater discharge conditions in coastal aquifers.

suggested that heavy pumping in the freshwater zone during the early 1900s caused saline water to move beneath the rivers into freshwater zones within the Winnipeg area. Eastward movement of the boundary was also observed in response to dewatering during construction of the Winnipeg floodway (Render, 1970). Pumping decreases over the last 30 years have resulted in the boundary moving back to its previous position.

In coastal regions, the incursion of seawater into freshwater aquifers (commonly referred to as saltwater intrusion) can be a negative consequence of groundwater extraction and/or development. When groundwater is pumped from aquifers that are in hydraulic connection with the sea, the induced gradients may cause a migration of salt water from the sea towards the well (active saltwater intrusion) (Figure 6.8). Long-term lowering of the water table due to declines in groundwater recharge may similarly result in saltwater encroachment (passive saltwater intrusion) (Figure 6.8).

Coastal aquifers in Canada have not yet been severely impacted by saltwater intrusion, although Prince Edward Island on the East Coast, and the Gulf Islands on the West Coast are examples of two regions where saltwater intrusion is a concern. The key to controlling any saltwater intrusion problem is to maintain a proper balance between water being pumped from the aquifer and the water amount recharging it. Constant monitoring of the saltwater interface is necessary to determine proper control measures.

One complicating factor in all cases of groundwater development is that its impact may not be noticed for many decades. Because development often occurs gradually (adding pumping wells as needed over time), its cumulative effects on water levels may be difficult to distinguish from natural groundwater level variations due to climate variability.

Identifying anthropogenic factors that cause water level declines is not straightforward.

6.2.4 Determining groundwater quantity sustainability

Historically, groundwater sustainability has been an issue for the individual well owner, who might want to have some assurance that the groundwater supply will continue indefinitely. Consequently, many of the traditional methods for groundwater sustainability assessment have focused on the well itself, and these evaluations have been carried out on a well by well basis.

Increased well development and concentration in particular regions has resulted in interference between wells, lowering of groundwater levels and streamflows. These problems have highlighted the need for new methods of determining groundwater sustainability, at a much broader scale.

Groundwater is but one component of the hydrologic cycle, and it is not possible to measure groundwater sustainability without considering how that groundwater resource is connected to surface water and land use.

Methods used to determine groundwater sustainability vary considerably because of the different assessment scales employed: these include the watershed scale, the aquifer scale, and the well scale (not necessarily listed in size order). Regional aquifers may span several watersheds, and one particular watershed may encompass multiple aquifers.

6.2.4.1 Well sustainability

Most methods used to determine groundwater sustainability at the well scale rely on pumping test, which are typically conducted following drilling to determine the appropriate pump size for the well. If the test is long enough, the data (water level decline in the well or drawdown as a function of time) can be extrapolated to estimate what the groundwater level will be at some later date. This approach has led to two methods widely used in specific regions of Canada: the Q_{20} method (in the Prairie Provinces) and the 100-day method (in BC).

Q_{20} Method: The Q_{20} concept (Farvolden, 1959) is based on a theoretical model for the flow of groundwater to a well in a confined aquifer (Theis, 1935; Jacob, 1940). It assumes that if the well is to last 20 years, the drawdown curve from a pumping test must not have a greater drawdown than what would be available where it intersects the 20 year line on a time scale. Farvolden (1959) considered two possible cases. The first is one where a stable pumping level is established in the well, indicating that recharge balances discharge. In this case, the specific capacity of the well can be calculated:

$$\text{Specific capacity } (C_s) = \text{Pumping rate / stable drawdown} \qquad (6.1)$$

The capacity of the well can be determined by taking into account a factor of safety:

$$\text{Capacity of the well} = C_s \times \text{available drawdown (H)} \times \text{safety factor (0.7)} \qquad (6.2)$$

where the available drawdown is the distance from the static level in the well to the top of the confined aquifer.

The second case considered by Farvolden is one where the water level continues to decline, indicating that the well is drawing water from storage. This case relates to the traditional Q_{20} method, in that the drawdown after 20 years of pumping is used to determine the well's sustainable yield. This long-term drawdown is determined either by extrapolating the log-log drawdown versus time curve, or by extrapolating the semi-log drawdown versus time line, following the methodologies of Theis (1935) or Jacob (1940), respectively. Farvolden (1959) defined the safe yield of a well as:

$$Q_{20} = (4 \times p \times T \times (H_A/8) \times S_F) / 2.3 \qquad (6.3a)$$

or

$$Q_{20} = 0.683\, T\, H_A\, S_f \qquad (6.3b)$$

where T is the transmissivity of the aquifer, H_A is the available drawdown (depth to the top of the aquifer minus the depth to the static level), and S_f is the factor of safety, for which Farvolden used 0.7.

The safety factor in both of these cases was chosen arbitrarily by Farvolden, and can be considered to represent other factors, such as well inefficiency, that may affect the available drawdown. Although Farvolden introduced this Q_{20} method, he did not explicitly use the notation Q_{20}: this notation was introduced by Tóth (1966).

Maathuis and van der Kamp (2006) review several other methods similar to the original Q_{20} procedure. Those take into account other conditions, such as short-duration pumping tests, to provide apparent safe yield estimates (Moell and Schnurr, 1976), consideration of well losses (Moell, 1975), and the use of local and regional transmissivity estimates (Bibby, 1979). Maathuis and van der Kamp (2006) propose a modification to the Q_{20} method wherein extrapolation of the drawdown curve is not necessarily that of the Theis or Jacob curve, but rather any appropriate drawdown curve for the aquifer (i.e., other analytical models that best represent the drawdown in the aquifer). Incorporating a factor of safety of 0.7, they suggest the following equation:

$$Q_{20} = 0.70 \times H_A \times Q_t / S_{20,\,Qt} \qquad (6.4)$$

where H_A is the available drawdown, Q_t is the rate of pumping used during the test, and $s_{20,\,Qt}$ is the estimated drawdown after 20 years of pumping at the pumping rate Q_t, calculated on the basis of the most appropriate aquifer model. This approach effectively allows for well losses affecting local drawdown (measured early in a pumping test), and establishes the long-term pumping rate based on the aquifer's response to pumping using the most appropriate aquifer model. A simplified equation can be derived from Equation 6.4:

$$Q_{20} = S_f \times H_A \times Q_t / [s_{100\,min} + (s_{20\,yrs} - s_{100\,mins})_{theoretical}] \qquad (6.5)$$

which uses the estimated drawdown after 100 minutes, $s_{100,\,Qt}$.

Maathuis and van der Kamp (2006) have also proposed the concept of R_{20}, the radius of influence of a well after 20 years of pumping. Radius of influence is the distance from the pumping well where the drawdown S_{R20} occurs after 20 years of pumping at the desired rate. Q_r equals some given limit, which might be set at about equal to the natural fluctuation of the water level in the aquifer, say 0.5m. This radius can be determined, using either the Theis or Cooper equations, by setting the drawdown to 0.5m, and calculating the

radius at which that drawdown occurs. This allows calculation of a pumping well's potential zone of influence, and determination of which other wells or surface water bodies might be affected by the pumping.

100-Day Method: The 100-day method is recommended for determining long-term capacity (sustainability) of a water supply source well in British Columbia. The 100 day time frame is used because most B.C. aquifers are considered to recharge within 100 days. Guidelines for this procedure suggest conducting a step-drawdown test to determine an optimum pumping rate, followed by a longer-term pumping test. The long-term capacity of the well is based on extrapolating the drawdown at the end of the test to 100 days, and using the 100-day's drawdown to determine the well's long-term specific capacity. A safety factor of 30 percent (0.30) is applied. Other conditions such as well interference, surface water–groundwater interactions, water quality and seawater encroachment may impact the well's long-term capacity, but are not explicitly taken into account with this method.

In fact, none of the above methods considers the influence of multiple pumping wells on the aquifer's sustainability. Usually when the pumping rates are relatively low, and the aquifer has low transmissivity, the pumping impacts from one additional well are not likely to extend more than a few kilometres from the proposed well site. Cases involving high pumping rates and large drawdowns within confined high transmissivity aquifers may require extensive mitigative actions (Maathuis and van der Kamp, 2006).

The cumulative effects of multiple pumping

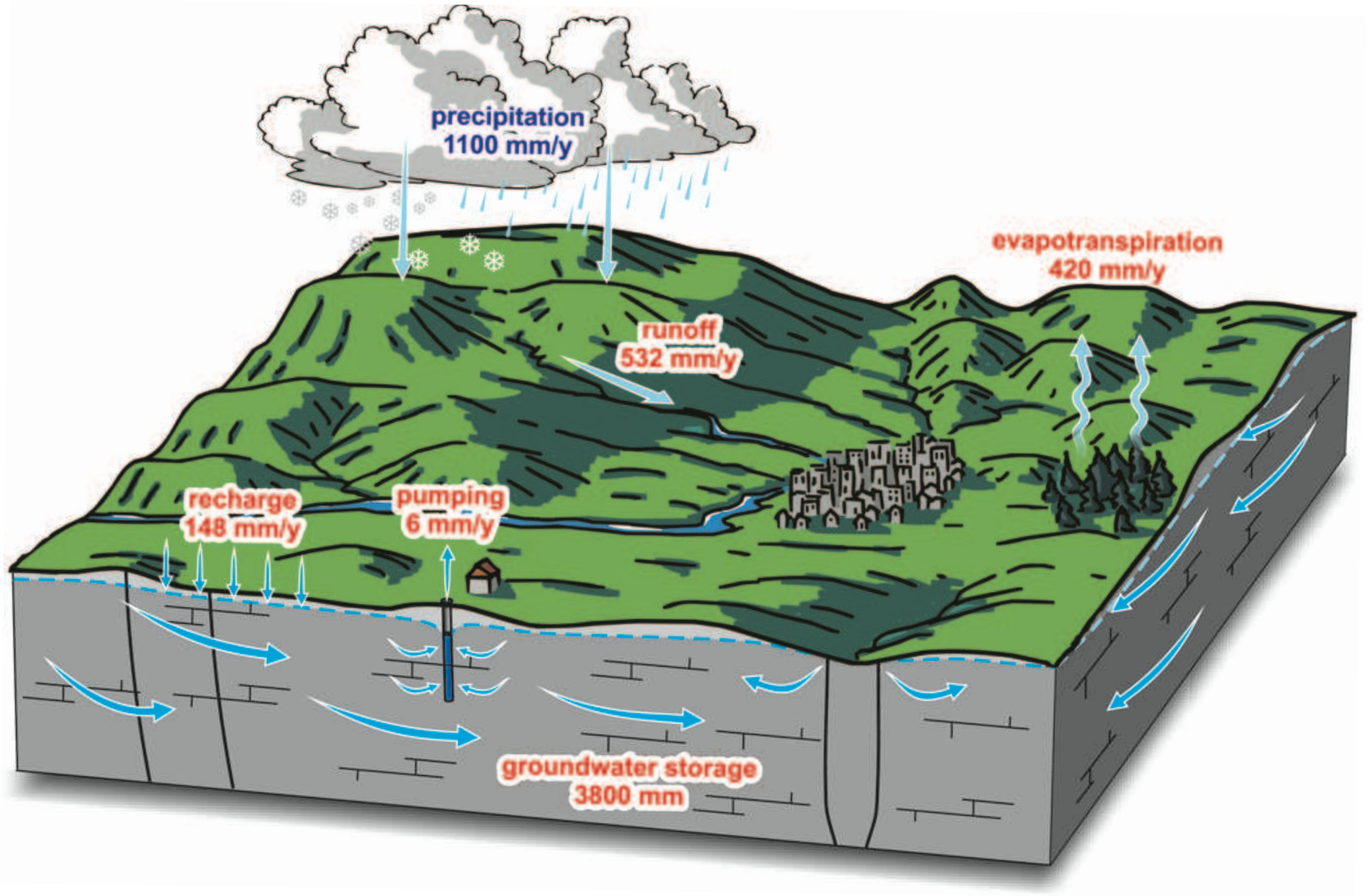


Figure 6.9 Elements of a regional water budget that can be used to assess sustainability.

wells in the same region create a composite cone of depression with a much larger radius of influence. In those areas where groundwater is being increasingly exploited, there is the risk that numerous small withdrawals from individual wells, each of which appears to have little impact, can add up to major consequences for the aquifer as a whole. Any estimation of an aquifer's (or watershed's) long-term sustainability must take into account all the groundwater uses and balance these with the aquifer's natural water budget.

6.2.4.2 Aquifer sustainability

Determining an aquifer's sustainability requires a comprehensive water budget analysis, which should result in an estimate of the net groundwater availability. Net groundwater availability is the difference between water inflow to the aquifer from precipitation, artificial recharge, surface water, etc., and the net water losses from the aquifer through evapotranspiration, pumping, discharge to surface water bodies, etc.

Elements within an annual water budget include precipitation, evapotranspiration, runoff, recharge and pumping (Figure 6.9). The budget assumes no changes in storage on an annual basis. As a result, it does not include storage in surface water bodies, storage in aquifers or storage in soil water.

Aquifer water budgets are often difficult to quantify from a physical processes perspective because of the large uncertainties in each budget components. Many aquifers extend over large areas. Precipitation is not uniformly distributed. The soils, subsurface geology, topography, land use/land cover, etc. are all spatially variable and thus, recharge is spatially variable (see Chapter 4). Evapotranspiration is a very difficult parameter to quantify both spatially and temporally. Additionally, there is limited information for most of the country on the amount of water actually pumped from aquifers on an annual basis. Another problem is that aquifer boundaries and surface watershed boundaries rarely coincide. Watersheds represent the most logical basis for managing water resources because watersheds are defined by topography. Water budget analysis on a watershed basis, however, may not include all parts of an aquifer, or there may be multiple aquifers within a single watershed.

Pressing concerns about water availability in some areas (the Prairies and B.C.'s Okanagan valley, for example) demand that comprehensive water budgets be developed for major aquifer systems, watersheds, or basins, despite the uncertainties and complexities outlined above. One of the most urgent resource management concerns is ensuring adequate in-stream flows for the ecosystems they support. This is not a trivial problem: it requires a full accounting of all water inflows and outflows at different times throughout the year.

Box 6-1 illustrates how numerical modelling is used to estimate the various water budget components for the Mirabel and Chateauguay aquifers in the St. Lawrence Lowlands. Two numerical models were developed to assess regional groundwater sustainability. The same methodology was applied in both cases: drawdown was obtained for different pumping rates applied uniformly over the study area, and the average predicted drawdown was used to estimate sustainability.

Developing regional scale models of aquifers (or watersheds) requires considerable data. The aquifers must be fully characterized with regard to area and depth, and in the geometry or architecture of the various geologic layers. Identification of natural hydraulic boundaries (rivers, streams, lakes) is important, as is quantifying aquifer recharge through direct precipitation and indirect contribution from surface water bodies, quantification of groundwater discharge to surface water bodies, and proper estimation of the pumping amount water removed from the system. In rural areas, some water is returned to the aquifer via septic system effluent, and in agricultural areas irrigation return flow (that amount of water not used by the crops) adds to the net recharge.

All water budget components are extremely difficult to quantify. Additionally, an overall water budget should also account for the amount of contaminated, and therefore unusable, groundwater, instream flow requirements needed to support ecosystems, potential changes in land use and/or land cover that might influence a water budget over time, changes in precipitation, recharge and evapotranspiration (ET) under natural conditions, climate change, virtual water imports/exports (water used to feed animals, or make wine, which are then exported), and water for manufacturing/conservation.

6.2.5 Climate change impacts on groundwater sustainability

Scientists have long been aware of the fact that both natural climate variability and climate change affect aquifer water levels. Groundwater, as important component of the hydrologic cycle, will be affected by climate change in regard to recharge, interactions between the groundwater and surface water systems, and changes in water use (e.g., irrigation) (Zektser and Loaiciga, 1993; Loaiciga et al., 1996). Future climate changes may impact the quantity and quality of regional water resources (Gleick, 1989). These changes, in turn, may lead to detrimental secondary impactson fisheries and other wildlife as a result of changes to the baseflow dynamics in streams (e.g., Gleick, 1986), disruption of the natural equilibrium in coastal aquifers (e.g., Custodio 1987; Lambrakis 1997; Vengosh and Rosenthal 1994), and a reduction in the volume of water stored in aquifers (Rosenberg et al., 1999; Loaiciga et al., 2000). Our understanding of the impact of climate variability and changes on groundwater resources, in terms of availability, vulnerability and sustainability of fresh water, remains limited.

To date, only a few studies have attempted to forecast how climate change might affect groundwater. Of these investigations, most have focused on groundwater recharge (see Chapter 4). (Appaih-Adjei and Allen, 2009; Chen and Grasby, 2001; Chen et al., 2002; McLaren and Sudicky, 1993; Moore et al., 2007; Piggott et al., 2001; Rutulis, 1989; Rivard et al., 2003, 2009; Scibek et al., 2007, 2009; Scibek and Allen, 2006a, 2006b; Toews and Allen, 2009a, 2009b).

Recharge timing and diverse aquifer characteristics complicate our ability to understand and to measure the impact of climate change on our groundwater resources (Rivera et al., 2004).

The response of an aquifer to shifts in climate, as measured by water level changes, is difficult to detect (e.g., Rutulis, 1989; Chen and Grasby, 2001, Rivard et al., 2004; Moore et al., 2007). Insufficient temporal data (short historic time series) often limits our ability to identify trends directly associated with climate change. Because information on groundwater extraction often nonexistent, it becomes difficult to distinguish between anthropogenic and natural influences on groundwater levels.

Different types of aquifers respond differently to surface stresses. Shallow aquifers, consisting of unconsolidated sediments, weathered or fractured bedrock, are generally more responsive to stresses imposed at the ground surface. Deeper aquifers tend to be more isolated from surface conditions by overlying aquitards (e.g., van der Kamp and Maathuis, 1991a). Shallow aquifers are affected by local climate changes, while water levels in deeper aquifers are affected by regional climate changes. Climate variability, which is of relatively short-term duration when compared to climate change, has a greater impact on shallow aquifer systems (Rivera et al., 2004), while deep aquifers have an increased capacity to withstand the effects of climate variability and, therefore, are able to preserve the longer-term trends associated with climate change. The deeper aquifers are also more susceptible to long-term declines in water storage.

There are many types of aquifers, and it is very difficult to place or locate a sufficient number of Canadian observation wells to be used for the detection of climate change signals. As a result, little research has been done in this country to relate well hydrographs with climatic variables. Nor has well hydrographic data been used on a systematic basis to address the question of climate variability impact on aquifers and groundwater resources: some regional assessments have been carried out (e.g., Maathuis and van der Kamp, 1986 for Saskatchewan; Moore et al., 2007 for BC), but from a national perspective, the only publication addressing these issues is Rivard et al. (2009).

6.3 GROUNDWATER VULNERABILITY AND WATER QUALITY RISK ASSESSMENTS

The term aquifer vulnerability has been defined, as "an intrinsic property of a groundwater system that depends on the sensitivity of the system to human and/or natural impacts" (Vrba and Zoporozec, 1994). According to these authors, intrinsic vulnerability is a function of hydrogeological factors, and specific vulnerability describes the potential impacts of land use and contaminants, in addition to hydrological factors. Focazio et al. (2002) define intrinsic sensitivity as "a measure of the ease with which water enters and moves through an aquifer; it is a characteristic of the aquifer and overlying material and hydrologic conditions, and is independent of the chemical characteristics of the contaminant and its sources," and aquifer vulnerability as "a function not only of the properties of the groundwater flow system, but also of the proximity of contaminant sources, characteristics of the contaminant, and other factors that could potentially increase loads of specified contaminants to the aquifer and (or) their eventual delivery to a groundwater resource."

In this chapter (and in keeping with terminology used in many jurisdictions across Canada), we will define **aquifer vulnerability** as a measure of the intrinsic susceptibility of an aquifer which represents the "tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer" (National Research Council, 1993). This is a qualitative measure, based on type, thickness and extent of geologic sediments overlying the aquifer, depth to water (or depth to top of confined aquifers), and the type of aquifer material. Aquifer vulnerability is distinct from **water quality** (or **pollution**) **risk**, which depends not only on intrinsic vulnerability but also on the presence of significant pollutant loading owing to the existing type of land use or nature of the potential contaminants. **Vulnerability mapping** is a common method for representing the relative susceptibility of an aquifer, both spatially and semiquantitatively, to contamination from surface sources.

Groundwater quality risk assessments typically involve a multi-step approach. The first step is a vulnerability assessment, followed by a hazard inventory (often within vulnerable areas), finally with a risk assessment. Defining wellhead protection areas through well capture zone analysis and development of plans for emergency responses are related activities often carried out at the local scale.

6.3.1 Assessing aquifer vulnerability

Any determination of aquifer vulnerability requires a solid understanding of both the study area gelogy and the hydrologic conditions contained within. Aquifer depth and the types of geological materials above it are also critical points to consider. Aquifers closer to the surface and overlain by pervious surface materials are more vulnerable to contamination, as compared to deeper aquifers covered with thick layers of impervious materials. Aquifer vulnerability is assessed by using a variety of scales including

- the broad landscape, perhaps at the watershed scale, to identify highly vulnerable areas outside of the areas of wellhead protection
- the wellhead protection areas (WHPAs) to ensure that existing supply wells are protected
- specific locations within the watershed, including those areas with significant groundwater recharge, designated either as highly vulnerable aquifers, or are sites for future groundwater supply

Assessment of aquifer vulnerability always begins with a characterization of the assessed area's geological conditions.

As of this date, it is generally recognized that insufficient data is available to perform specific vulnerability mapping, although there is a higher degree of scientific soundness in "specific" vulnerability maps for specific pollutants (e.g., Foster, 1987; Canter et al., 1987). Consequently, researchers have developed generic mapping systems that are simple enough to apply the generally available data, and are capable of making best use of that data in a technically valid and useful manner. Several such vulnerability evaluation and ranking systems have been developed and applied (e.g., AVI, GOD, DRASTIC, SI, EPPNA and SINTACX), with examples provided by Albinet and Margat (1970), Haertle (1983), Aller et al. (1987), Foster (1987) and Vrba and Zaporotec (1994).

The purpose of groundwater vulnerability assessments is to characterize the contamination potential within a specific geologic setting and to define locations that may be more vulnerable to this contamination than others. These vulnerability methodologies consider that the natural environment protects itself when a contaminant is introduced. Piscopo (2001) considered three groundwater system elements in his method: (1) contaminants entering the system and constituting a threat; (2) soil and rock above the water table forming a barrier to contaminants percolating down from the surface, and (3) the groundwater resource below the water table that could be damaged should contaminants penetrate the barrier.

Vulnerability is evaluated by considering the thickness and permeability of the material situated above the aquifer. Low-permeability surficial soils, composed largely of clay and silt, are usually less likely to transmit significant quantities of contaminants when compared to high-permeability soils such as sand and gravel. Low-permeability materials create aquitards which function as barriers to contamination. Thickness of the overlying materials plays an important role, however, because contaminants applied, deposited or spilled on or near the ground surface, will be less attenuated and will reach an aquifer more quickly in those locations where the overlying material surface is thin. Fractures or other openings in an aquitard overlying the aquifer can also negate the natural protection. In those areas where bedrock is exposed at surface, vulnerability will be highly dependent upon the degree and inter-connectivity of fracturing.

6.3.2 AVI

AVI quantifies vulnerability by the hydraulic resistance (c) to vertical flow of water through geologic sediments above the aquifer. Hydraulic resistance is calculated from the thickness (d) of each sedimentary layer and the hydraulic conductivity (K) of each of the layers (Equation 6.6).

Hydraulic resistance (c) =

$$\sum d_i / K_i, \text{ for layers 1 to i} \quad (6.6)$$

Typically, saturated hydraulic conductivity (K_{sat}) is

TABLE 6.1 AVI CATEGORIES

HYDRAULIC RESISTANCE, C (YEARS)	LOG (C)	VULNERABILITY CATEGORY
< 10 years	< 1	extremely high vulnerability
10–100 years	1 to 2	high vulnerability
100–1,000 years	2 to 3	moderate vulnerability
1,000–10,000 years	3 to 4	low vulnerability
> 10,000 years	> 4	extremely low vulnerability

the variable most often used, although it produces conservative hydraulic resistance values (higher vulnerability) for unsaturated sediments above the water table. Thickness of individual sedimentary layers can be calculated directly from well records. Hydraulic resistance (c) has the time dimension (e.g., years) and represents the flux, or time per unit gradient of water flowing downward through the various sediment layers to the aquifer. The lower the hydraulic resistance (c), the greater the vulnerability.

A vulnerability map is constructed by calculating the logarithm of the hydraulic resistance (log c) for each well site and by delineating or contouring areas of similar log c (AVI) values. Resultant AVI ratings indicate surficial materials' potential to transmit water with contaminants to the aquifer over a period of time: these ratings can be grouped into vulnerability categories (Table 6.1). A location with a low class rating implies that water percolating through its surficial materials takes a long time (in the range of thousands of years) to reach the aquifer. On the other hand, a location with a high class rating suggests that contaminated water will reach the aquifer within "tens" of years.

The AVI method has been used extensively across Canada. Here is an AVI map for Alberta (Figure 6.10).

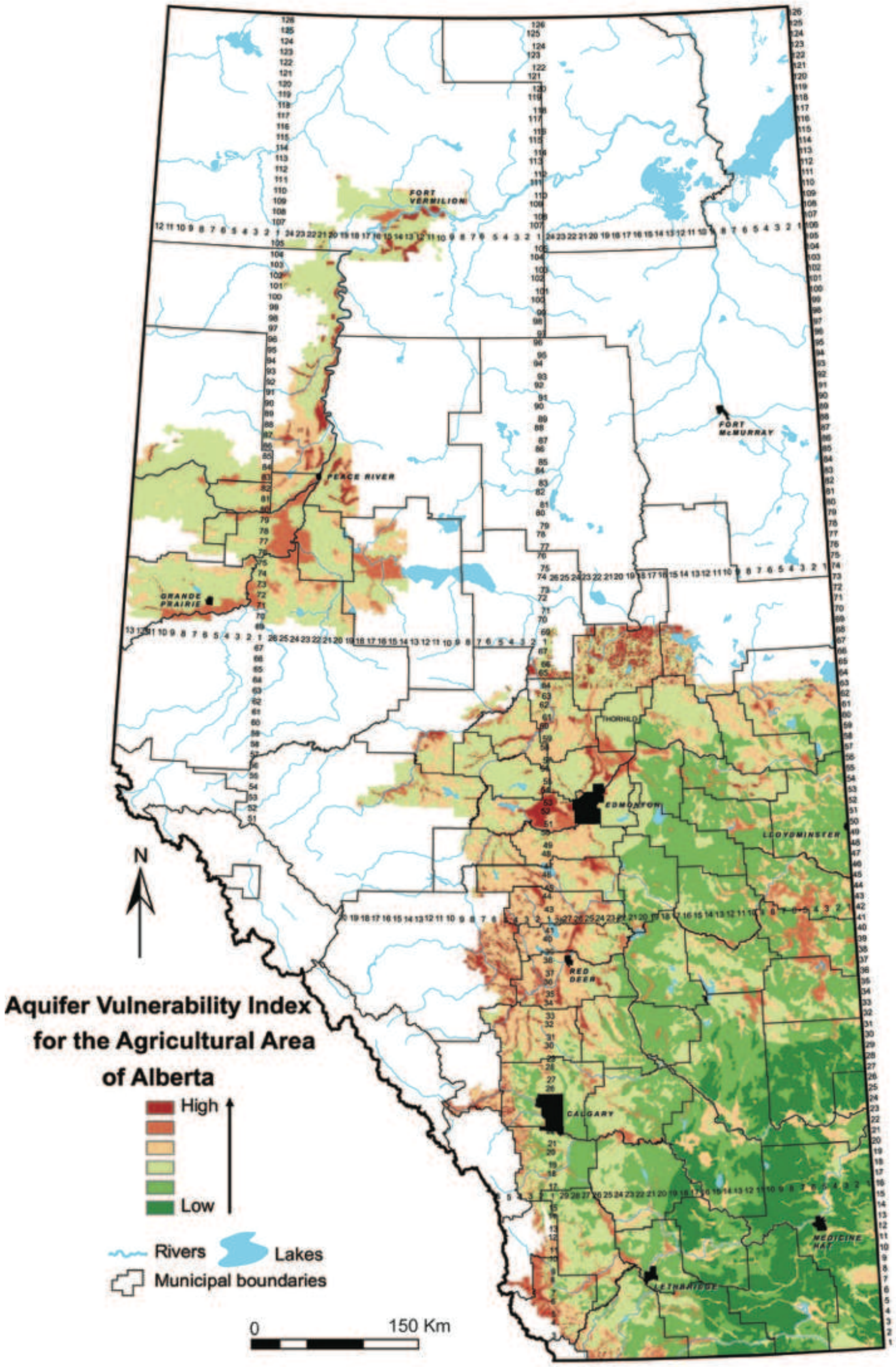


Figure 6.10 AVI map for the agricultural areas of Alberta (Alberta Government, 2005).

6.3.3 DRASTIC

DRASTIC was developed by the U.S. EPA (Environmental Protection Agency) as a standardized system for evaluating groundwater vulnerability (Aller et al., 1987). DRASTIC's primary purpose is to provide assistance in resource allocation and prioritization of the many types of groundwater-related activities. Like AVI, DRASTIC can be used to establish priorities for groundwater monitoring in specific areas. DRASTIC can also be used with other information (e.g., land use, potential contamination sources, and beneficial aquifer uses) to identify those locations where special attention or protection efforts are warranted.

The DRASTIC model contains four assumptions:

1. The contaminant is introduced at ground surface
2. The contaminant is flushed into the groundwater by precipitation
3. The contaminant has the mobility of water
4. The area being evaluated by DRASTIC is 100 acres or larger

DRASTIC is a composite rating of the **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography slope, **I**mpact of the vadose zone and the hydraulic **C**onductivity of the aquifer (Figure 6.11).

Depth to Water (D) represents the thickness of geologic material above the water table. Groundwater is more vulnerable to contamination when the water table is close to the surface and the soil, or rock barrier zone above the water table is thin, allowing little capacity for natural filtration of contaminants before they reach the water table. Net recharge (R) reflects the total amount of water per unit area percolating from the surface to the water table. The greater the water flow, the more likely contaminants will reach the groundwater resource. Key factors influencing recharge include precipitation, topography and the properties of soil and the surficial geology materials above the water table. Aquifer Media (A) represents the character of the consolidated or unconsolidated material which serves as an aquifer. Path length and travel time of groundwater within an aquifer depend on the grain size of the bedrock and the presence of fractures within the aquifer. The effectiveness of soil (S) to act as a barrier to surface contaminants depends on its physical properties. In general, soils containing clay properties and with small grain sizes are less permeable and are more effective as barriers to contamination. The slope of the land or topography (T), coupled with changes in slope can influence the proportion of rainfall that forms runoff compared to the water volume that infltrates the soil. When slopes are low, there is a greater likelihood that a pollutant will infiltrate an aquifer through the ground surface. The impact of the vadose zone (I) represents the unsaturated zone above the water table: the texture of soil and rock within this zone determines how rapidly water and, thus contaminants will infiltrate downwards toward the water table. Conductivity (C) reflects the rate of groundwater flow through an aquifer. Rapid flow allows rapid contaminant spread. Like the "I" parameter, conductivity reflects the rate at which water flows through the aquifer.

Each of the hydrogeological factors of DRASTIC is assigned a rating from 1 to 10 based on a range of standard values. These ratings are then multiplied by a relative weighting factor, ranging from 1 to 5 (Equation 6.7):

$$\text{DRASTIC Index} = 5D + 4R + 3A + 2S + 1T + 5I + 3C \qquad (6.7)$$

The most significant factors have a weight of 5; the least significant a weight of 1. The final DRASTIC index represents a relative measure of groundwater vulnerability; the higher the index, the more vulnerable the aquifer to contamination.

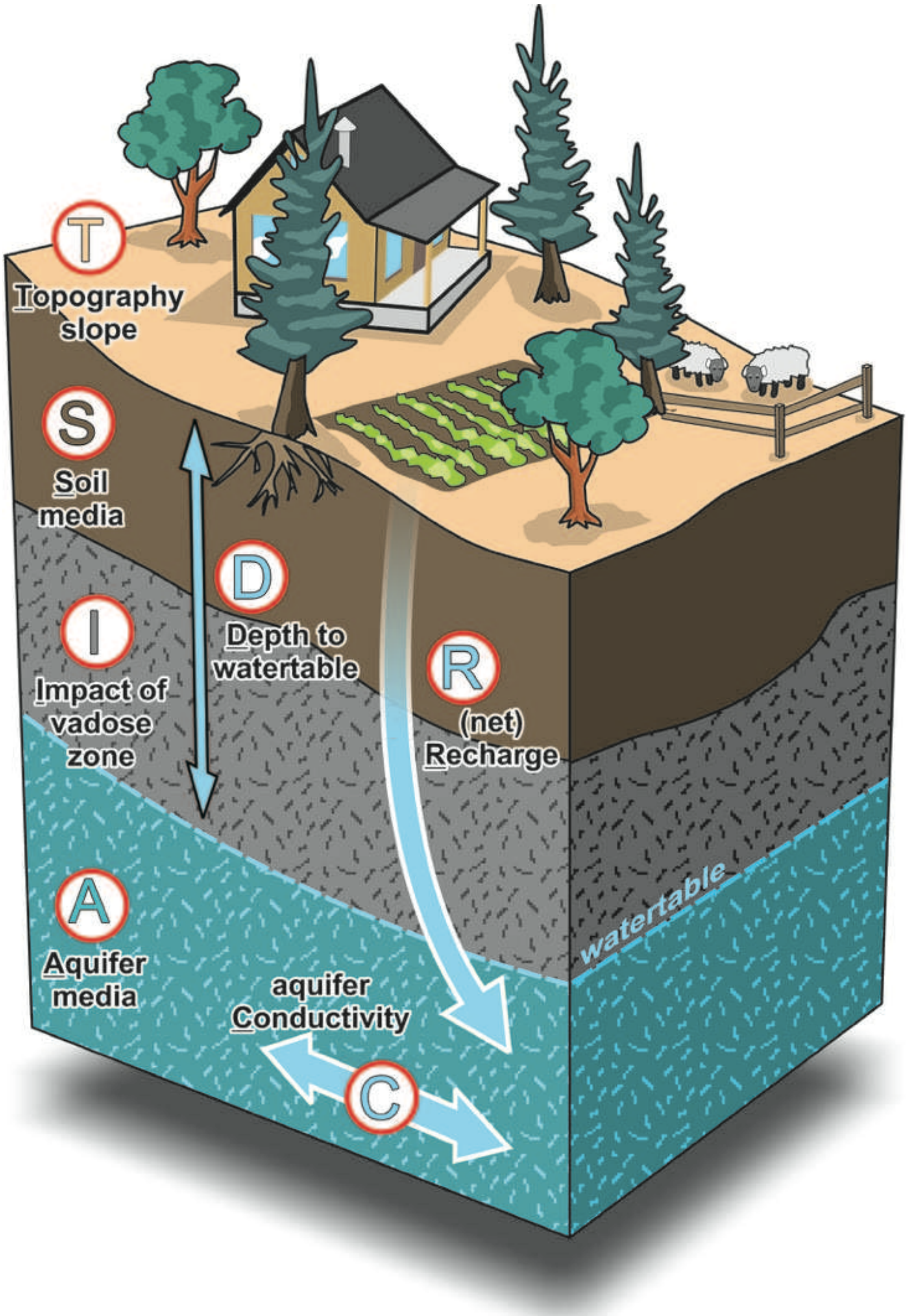


Figure 6.11 The DRASTIC factors (figure courtesy of the Geological Survey of Canada).

The smallest DRASTIC index rating is 23 and the largest in 226. Although DRASTIC is physically based, the final DRASTIC index, unlike AVI, has no physical meaning, but rather is purely an index. One advantage of DRASTIC over AVI, however, is that it includes a wider range of those parameters thought to influence the transport of contaminants through the vadose zone.

A modified DRASTIC methodology has been developed for aquifers that are strongly influenced by fractures (Denny et al, 2006). This methodology, DRASTIC-Fm, is highlighted in Box 6-2 with the Gulf Islands in British Columbia used as the case study area.

6.3.4 Comparison of vulnerability mapping methods

In recent years, capabilities of geographical information systems (GIS) have vastly improved our ability to construct vulnerability maps. Such maps were formerly done on a well-by-well basis, with indices for individual wells plotted and contoured. Today, GIS allows multiple spatial datasets—soil maps, geologic maps, digital elevation models (DEMs), etc.—to be analyzed, assigned relevant indices, and synthesized into composite maps such as those described above for AVI and DRASTIC. Consequently, aquifer vulnerability mapping is rapidly becoming a common tool of groundwater risk assessment frameworks in many jurisdictions across Canada.

Other aquifer vulnerability mapping methods, such as the BC Aquifer Classification System (see Chapter 9) or modifications of those methods described above are also used across the country. No particular vulnerability mapping method is necessarily better than another.

Wei (1998) evaluated AVI and DRASTIC against each other in the southwestern B.C's Lower Fraser Valley only to find that both indexes were generally consistent. Low AVI values corresponded with high DRASTIC indexes (high vulnerability), while high AVI values corresponded with low DRASTIC indexes (low vulnerability). Despite these general consistencies, DRASTIC indexes between 100 and 160 spanned all five AVI vulnerability categories, suggesting that DRASTIC may not be as sensitive as AVI for indicating pollution potential of aquifers with moderate vulnerability. Wei also noted that DRASTIC indexes of >160 (high vulnerability) and <80 (low vulnerability) fell under the extremely high and extremely low to low vulnerability AVI categories, respectively.

6.3.5 Wellhead protection

The purpose of wellhead protection is to prevent any contamination of groundwater used for drinking water. A **wellhead protection area** (WHPA) is the location immediately surrounding a well that must be protected from potential sources of surface contamination. The WHPA represents a surface projection of the entire three-dimensional capture area from which the water pumped from the well or well-field originates (Figure 6.12). The entire recharge area for the well (Figure 6.12) surrounds the WHPA.

Several jurisdictions across Canada (as well as the United States Environmental Protection Agency—EPA) have specific guidelines for defining wellhead protection areas. For the most part, these guidelines are based on defining a **well capture zone**(s), whose size(s) is/are influenced by the well pumping rate, aquifer porosity, and hydraulic conductivity. Size and shape are influenced by hydraulic gradient and flow direction, the orientation and density of fractures/faults. They are also influenced by dissolution features like those in karst geology wherein the capture zones of rock aquifers may extend for many kilometres due to permeability of fractures, faults and dissolution channels.

Well capture zone analysis presents a number of difficulties and uncertainties of which the most important relates to the cumulative effect of pumping from a number of wells situated in close proximity. When this occurs, the capture zones for individual wells coalesce, effectively creating a larger composite capture zone than those of the individual wells. As a result, analysts look at well clusters.

Contaminants, such as pathogens or chemicals, have varying fates and degrees of persistence, and scientists must consider times of travel (TOT) when defining well capture zones. Bacteria, for example, have a limited life span and an adequate time of travel from the point of entrance to the well may

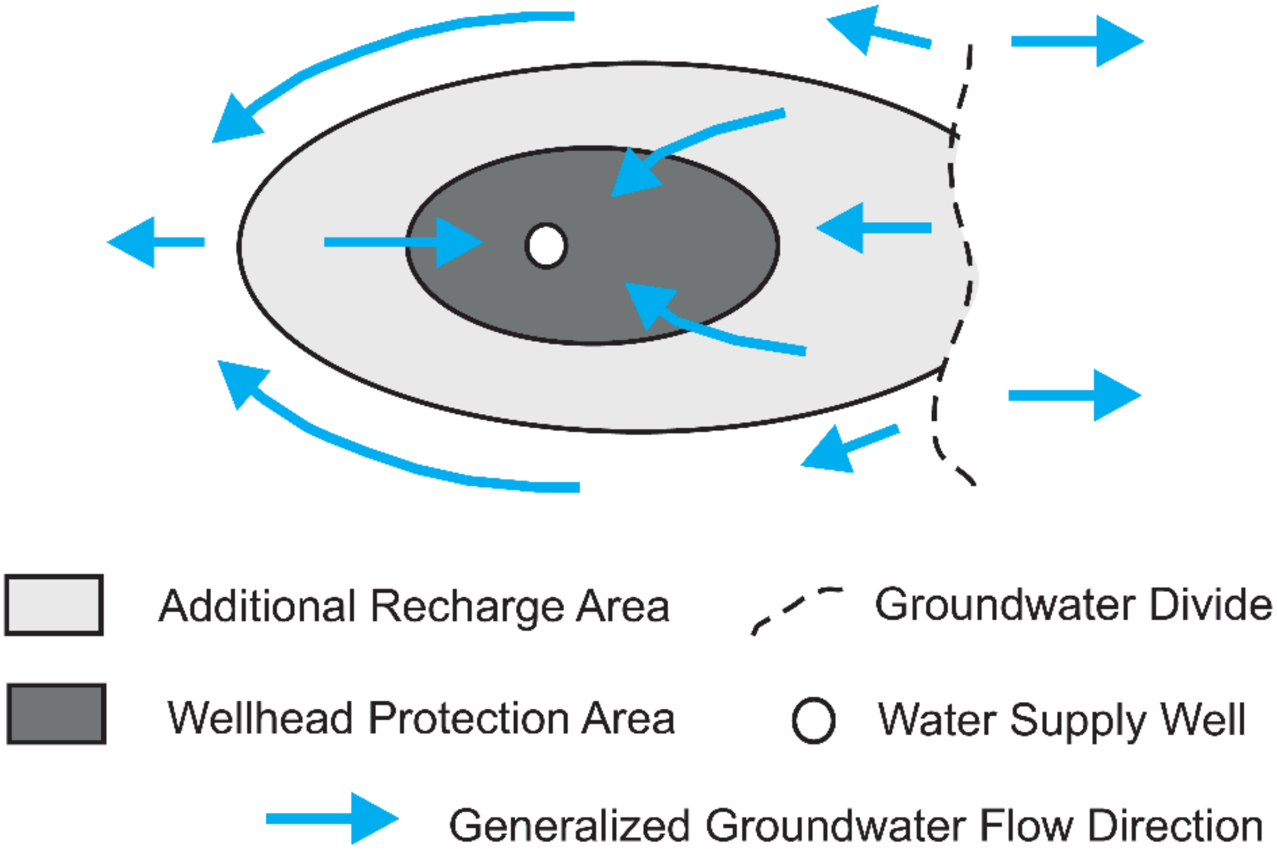


Figure 6.12 Wellhead protection area (WHPA) and additional recharge area surrounding a water supply well.

effectively inactivate these organisms. Similarly, over time, some chemical contaminants degrade into lower risk compounds or are adsorbed by the geological materials encountered along the flowpath. Other chemicals, however are stable in a groundwater setting and the risk from their presence may only be attenuated through dilution along the flowpath.

The Ontario Ministry of Environment recommends that each WHPA (for municipal groundwater wells) be sub-divided into well capture zones to differentiate between, and effectively manage, potential risks posed to well water quality from various types of microbiological and chemical contaminants that might enter the water table and/or move with the groundwater flow (Ontario Ministry of Environment, 2001). At a minimum, the Ministry recommends three well capture zones be delineated for each municipal production well/well field:

1. **Zone 1:** 0 to 2 years saturated time of travel (TOT). Land uses in this zone need to be monitored and managed to avoid all possible risks, including those from bacteria and viruses. Within Zone 1, a 50-day TOT area should be identified to recognize potential risks from day-to-day activities of the water utility itself or other contaminant sources.
2. **Zone 2:** 2 to 10 years TOT. The main focus of land use management in this zone should be to minimize risks from all chemical contaminants, although bacterial and viral risks may still be a concern.
3. **Zone 3:** 10 to 25 years TOT / Zone of Contribution. The land use management in this zone needs to address risks from

persistent and hazardous contaminants.

The methods used for defining these capture zones range from simple and inexpensive to complex and costly.

Calculated Fixed Radius method: This procedure, also known as the "cylinder method", is easy to use and is based on simple hydrogeological principles that require limited technical expertise. Calculated fixed radius capture zones are circular areas whose radius is determined using the formula:

$$r = \sqrt{[(Q \times t) / (\pi \times b \times n)]} \qquad (6.8)$$

where:
r = radius (distance from well) in metres
Q = maximum approved pumping rate of the well (m^3/s)
t = saturated travel times for each well capture zone (sec)
b = saturated thickness of screened interval (m)
n = porosity
$\pi = 3.14159\ldots$

The method, however, tends to overprotect down-gradient and under protect up-gradient areas because it does not account for regional gradients. Unless combined with flow system mapping, this method should not be used for unconfined aquifers or for confined aquifers with a sloping potentiometric surface.

Uniform Flow Method: This procedure utilizes analytical expressions to delineate capture zones. These include

1. the distance to down-gradient null point:
$X_L = Q / (2 \times \pi \times K \times b \times i)$

2. shape of outer streamline:
$X = - Y / \tan [(2 \times \pi \times K \times b \times i) / Q \times Y]$,

where the boundary limit (asymptotic width) of the capture zone is:
$Y_L = \pm Q / (2 \times K \times b \times i)$; and

3. upgradient distance as a function of time:
$X_t = K \times i \times (t / n)$

where:
X = distance along length of capture zone (m)
Y = width of capture zone as a function of X (m)
Q = maximum approved pumping rate of the well (m^3/s)
K = hydraulic conductivity (m/s)
b = saturated thickness of screened interval (m)
i = hydraulic gradient
t = saturated travel times for each well capture zone (sec)
n = porosity
$\pi = 3.14159\ldots$

This method is more flexible than standard analytical models because it can conform to variability in flow direction. The disadvantage of this method is that it generally does not take into account hydrologic boundaries (streams, lakes, etc.) and aquifer heterogeneities, and it assumes no recharge. It is also limited to two-dimensional analyses of flow systems and capture zone delineation.

Analytical or **Numerical Methods:** The most sophisticated methods for determining a well capture zone are based on field observations of aquifer characteristics during a detailed pumping test, coupled with calculations or numerical modelling designed to predict long-term aquifer conditions. These types of delineation methods require a qualified hydrogeologist and may be appropriate when siting new large wells or when a source protection program emphasizing extensive land use restrictions is planned. These methods require data regarding well production rate, the aquifer's lateral extent, thickness, hydraulic conductivity and flow gradients. These advanced methods are suitable for accurately delineating capture zones where there is a significant presence of: (1) discrete fractures, (2) anisotropy, (3) spatial variations in hydrogeological parameters, (4) vertical movement of water and variation in total hydraulic head with depth, and/or (5) changes in water levels seasonally or through time.

6.3.6 Integrating land use and groundwater into decision making

Land use and water resources are unequivocally linked. Land type and intensity of its use can have a substantial impact on the receiving water resource. Although, for the most part, water quality across Canada is good, an increasing population, development pressures, minimal (or the absence of) integrated land use planning, and competition for water resources, continually contribute to the water resource degradation. Both here and worldwide, the protection and provision of fresh water (in terms of quality and quantity) have become a top concern of political leaders and the general public alike. Indeed, this changing focus has created a whole new vocabulary devoted to water resources. Terms such as multi-barrier approaches to source protection, source protection plans, wellhead protection plans, and integrated water resources management (IWRM) are referred to commonly on government-hosted websites. All of these phrases stress the need for comprehensive approaches for protecting water.

Not all groundwater resources are equally vulnerable to contamination, and areas with similar land uses and contamination sources may have different degrees of vulnerability and, therefore, different response rates to protection and management strategies. Thus, as hydrogeologists seek to determine groundwater resource vulnerability, they must consider all elements of the natural landscape: land use, contamination sources, land cover, surface and subsurface materials, seasonal variations in surface and subsurface hydrology, and man-made features.

Another complication is the fact that the relationship between land use and water quality is bidirectional. Land use activities can have direct impacts on groundwater resources, while water quality (and quantity) exerts strong influences on the siting of land use activities. Land use is, in part, determined by environmental factors: soil characteristics, climate, topography, and vegetation. Thus, successful land management requires a solid understanding of the relationship between land use/land cover and water resources. The physical and chemical processes between earth's atmosphere, its land surface and its hydrosphere are dynamically linked and demand models which can represent these coupled processes accurately. Such models are extremely difficult to develop and require large amounts of data (of which there is a paucity in most areas of this country).

Regional- and local-scale aquifer vulnerability assessments provide an effective means of assembling key information assets, of identifying environmental trends, and of prioritizing the need for detailed site-specific investigations within groundwater environments (Bekesi and McConchie, 2002; Aller et al., 1987). Canada's provinces and territories have primary jurisdiction over (ground) water resources and (ground) water supply, and each province/territory may regulate its groundwater resource differently (Nowlan, 2007). The Ontario Clean Water Act (Draft Guidance Modules http://

www.ene.gov.on.ca/envision/water/cwa-guidance.htm), for example, requires that source water areas sensitive to groundwater pollution be identified through vulnerability analysis, issues evaluation and followed by a threats inventory.

An issues inventory details problems currently existing in the source water, or with problems which might be reasonably predicted to become source water issues should rising trends continue.

Threats are activities on the landscape that, if managed improperly, may cause future problems. Potential pathways, such as water wells, are also considered as possible threats. Hazard ratings (high, medium, or low) are assigned to each chemical or pathogenic contaminant of concern. The final water quality risk assessment includes a definition of whether there is significant risk, moderate risk, low risk, or negligible risk in terms of human health and/or vulnerability of the drinking water source.

Other jurisdictions, for example British Columbia, have no formal groundwater quality risk assessment frameworks, but offer tools to water purveyors and municipalities for developing wellhead protection plans (e.g., the BC Wellhead Protection Toolkit http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/wells/well_protection/pdfs/intro.pdf, the BC Aquifer Classification System http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/Aq_Classification/Aq_Class.html).

Although typically regulated at the provincial or territorial level, source water protection is usually carried out at the local level and can involve multiple jurisdictions, if a watershed approach is used. There is a growing interest on the part of municipalities, regional districts, conservation authorities, and the like, to consider groundwater supply and its protection in future planning. This interest is largely a consequence of legislation, but also in response to growing concerns related to groundwater resources. One example wherein a local government has used groundwater information for planning purposes is the Town of Oliver in B.C.'s Okanagan Valley (Box 6-3). In this community, aquifer vulnerability maps and well capture zones for municipal wells were embedded in the official community plan. These maps were also included in a land use allocation model used to evaluate build-out scenarios for future growth.

Ideally, groundwater protection should be considered alongside surface water protection, because the two are inextricably linked, and because watersheds are defined by topography, they represent the most logical basis for managing water resources. Once we consider the water resource as a focal point, a more complete understanding of overall conditions in an area and the stressors that affect those conditions can be achieved. Management will then be better equipped to determine what actions are needed to protect or restore the resource.

Traditionally, water quality improvements have focused on explicit pollution sources (e.g., mining effluent) or specific water resources (e.g., a river segment or wetland). While this approach may be successful in addressing specific problems, it often fails to address the more subtle and chronic issues that can contribute to a watershed's decline. Major features of a watershed protection approach include targeting priority problems, promoting a high level of stakeholder involvement, integrating solutions which make use of the expertise and authority of multiple agencies, and measuring success through monitoring and other data gathering.

6.4 PLANNING FOR THE FUTURE

Groundwater availability and its use depend on a number of factors affecting both the natural (or raw) resource and the developed resource (that part of the natural resource that is reliably available for use). Sustainability of groundwater resources cannot be defined as an absolute concept: it is relative, with many variations. We described in section 6.2.2, how "Groundwater development can be considered sustainable if it is used in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences." According to this definition, we are not willing to accept negative consequences to the environment, to the economy, or to society, consequences that may be caused by unsustainable groundwater development; these consequences must be quantified before decisions are made. This is one of the main challenges for sustainable development of groundwater resources in Canada: we need to fill in the gaps in groundwater knowledge across this country.

Sustainable development of groundwater resources is not merely a scientific concept: it is a perspective that can frame scientific analysis. The evolving concept of sustainability presents a challenge to hydrogeologists as they translate complex, and sometimes unfamiliar, socio-economic and political questions into technical questions which can be quantified systematically. Groundwater scientists can and should contribute to sustainable groundwater resources management by presenting the longer-term implications of groundwater development as an integral part of their analysis (Rivera, 2008).

As seen in the previous sections, the overall security of groundwater resources is strongly linked to water sustainability (i.e., its availability and use), and its vulnerability to contamination. These elements need to be considered holistically and decisions made based on aquifer knowledge (hydrogeological maps, water budgets), as well as social (water demands), political (water laws and regulations), economic and environmental issues (ecosystem needs). Developing sustainable management strategies requires that decision-makers have a comprehensive understanding of these demands and challenges, and a detailed awareness of the economic and political instruments at their disposal (Trainer, 2010).

The physical and chemical characteristics of an aquifer may be used as indicators of the quality and quantity of groundwater, but these characteristics must be considered jointly with societal factors that determine actual groundwater availability, coupled with society's tolerance of the consequences of groundwater use for long-term security. We need to begin with some physical definition of water availability and then consider all other factors in order to make informed decisions regarding water management.

Science plays a very important role in this procedure, but science alone is not sufficient for managing groundwater resources.

6.4.1 Challenges in Canada

Sustainable use of groundwater resources demands knowledge of recharge and discharge, and information on water use/needs for domestic, agriculture and industry activities and for ecosystem services. This information is used for water balance modelling, which can be accomplished either through the use of simple accounting or by creating sophisticated numerical groundwater flow models for individual aquifers (or any other management unit, e.g., watershed, where groundwater is withdrawn by humans and/or needed by ecosystems). The Okanagan Basin Supply and Demand Study, for example, has experimented with both water balance accounting and numerical modelling to determine current and future projected water balances for the basin.

Studies such as that profiled in Box 6-1 have employed numerical models. This level of analysis requires accurate water balance data derived from assessments and long-term monitoring data (which is currently limited or nonexistent, with the exception of a few well studied and monitored aquifers across the country). Our knowledge of groundwater components in the water cycles of Canada, from local to regional scales, is not adequate or sufficiently comprehensive. When Trainer (2010) summarized the key findings of a report by the Council of Canadian Academies (2009), she noted "a lack of consolidated knowledge to define Canada's groundwater endowment and supply, coupled with a limited understanding of groundwater economics, represents a significant impediment to informed policy-making and long-term sustainable resource planning. The Council's 15-member panel—comprised of leaders in groundwater science as well as experts in the social, economic, and legal fields relevant to sustainable groundwater management—concluded that a Canada-wide sustainability framework, applied at all levels of government, is required to improve the management and understanding of Canada's groundwater.

Additionally, the Panel identified five sustainability goals (summarized below from the Council of Canadian Academies, 2009) needed to define a framework upon which a system-based approach to sustainable groundwater management could be developed: The first goal stated that to be sustainable, groundwater management must seek to prevent continuous, long-term declines in regional groundwater levels. In order to meet this goal, a comprehensive understanding of large-scale groundwater flow dynamics is required. The development of a common framework for aquifer categorization would allow integration of data from local studies into broader regional and national assessments.

The second sustainability goal required that groundwater quality must not be compromised by a significant degradation of its chemical or biological character. Sustainable groundwater management must seek to both prevent groundwater contamination in the first place, and to remediate and restore already-contaminated groundwater.

The third goal sought a sustainable management plan which balanced the human benefits of groundwater extraction against the ecosystem benefits realized by maintaining adequate stream baseflow, and wetland, river, and lake habitats.

The fourth goal spoke to the achievement of economic and social well-being. The economic benefits of sustainable management policies should be considered in the context, not just of direct economic impacts but also in contribution to Canada's environment and society. In order to promote efficient water usage, end-users should be aware of the full costs and benefits of their water consumption.

The fifth goal emphasized the need for good water governance. Water governance can be defined as the range of political, organizational and administrative processes used to articulate interests, receive input, make and implement decisions, and hold decision-makers accountable. Good governance must ultimately include the means to achieve balance among the other four sustainability goals —failure to do so means that groundwater management decisions will likely favour socio-economic interests over ecosystem and environmental interests, leading to situations that are inherently unsustainable.

6.4.2 Recommendations

To overcome the knowledge deficit on groundwater resources, Canada needs to invest in comprehensive aquifer assessments and to make long-term commitments for collecting, maintaining and analyzing groundwater data. Future studies in water stressed areas, or in areas where aquifers may be highly vulnerable to contamination, should aim to collect higher quality data, with enhanced spatial and temporal resolution and at increased precision compared to data collected in the past. Measurement techniques can be borrowed from other disciplines and adapted to provide new methods for determining the value of key variables. Data from new sensors and from existing networks must be integrated, and new observation networks established (in British Columbia, for example, recent efforts have sought to eliminate redundant data collection from observation wells and to install new observation wells in targeted areas). And lastly, measures for quality control, quality assurance, and for data sharing need to be established (among and within jurisdictions) in order to manage groundwater resources of shared aquifers.

Long-term monitoring of groundwater levels, groundwater quality and groundwater use will go a long way to support sustainability and source water protection efforts.

BOX 6-1 GROUNDWATER SUSTAINABILITY IN THE ST. LAWRENCE LOWLANDS

Groundwater sustainability was estimated for two regional aquifers located in the St. Lawrence Lowlands, southwestern Quebec (Nastev et al., 2005; Nastev et al., 2006) (Figure 6.13). The study area of the Mirabel aquifer encompasses approximately 1220 km^2 just north of Montreal. That of the Châteauguay River basin covers 2850 km^2 on the south shore of the St. Lawrence River. These two regions are relatively densely populated with more than 450,000 inhabitants;

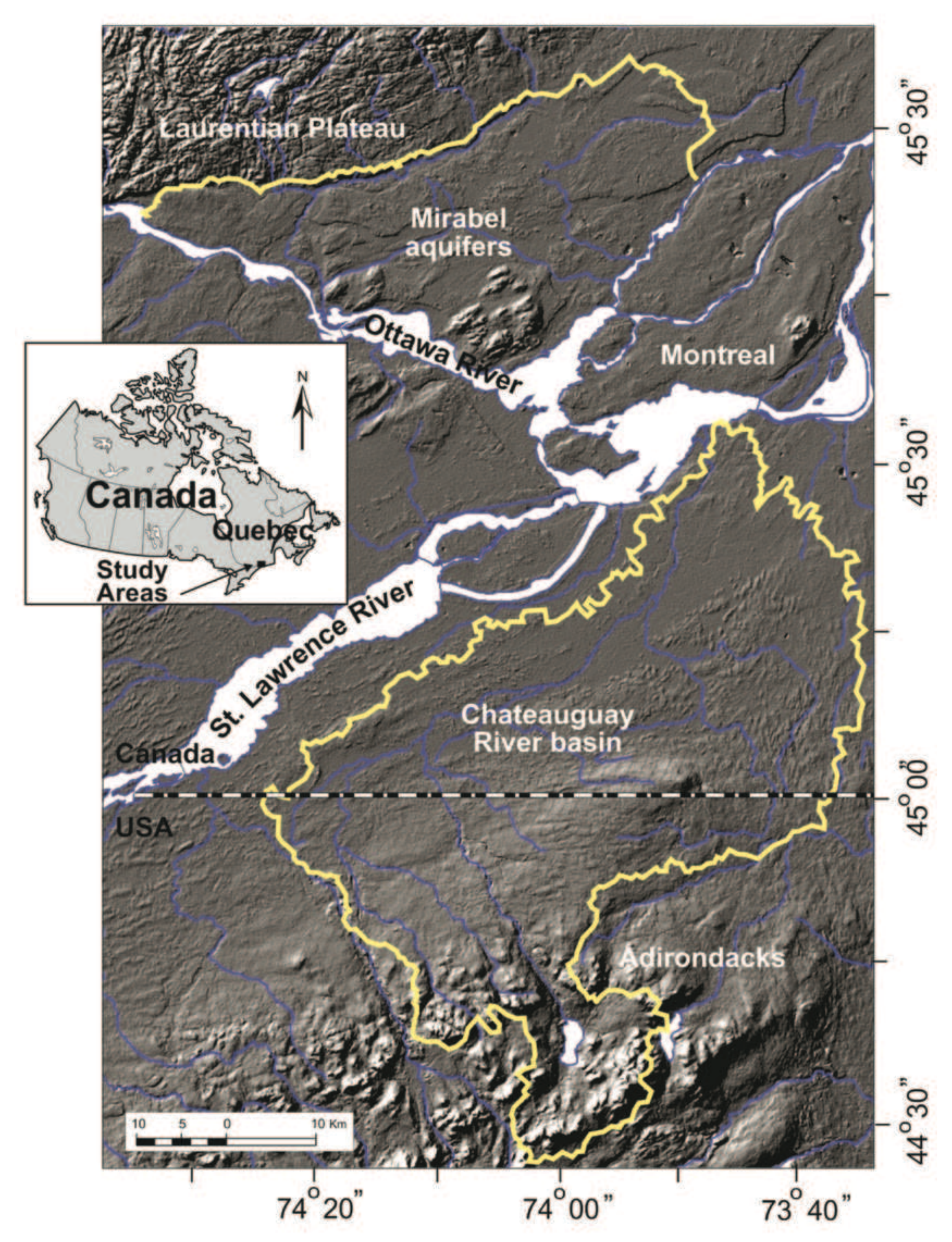


Figure 6.13 Location of the study areas.

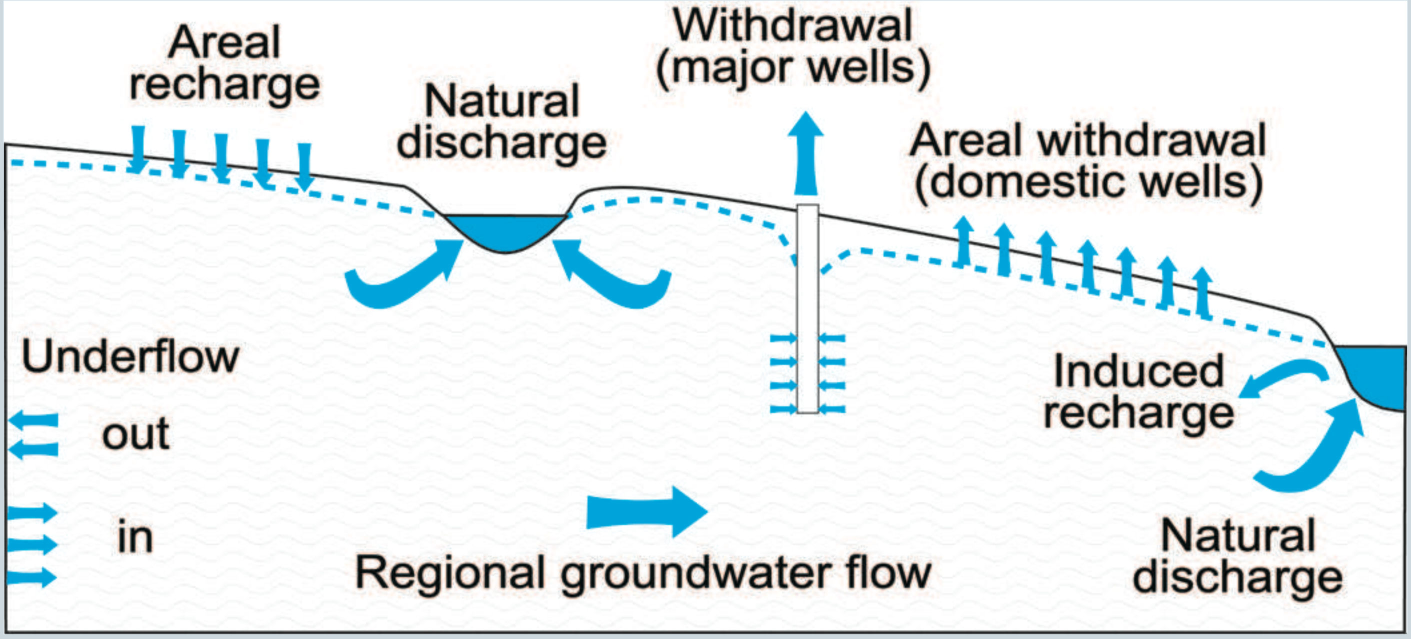


Figure 6.14 Schematic presentation of the long-term groundwater balance components for the Mirabel aquifer in Mm^3/year (Nastev et al., 2005).

both locations have intensive agricultural and industrial activities. The population, located mainly in the rural communities, is heavily dependent on groundwater for its daily needs. In addition, the Chateauguay basin forms a transboundary aquifer extending across northern New York State. The regional aquifers consist of sedimentary strata of the Lower Paleozoic period: sandstones, carbonate-dominated dolostone rocks, and limestones. They are underlain by crystalline Precambrian rocks which crop out to the north as the Laurentian Plateau (Canadian Shield) and to the south as Adirondack highlands. The groundwater flow in sedimentary rocks occurs primarily through sub-horizontal bedding planes and sub-vertical fractures and joints.

Lack of knowledge of the groundwater flow and of the availability of the groundwater resource in the region precludes the formulation of suitable groundwater management plans. Two numerical models of the regional groundwater flow were developed as essential tools for the assessment of the regional sustainability of the groundwater resource. The simulated steady-state groundwater balance components for the Mirabel aquifer are schematically presented in Figure 6.14. Assuming the useful depth of the aquifers from which groundwater can be practicably extracted to 200 m and an average effective porosity of 1%, the total volume of the stored groundwater was estimated at 2,400 Mm^3 and 5,700 Mm^3 for the Mirabel and the Chateauguay aquifers, respectively. Thus, the renewable quantity of the groundwater on an annual basis within the regional aquifers, obtained as the ratio between the regional groundwater flow and the volume of stored groundwater, varies in the range of 4–5%. The groundwater withdrawal for various uses amounts to only 0.6–0.7% of the groundwater present in storage.

Calibrated steady-state numerical models were used to simulate predictive scenarios. The withdrawal rates were assumed as successively increasing extraction rates applied uniformly on the top of the modelled domains. The long-term effects of the applied withdrawal rates were defined by the resulting average regional drawdown values

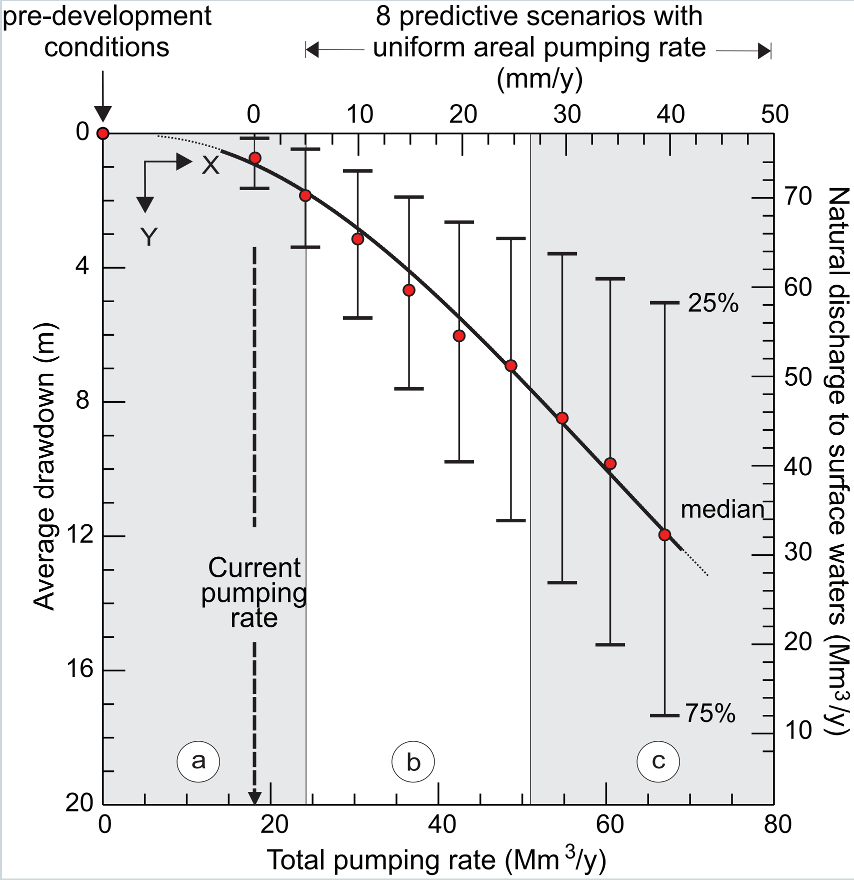


Figure 6.15 Simulated drawdowns and discharge rates for imposed uniform withdrawal scenarios for the Mirabel aquifer: (a) sustainable pumping, (b) pumping with increased drawdowns, (c) non-sustainable pumping (Nastev et al., 2006).

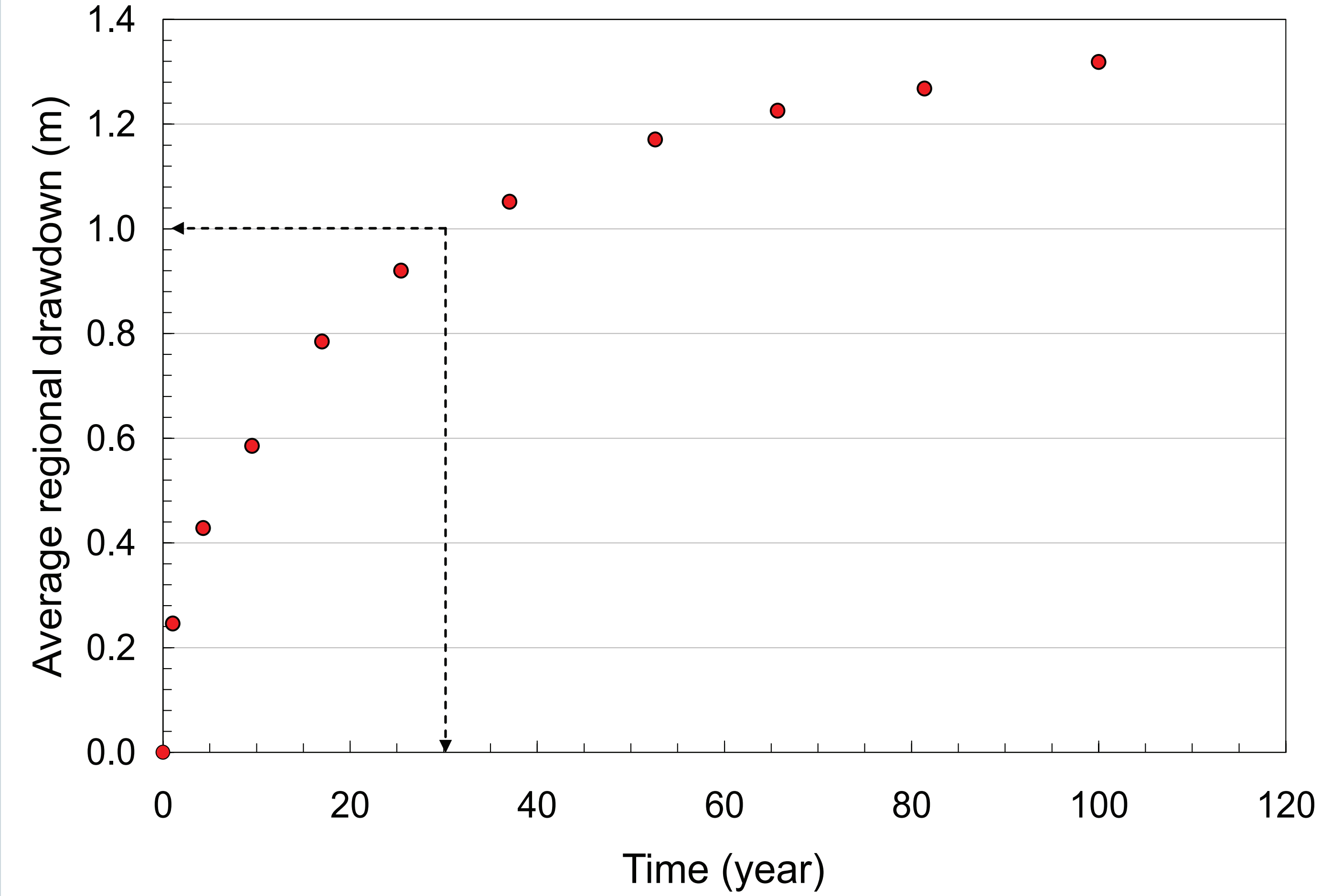


Figure 6. 16 Evolution of the simulated regional drawdown for the Chateauguay aquifer.

as the only considered negative impact. In this way, a cause-effect (pumping rate-drawdown) relationship was defined. The simulated average drawdown for the Mirabel aquifer is depicted against the imposed groundwater withdrawals in Figure 6.15. For comparative purposes, the additional uniform withdrawals are expressed in mm/year on the upper x-axis. To avoid hypothetical situations where extreme drawdowns could have been obtained, the maximal withdrawal rate was limited to 40 mm. One additional simulation was conducted with no withdrawal at all. This last scenario represents the flow in pre-development conditions.

The computed drawdown is not a random variable but rather is influenced by the simulated hydrogeologic conditions. In this case, the Gaussian distribution is no longer valid. The regional drawdown values are estimated with percentiles. The median represents the average estimate for which 50% of all drawdown values fall below. The distance between the 25th and 75th percentile indicates the range which includes 50% of the drawdown values, 25% of the drawdown values were left outside on each side of this range. Using the hand-fitted curve, it is possible to approximately estimate the average drawdown for a given regional withdrawal rate. The results show that simulated drawdown increases faster with the increase of the withdrawal rate. As the recharge component remained constant during the simulations, the applied uniform withdrawal rate is accounted for mainly by capturing of the natural groundwater discharge.

Three distinct zones are evident (Figure 6.15). The first zone (a) covers the range of sustainable pumping rates of up to 24 Mm^3/year. In this zone, the simulated drawdowns are relatively low (<2 m), and increase slowly as pumping rates increase. The second zone (b) is characterized by increased withdrawal rates. It starts from the inflection point of the fitted drawdown/pumping curve, and extends to the point where the pumping rate equals the discharge rate. Although the average drawdowns may not seem to be very high under current conditions of groundwater use in south western Quebec, they are considered high because most of the pumping wells are shallow wells that intercept only the upper portion of the regional fractured aquifers. The third zone (c) displays non-sustainable pumping rates larger than 51 Mm^3/year, wherein the withdrawal rate would exceed the natural discharge rate to streams and rivers, a function of the natural recharge rate under given climate conditions. A pumping rate that exceeded 51 Mm^3/year would reduce the discharge to surface water by 20% to 40% and could eventually lead to the drying of some streams. This could result in critical water levels and in groundwater shortages. Furthermore many wells would need to be re-drilled to increase aquifer penetration.

Finally, transient simulations were conducted in order to obtain the long term piezometric trends. As rare information exists over the historic evolution of the groundwater withdrawal, these scenarios were run assuming that the entire extraction rate was applied at time zero. Figure 6.16 depicts the evolution of the simulated regional drawdown for the Chateauguay aquifer.Even after hundred years, the model does not reach steady state conditions resulting in the maximal drawdown of 1.48 m.

BOX 6-2 AQUIFER VULNERABILITY IN FRACTURED ROCK AQUIFERS

Like many communities situated in close proximity to urban centres, the southern Gulf Islands, located in the Georgia Strait between Vancouver and Victoria (Figure 6.17), are experiencing significant development pressures. Groundwater quality issues in the Gulf Islands have been amplified by improper disposal of agricultural waste, failed septic systems, pesticides and saltwater intrusion due to both natural conditions and over-pumping. The subdued topography of the Gulf Islands lends itself to the presence of few lakes able to support domestic and agricultural uses; therefore, the majority of residents rely on fractured bedrock aquifers as a primary source of fresh water.

The Gulf Islands are a group of 40+ islands that range in area from ~1-75 km^2 and are characterized by a generally northwest–southeast trend and elongation defined by linear ridges and valleys. Elevations range from 100 to 200 m, reaching a maximum of about 350 m on Saltspring Island. Coastlines are typically rocky, with either long expanses of low relief bedrock sloping shallowly into the ocean or, alternatively, steep cliffs and narrow rocky beaches.

The geology and hydrogeology of this region have been researched extensively (e.g., Allen et al., 2002; Allen et al., 2003; Mackie, 2002; Mackie et al., 2001; Journeay and Morrison, 1999;

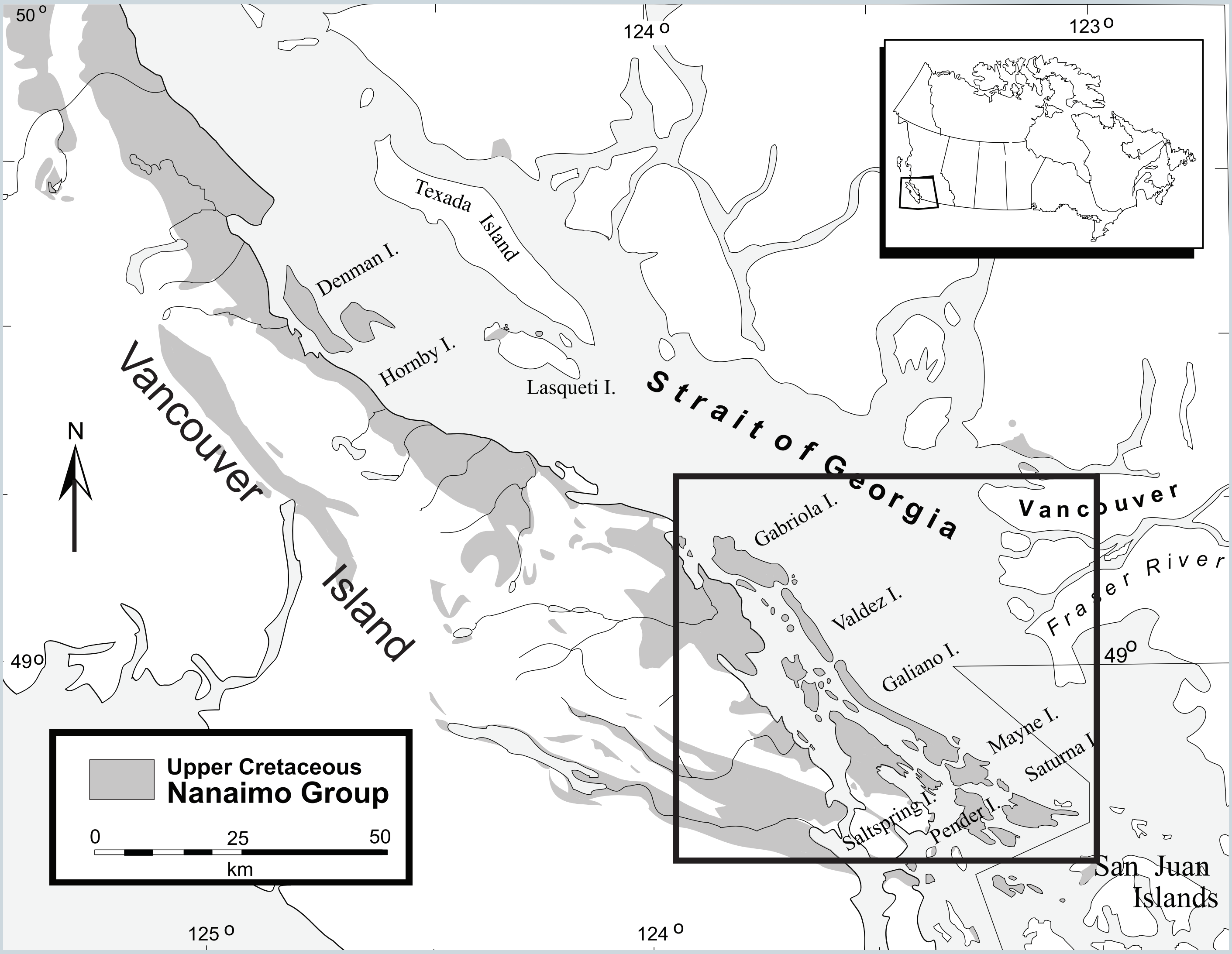


Figure 6.17 Location of the southern Gulf Islands in southwestern British Columbia.

England, 1990; Dakin et al, 1983; Hodge 1995). The Nanaimo Group (Mustard, 1994) forms the majority of bedrock of the Gulf Islands, and consequently, the majority of the water-bearing units on the islands. Unconsolidated deposits, of dominantly glacial and/or marine origin do not constitute a volumetrically significant percentage of the exposed geology on any of the islands, yet are anticipated to have a significant control on recharge.

The Nanaimo Group formations do not represent a true "layer cake" stratigraphy, but are composed of laterally thickening and thinning units with both conformable and sharp, erosive contacts. Lithology varies in grain size both between and within formations. Sandstone-dominated formations contain little structure, and can attain thicknesses of 100s of metres, with only minor fine grained interbeds. Silts and muds dominate mudstone formations, with significantly lower bed thickness (mm to cm). Structurally, the Gulf Islands are characterized by gentle folds with bedding that dips in the range of 5-15 degrees, with numerous small- and large-scale discrete fractures and faults. The present distribution of Nanaimo Group formations is the result of multiple regional deformational events (e.g., Journeay and Morrison, 1999). As well, the Gulf Islands have undergone glacio-isostatic deformation in response to multiple Quaternary glaciations (Clague, 1983), which have resulted in upwards of 50 m of vertical isostatic rebound.

Due to the low primary porosity and permeability of the solid bedrock, groundwater is derived primarily from fractures as secondary permeability. Higher joint densities characterize the more thinly-bedded mudstone-dominated units, notably within the transition zones between formations where mudstone bedding thickness is generally small (Mackie, 2002). This suggests that thinly-bedded mudstone-dominant units may have a higher permeability where they are in contact with sandstone. In contrast, the sandstone-dominated formations, with much lower fracture densities, may act more as impermeable blocks with significantly more widely spaced, discrete flow zones or pathways. In this respect, intra-formation heterogeneity, in the form of fine grain interbeds within coarse grain formations, may create pockets of more highly fractured rock, which, if connected to a recharge zone, may form an "intra-formation" aquifer. Similarly, at the contacts between formations, there may be enhanced permeability in those areas where there is transitional bedding.

Structures visible at the 1:75,000 (regional scale) can be characterized on the ground as fault or fracture zones up to 10's of metres in width. These structures are often identified by lineaments that are zones of high weathering or ridges. On the Gulf Islands it was found that fracture density tends to increase by at least a factor of ten in the presence of a regional-scale fault (Mackie, 2002). Many mesoscale fractures, which cross-cut all formations, were identified on the islands; these may represent discrete flow paths or narrow (metre-scale) flow zones. These fractures tend to be older than lineament-scale fault and fracture zones and may not have as significant an effect on groundwater flow at the island scale, but they may be important at the local scale.

From a hydrogeologic perspective, the larger fracture zone structures are interpreted to have a significant effect on groundwater flow, particularly at the regional scale. Discrete fracture modelling (Surrette and Allen, 2008; Surrette et al., 2008) indicates that the permeability of fracture zones is higher than that of the sandstone- and mudstone-dominant lithologies. Furthermore, Allen et al. (2003) found that flow in most wells located near mapped lineaments was highly influenced by linear flow and that the hydraulic properties calculated for wells situated near such features were consistently higher than those for wells away from lineaments. These observations support the interpretation that large-scale fault and fracture zones exercise a dominant control on the hydrogeology, and probably act as conduits for groundwater flow at the regional scale. Thus, vulnerability maps for this structurally-controlled region would best be represented with a conceptual model that captures permeability variations derived from fracturing at a range of scales.

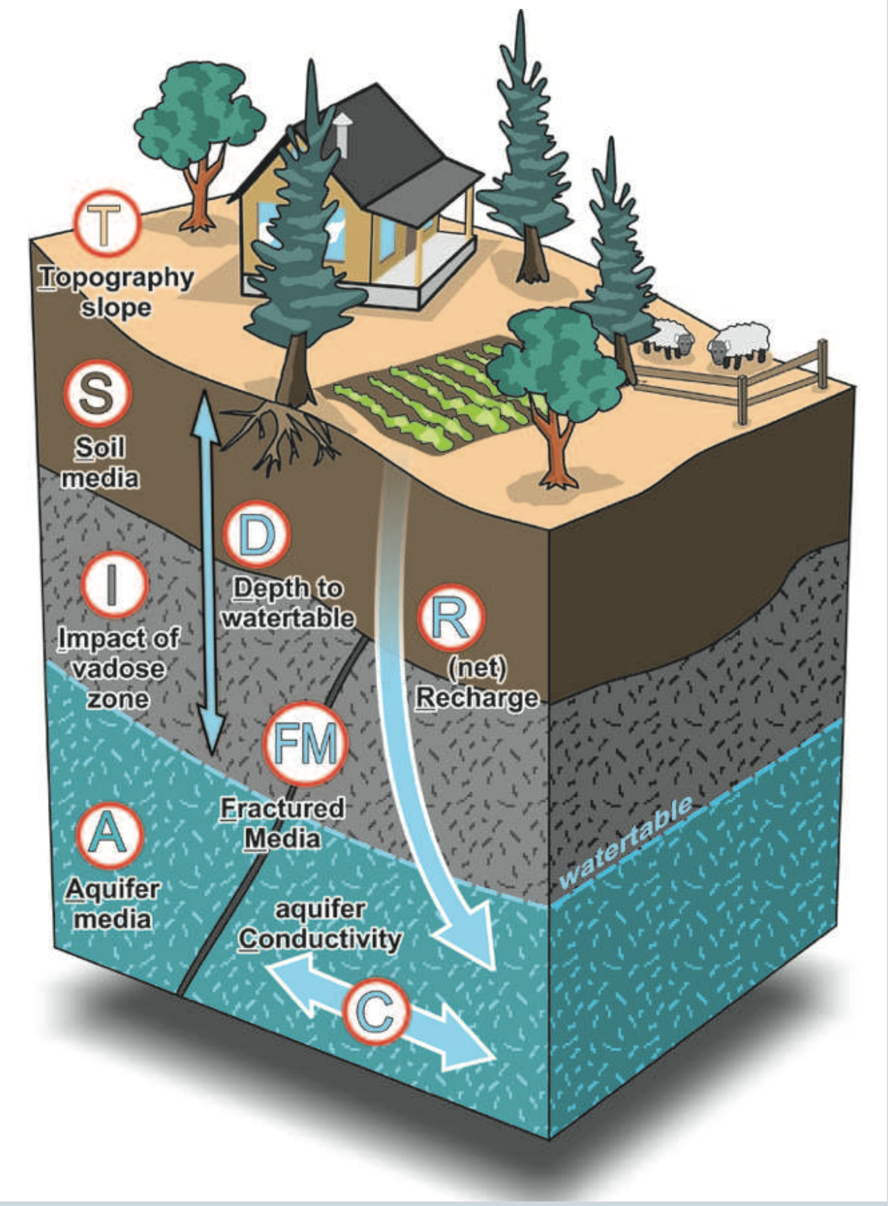


Figure 6.18 DRASTIC Methodology parameters. This figure differs from Figure 6.11 in that it incorporates the Fm parameter, which represented discrete fracture zones (figure courtesy of the Geological Survey of Canada).

A commonly-used aquifer vulnerability mapping method is DRASTIC, which parameterizes the physical characteristics that impact groundwater pollution potential (Aller et al., 1987). The term "DRASTIC" is an acronym for seven model parameters (Table 6.2, Figure 6.18). While the "A" (Aquifer media) parameter can incorporate the bulk effect of fractures on permeability, the spatial extent and characteristics of fault and fracture systems are not represented. To this end, a modified vulnerability mapping method, namely DRASTICFm, was developed, which identifies the impacts of structurally-controlled aquifers on the quality of groundwater resources (Denny et al., 2006). The Fm parameter takes into account three primary characteristics that dictate the impact of a discrete fracture network: orientation, length and fracture density (Singhal and Gupta, 1999). These three characteristics are combined into an eighth DRASTIC parameter and assigned the same weight as Aquifer Media (Table 6.2). DRASTICFm was determined to be the most representative model due to its capacity to synthesize the information sets available within the region, while identifying hydrogeological and hydrostructural trends between islands.

As an index-based model, DRASTIC assigns relative weights to each of its parameters. These weights are allocated based on a parameter's contribution to the overall susceptibility of an environment. Within each parameter, ratings are assigned to define the significance of one characteristic over another. Ratings for individual parameters were determined from direct consultation with the DRASTIC EPA manual (Aller et al., 1987) and from the application of DRASTIC to other study areas within similar environments in British Columbia (e.g., Wei et al 2004; Wei et al., 1998).

In order to properly represent the parameters within the DRASTIC methodology from a spatial context, a comprehensive collection of Geographic Information System (GIS) datasets was compiled. Key input datasets into this model include soil, bedrock geology, a water well database and a DEM. In order to bring consistency to the varying

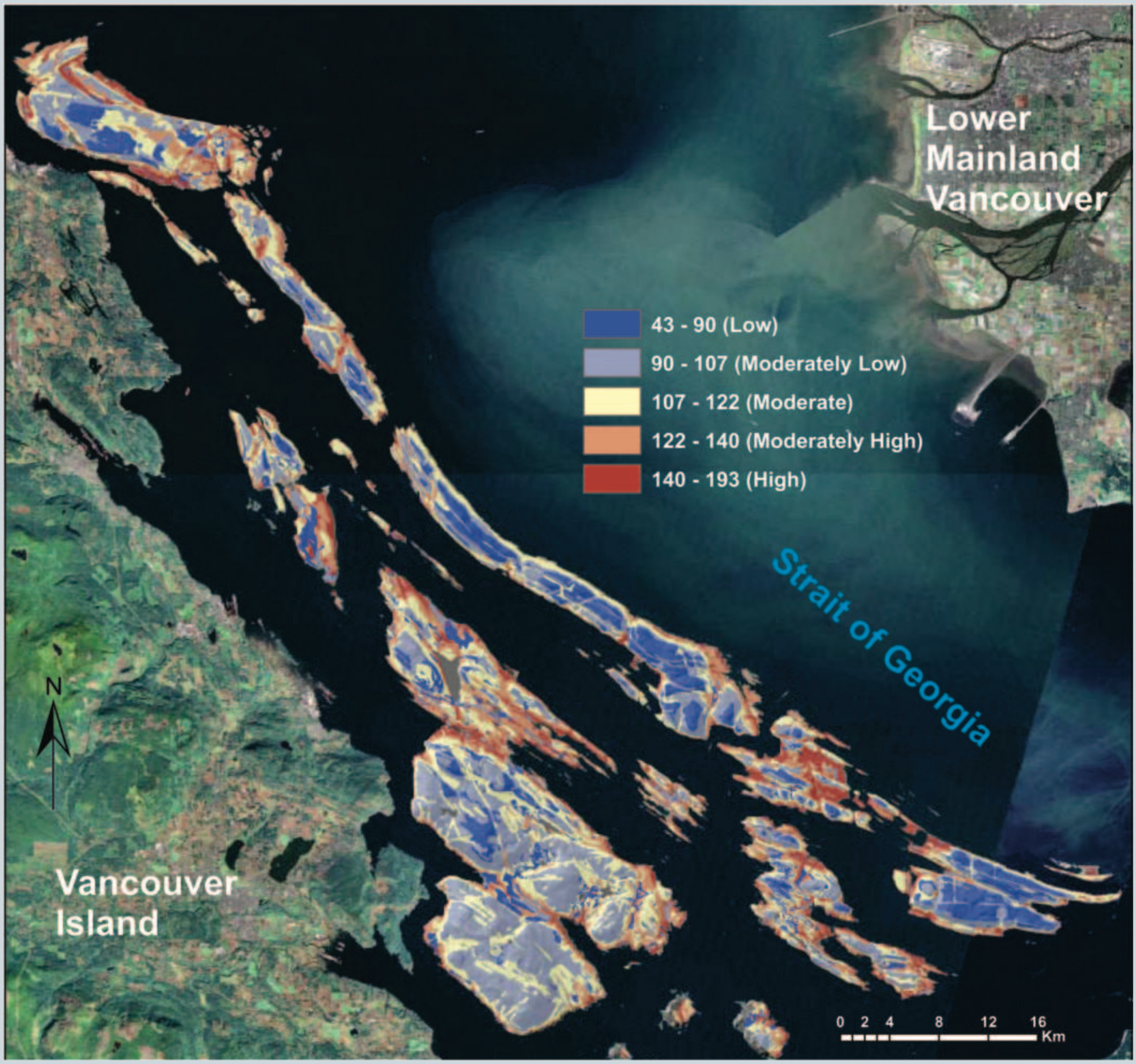


Figure 6.19 DRASTIC-Fm model output for the Gulf Islands.

TABLE 6.2 DRASTIC-FM PARAMETER DEFINITIONS AND WEIGHTS

Hydrogeologic Factor	Weight
D – Depth to Water	5
R – Net Recharge	4
A – Aquifer Media	3
S - Soil Media	2
T - Topography	1
I – Impact of Vadose Zone Media	5
C – Aquifer Hydraulic Conductivity	3
Fm – Fractured Media	3

scales of the input datasets, a constant scale was determined by the DEM (25m) and each of the layers was converted to a raster dataset. Each cell in the model output dataset is represented by a vulnerability value which corresponds to the cumulative rating of all parameters.

Model outputs were classified into 5 categories of vulnerability ranging from high to low with vulnerability rates ranging from 43 (low) to 193 (high) (Figure 6.19). General trends in the model outputs include regions of high vulnerability around island perimeters where instances of saltwater intrusion are prevalent, and in valley regions where the topography changes, recharge rates are high and structures are present. The model is quite sensitive to changes in the D (Depth to aquifer) and the presence of faults and fractures (Fm). Regions of moderate to low vulnerability (43-107) exist primarily in poorly drained soil layers with significant clay deposits. These regions occur primarily in the central portions of the islands where the thickness of material above the aquifer is greater than 10 m deep.

Regions of moderately-high to high vulnerability (107-193) exist primarily at the periphery of the islands and in areas of exposed rock where there is little or no soil material to provide a potential obstruction for a contaminant to move vertically into the vadose zone.

The overall impact of the presence of fault and fracture systems tends to augment the vulnerability of the regions within proximity to a structure. For example, the presence of faults and fractures within regions of low vulnerability increases the vulnerability range to moderately-low. This is particularly evident in the southern portion of Salt Spring Island and the central portion of Saturna Island where the presence of faults and fractures have augmented the vulnerability from moderate (107–122) to moderately high (122–140) and moderately low (90–107) to moderate (107–122), respectively. the impact of the fracture density on individual faults and fractures appears to have the most significant impact on vulnerability.

BOX 6-3 INTEGRATING GROUNDWATER SCIENCE INTO DECISION MAKING

(FROM LIGGETT ET AL., 2006)

The Okanagan Valley in south central British Columbia (Figure 6.20) has seen unprecedented population growth over the past few decades, and development continues to put pressure on water supplies in this semi-arid region. In addition, the Okanagan is one of Canada's primary agricultural areas, and a popular tourist destination. Most water supplies in the Okanagan are from surface water sources, but these are close to being fully allocated. Thus, there has been a growing interest in exploiting new groundwater resources. With an increase in demand, there will be a greater emphasis placed on strategies for groundwater protection. Likewise, sustainable community development is an important topic of discussion for communities, governments, and researchers. It is within the context of sustainable development and aquifer protection that this study took form.

In 2005–2006, Greater Oliver, situated in the south Okanagan, participated in the Smart Growth on the Ground (SGOG) initiative in support of sustainable community development. SGOG is a collaborative project between SmartGrowth BC, the Real Estate Institute of BC, and the Design Centre for Sustainability at the University of British Columbia (UBC). This team of researchers and facilitators works with communities to adopt necessary by-laws, programs and regulatory changes toward the development of a sustainable community design. Greater Oliver was chosen as one of three pilot study communities in BC. Other SGOG participants included Maple Ridge and Squamish. The primary outcome of this process was a concept plan that was developed as part of a participatory planning process culminating in a design charette[5]. The concept plan outlines recommendations on growth patterns and environmental, social and economic priorities highlighted by representatives of community-identified stakeholder groups. Water scarcity and water quality were identified as key priorities during the initial phases of the SGOG process in Greater Oliver due to the projected population growth coupled with agricultural (fruit crops, vineyards) and recreational activities that rely on water. Population growth and subsequent development in the valley are inevitable. To ensure that development occurs in a sustainable manner, a community must identify where development will occur and what sustainable measures (proximity to public transit or rain catchment systems, for example) will be adopted into new development projects.

Various tools are used to facilitate the planning process. The LUAM (land use allocation model) is a land use planning tool that prioritizes locations of new growth based on constraints and indicators identified by the community (e.g., Cromley and Hanink, 1999). The LUAM criteria for Oliver were grouped into several classes, including land use policy, land cost, amenities, infrastructure, market proximity, physical characteristics, hazard, health, and ecological setting according to specific criteria. The LUAM for Oliver was created in a commercial suite of "what-if" scenario modelling and landscape visualization tools called CommunityViz^{TM} (Placeways, LLC, 2010). This software integrates available information, knowledge and community values in real-time to identify trade-offs and consequences between different prospective land use planning scenarios. LUAM outputs identify regions of desirable future development. Each grid cell represents the cumulative ranking of all criteria multiplied by weightings that reflect community values.

Vulnerability maps represent an effective means of synthesizing complex geologic and hydrogeologic information so it they can be used by planners and policy-makers toward the development of sustainable resource management plans and future growth strategies (Aller et al. 1987). An aquifer vulnerability map was created for Electoral Area C in Greater Oliver using the DRASTIC method (Aller et al., 1987) (Figure 6.20). Details concerning the methodology can be found in Liggett et al., (2006). Ultimately, all seven DRASTIC parameters

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[5] A charette is a planning technique that takes place over several days and allows all community decision-makers (municipal officials, developers and local residents) to be together at the same time to find solutions to known issues and develop a sustainable plan for their community. The Oliver charette took place in May 2006.

Figure 6.20 Okanagan Valley, B. C. Outlined area is Greater Oliver.

were mapped in ArcGIS 9.1 (ESRI, 2005) and converted into raster format. The seven raster maps were multiplied by their respective weights and added together (Figure 6.21) to produce the final, spatially distributed, map of intrinsic aquifer vulnerability (Figure 6.21). Vulnerability ranges from 35 to 171 of a possible 230. Generally, the sand and gravel aquifers in the valley bottom are more susceptible to contamination than the igneous and metamorphic aquifers in the valley uplands. The shallow depth to water in the valley bottom, along with high ratings assigned to aquifer media and aquifer conductivity result in a highly vulnerable valley bottom aquifer.

Aquifer vulnerability provided an important

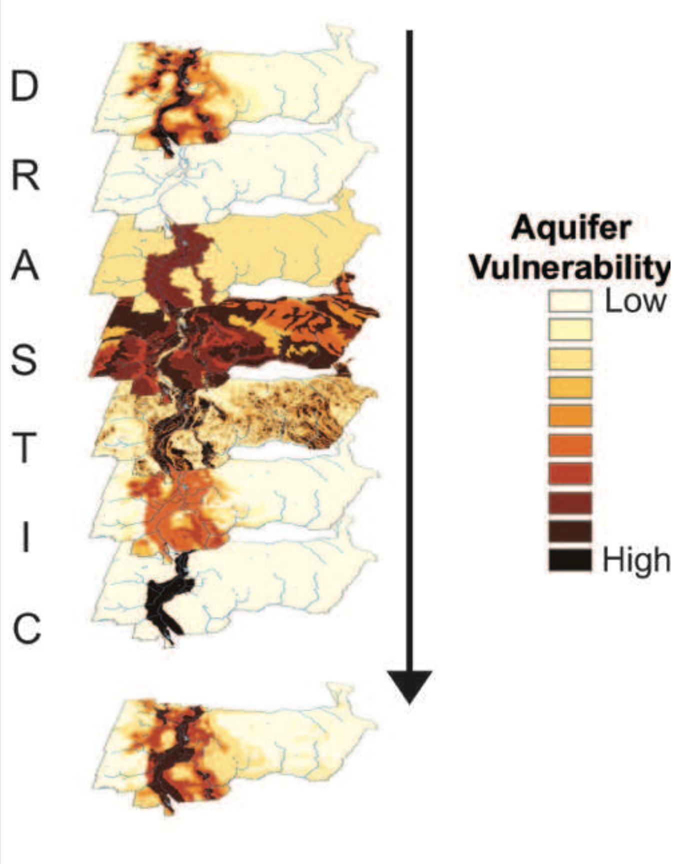


Figure 6.21 Seven DRASTIC input characteristics for the Greater Oliver aquifer vulnerability maps. The lowest map in the sequence shows the final DRASTIC map constructed by weighting the seven input maps—also reproduced in Figure 6.22.

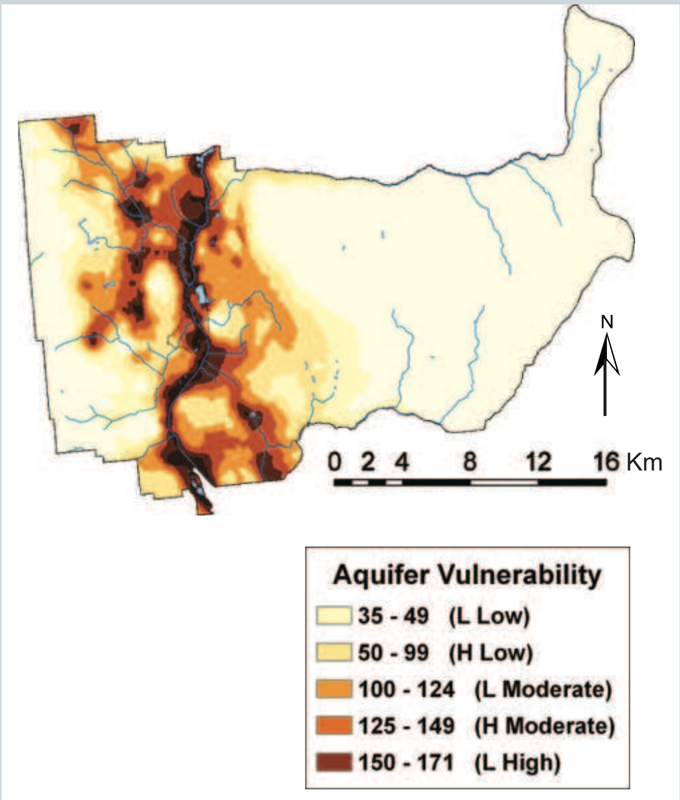


Figure 6.22 Relative intrinsic aquifer vulnerability in the Greater Oliver area.

constraint for the LUAM. It was used to identify the likelihood of groundwater quality issues in future residential or commercial settlements. It is anticipated that the positive results of this process will highlight the importance of using LUAMs, and datasets such as aquifer vulnerability maps, to represent all facets of land use planning in support of sustainable community development.

BOX 6-4 DELINEATING WELLHEAD PROTECTION AREAS—COMPARATIVE STUDY OF METHODS

Human activities, whether agricultural, industrial, commercial, or domestic, can contribute to groundwater quality deterioration. In order to protect the groundwater exploited by a production well, it is essential to develop a good knowledge of the groundwater flow system and to delineate the area surrounding the well within which potential contamination sources should be managed. Such an area is referred to as the wellhead protection area (WHPA). Regionally, the protection of groundwater resources involves land management and restrictions on potentially polluting activities in more vulnerable areas, especially recharge zones. This assessment of aquifer vulnerability is made on the basis of regional hydrogeological mapping.

The U.S. EPA (1991b) defines a WHPA as "the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field." This zone can also be referred to as the zone of contribution (ZOC), i.e., the two-dimensional (2D) projection to the land surface of the aquifer volume containing all the groundwater that may flow toward a pumping well over an infinite time period. The zone of influence (ZOI) is the cone of depression caused by pumping. The zone of travel (ZOT) is defined within the ZOC and can be described as an isochrone indicating the time necessary for water or a conservative contaminant to reach the well from that location (Figure 6.23)

Several methods exist for delineating WHPAs; these differ in their degree of complexity and their precision. Naturally, the integration of more geologic and hydrogeologic characteristics of the study area increases the precision of any given method (Barlow, 1994; Livingstone et al., 1996; Bair and Roadcap, 1992; Ramanarayanan et al., 1992). From a practical perspective, the most appropriate method for WHPA delineation should be the one that simplifies the flow system as much as possible while still preserving its geological and hydrologic characteristics.

Example of WHPA delineation

Several studies have been conducted to compare WHPA methods (Springer and Bair, 1992; Forster *et al*. 1997; Bates and Evans, 1996; Paradis et al., 2007). The recent study from Paradis et al. (2007) has provided a comparison of methods for WHPA delineation in order to identify an efficient method that will be easy to use and cost-effective as well as providing a realistic delineation of the WHPA in the alluvium context. Methods selected range from simple approaches to complex computer models and include: calculated fixed radius (infiltration method), uniform flow equation (Todd, 1980), time of travel (TOT) equations (Bear and Jacob, 1965), HYBRID method (Paradis, 2000), flow system mapping, semianalytic method WhAEM (Haitjema et al., 1994), and the numerical model MODFLOW-

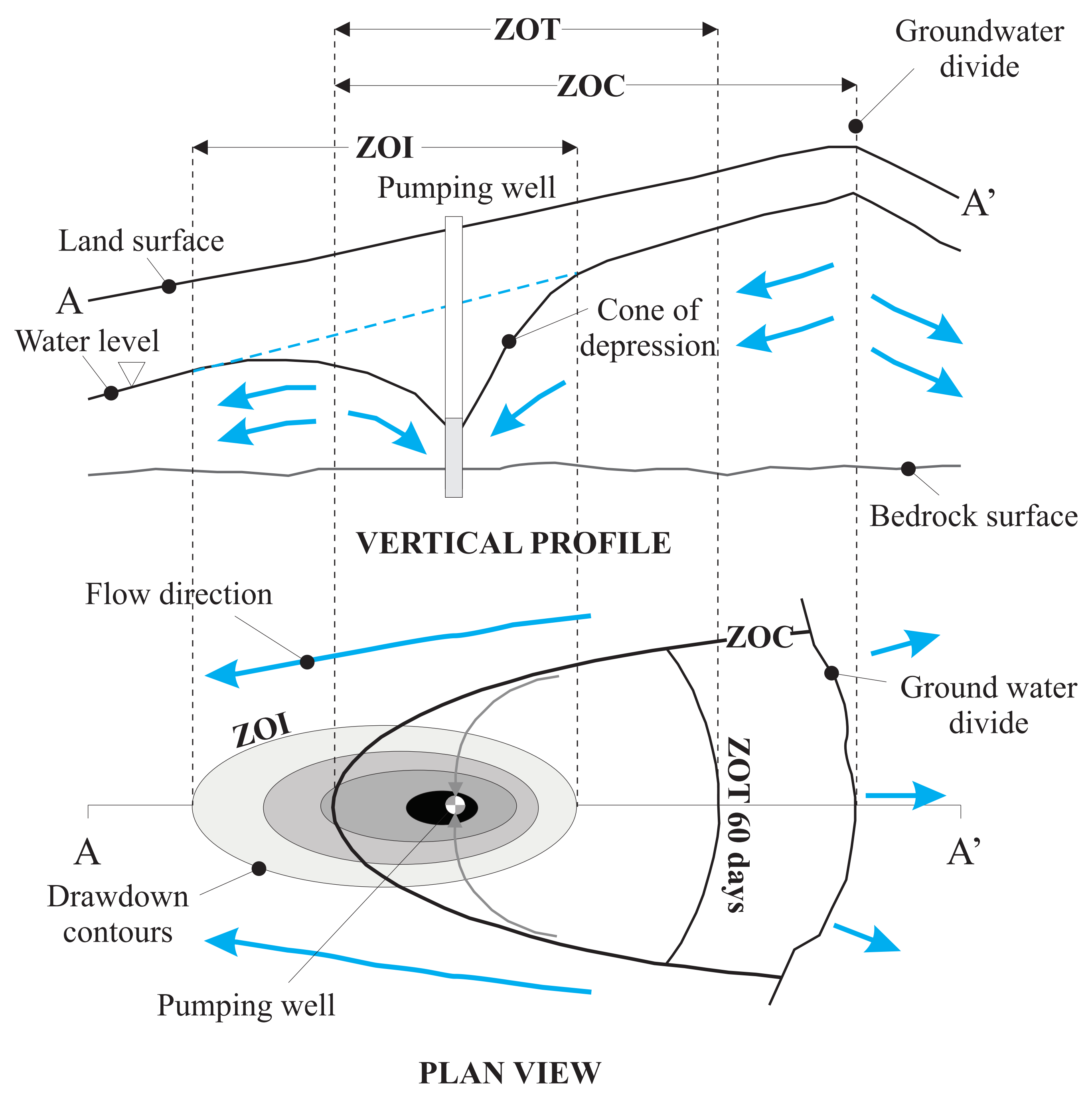


Figure 6.23 Relationship between zone of influence (ZOI), zone of transport (ZOT), and zone of contribution (ZOC) in an unconfined porous-media aquifer with a sloping regional water table (modified from USEPA, 1987).

MODPATH (McDonald and Harbaugh, 1988; Pollock, 1989) (Table 6.3).

For comparison purposes, all of these methods were used to calculate the WHPA of a test-bed site composed of an unconfined granular aquifer located in a thick sequence of deltaic and littoral sand deposits ranging from 10 to 30 m depth underlain by the Precambrian rocks of the Canadian Shield (Fagnan et al., 1999). This sandy aquifer features a series of small terraces which slope both sides of water divide, to the Aux-pommes River to the south and to the Jacques-Cartier River to the north

TABLE 6.3 WELLHEAD PROTECTION AREA (WHPA) METHODS CHARACTERISTICS

(FROM PARADIS ET AL., 2007)

METHOD OF WHPA DELINEATION	PARAMETERS	ADVANTAGES	DISADVANTAGES
Mass balance: Infiltration equation (USEPA, 1987) Cylinder equation (USEPA, 1987)	* Recharge * Time of travel * Pumping yield * Porosity (specific yield) * Saturated aquifer height/thickness	* Low cost * Easy and fast to use with less data * Low technical knowledge required	* Independent of specific flow condition * Over simplification
Analytical : Uniform Flow (Todd, 1980) TOT[1] (Bear and Jacob, 1965) TOT[1] (Darcy's Law)	* Hydraulic gradient * Hydraulic conductivity * As for Mass balance except * no recharge	* *idem* Mass balance	* *idem* Mass balance
Semi-analytical: WhAEM (Haitjeima et al., 1994) CAPZONE-GWPATH (Bair et al, 1991; Shafer, 1990)	* *idem* Analytical * Simple flow limits * Limited parameter uncertainties	* Based on idealized setting * Useful for simple flow system and recharge (WhAEM) * Non-uniform regional flow field may be superimposed (CAPZONE)	* Isotropic and homogeneous conditions * Infinite extent aquifer assumption * Complex recharge not directly taken into account
Hydrogeologic Mapping: Potentiometric (flow system) map	* Physical and hydraulic limits	* Economic and precise for shallow granular aquifer * Often the only method useful in karst and fractured media	* Must be combined with other methods * Not quantitative * Does not represent TOT * Expensive for complex settings
Combined methods: HYBRID (Paradis, 2000)	* *idem* Mass balance and Analytical * Physical and hydraulic limits	* Low cost * Easy and fast to use for simple aquifer * Good precision for homogeneous and isotropic aquifer	* Imitative form of WHPA in homogeneous and isotropic setting
Numerical Modelling: MODFLOW-MODPATH (McDonald and Harbaugh, 1988; Pollock, 1989)	* Every hydrogeological parameter * Physical and hydraulic complex limits represented * Parameter uncertainties	* May represent most hydrogeological settings * Quantitative and predictive tool	* Required good conceptual model * High data and expertise needed * May require high computational effort

[1] TOT = Time of travel

(Figure 6.24). The result is a narrow aquifer that extends several tens of kilometres long and only 1 or 2 km wide (Fagnan et al., 1999). The underlying bedrock constitutes the impermeable base of the aquifer. This aquifer serves as the water supply for the town of Pont-Rouge which consists of 20 drive-point piezometers.

The reference ZOC for the site was delineated from a potentiometric map based on the summer water levels. This map was drawn using spatial interpolation of more than 300 water level measurements taken within the granular aquifer. The map considered the interaction between ground and surface water and the physical

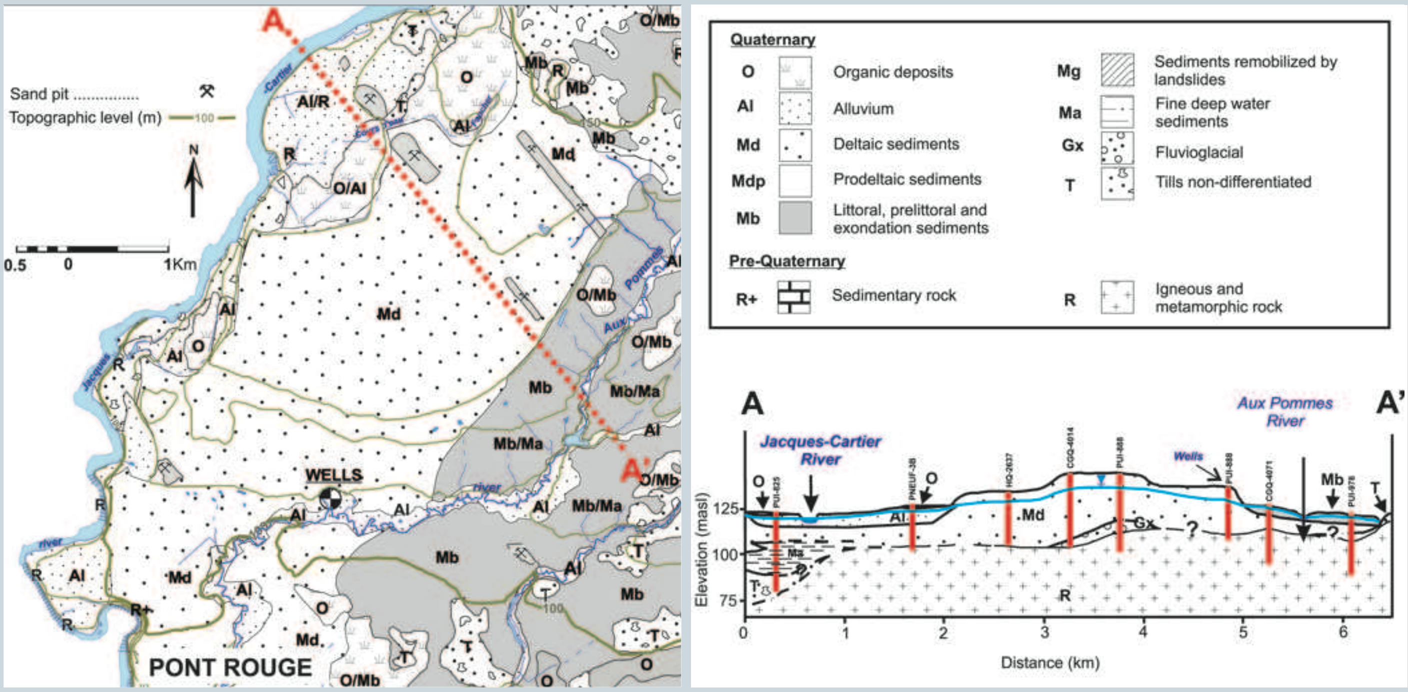


Figure 6.24 Geological map and cross-section of the aquifer.

boundaries such as rock outcrops and seepage faces. Moreover, the total area of the ZOC was constrained by a water balance between the water supply extraction rate and aquifer recharge. Table 6.4 shows hydrogeological parameters used for ZOC delineation.

Comparison of results

Figure 6.25 shows that the majority of the methods depicted a ZOC up-gradient from the pumping wells, and extending all the way to the groundwater divide. Only the cylinder infiltration method presented a ZOC equally distributed around the pumping wells. It also appears that the ZOC width as defined by the uniform flow and WhAEM methods was too narrow in comparison with the reference method provided by the potentiometric mapping technique. Consequently, only the potentiometric mapping, MODFLOW/ MODPATH and the HYBRID methods provided realistic delineation of the ZOC. One of these three methods (or all of them) may be applied, depending on the amount of data and the effort available. Generally, however, the most simple and cheapest method is applied first and should more precision be needed, or a counter-verification required, the more expensive methods are then utilized.

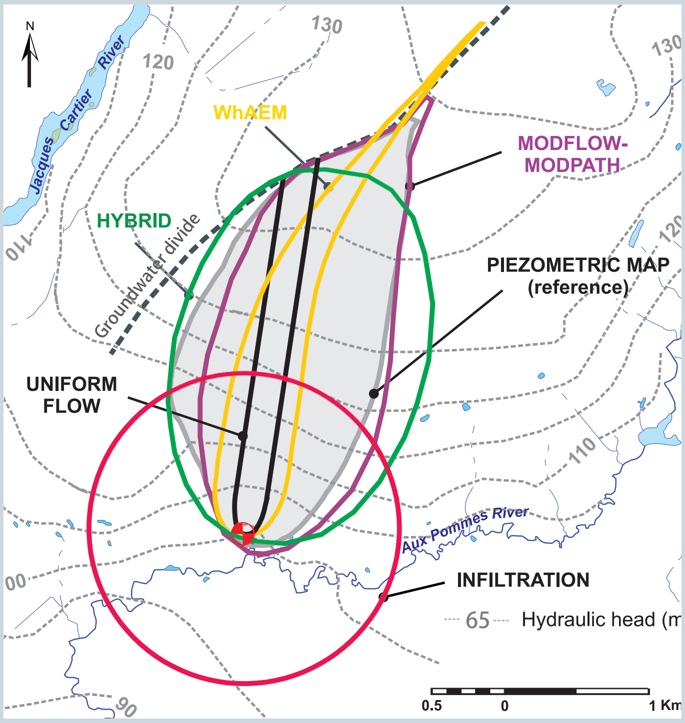
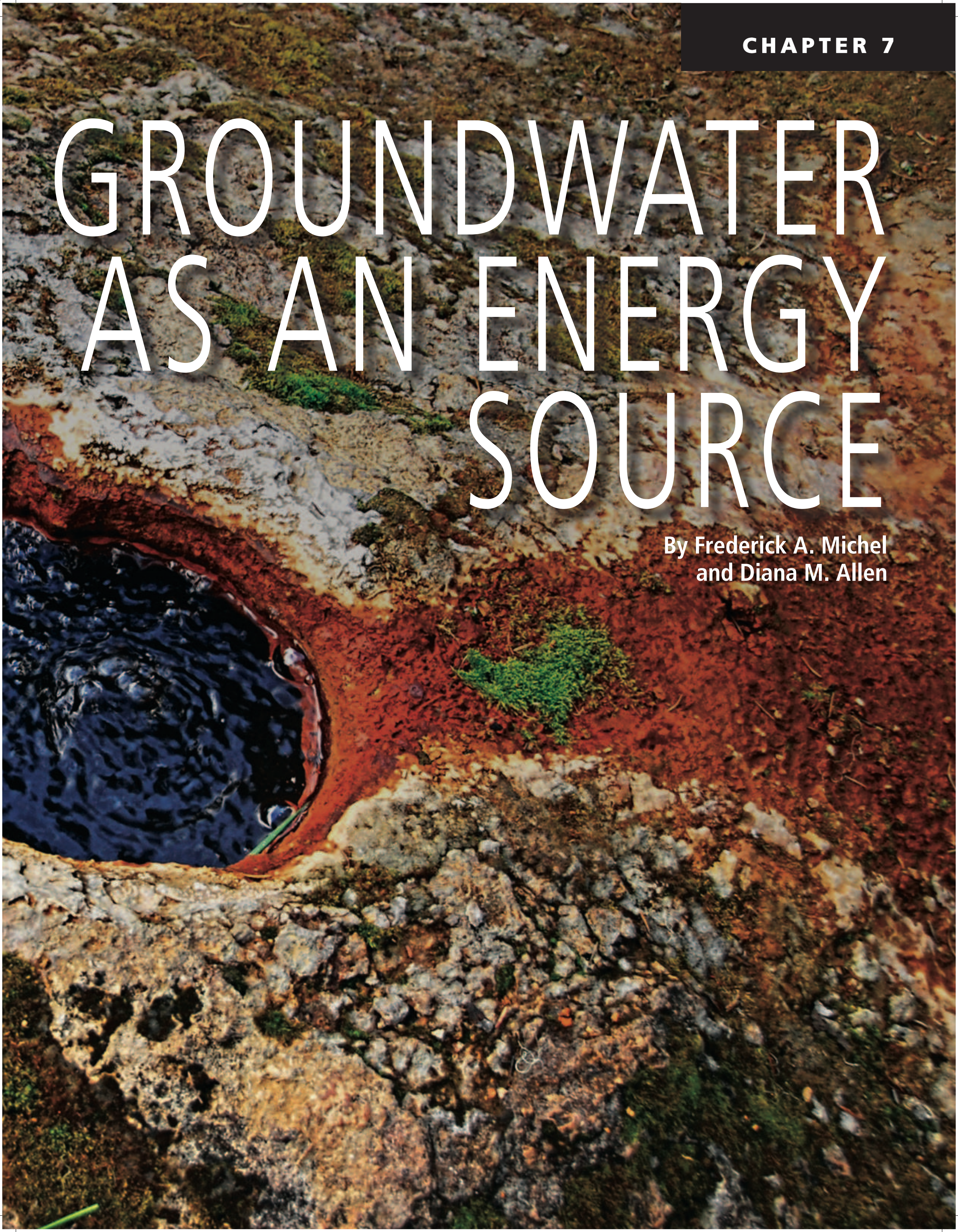


Figure 6.25 Comparison of the ZOCs at the Pont-Rouge site (modified from Paradis et al., 2007).

TABLE 6.4 HYDROGEOLOGICAL PARAMETERS USED BY WHPA METHODS FOR THE ZONE OF CONTRIBUTION (ZOC) OF PONT-ROUGE'S WATER SUPPLY. METHOD OF REFERENCE IS IN ITALICS AND ADJUSTED DATA ARE IN BOLD. (MODIFIED FROM PARADIS ET AL., 2007)

METHOD FOR ZOC AT PONT-ROUGE	YIELD (M^3/D)	SATURATED THICKNESS (M)	HYDRAULIC GRADIENT (%)	HYDRAULIC CONDUCTIVITY (M/D)	RECHARGE (MM/Y)	EFFECTIVE POROSITY (%)	NOTE
Hydrogeologic mapping							Up and down gradient limits obtained with piezometric map
Uniform Flow	2603	12.5	1.1	75			
Infiltration	2603				254		
HYBRID	2603				254		Up and down gradient limits obtained with piezometric map and total WHPA area using infiltration equation
WhAEM		*[1]		**17**	**3750**[*2]	20	*[1] Base aquifer elevation fixed at 80 m *[2] recharge artificially increased on one side of the model to overcome the limitation that the model cannot accommodate sloping aquifers
MODFLOW-MODPATH	2603	*[3]		**5-35**	**254**	20	*[3] Variable base aquifer elevation obtained with boreholes interpolation



CHAPTER 7

GROUNDWATER AS AN ENERGY SOURCE

By Frederick A. Michel
and Diana M. Allen

Figure 7.1 Nahanni Headwater hot springs (64°C) near Tungsten, N.W.T. discharge from a still warm Cretaceous-age quartz monzonite intrusive.

7.1 INTRODUCTION

Rising energy costs during the past two decades have created an increasing worldwide interest in exploring and developing alternative energy sources. An adequate supply of electricity is critical for everything from of manufacturing to computers, for lighting, and for heating and cooling our buildings. As energy demands continue to climb, much of the focus today has shifted towards using renewable energy sources, such as wind, tidal, solar, hydro, biomass, and geothermal, for electricity production. The Governments of Nova Scotia and Ontario have recently announced major policy changes to significantly increase the percentage of electricity produced by renewable energy.

Surface water, flowing in rivers and lakes, is well known as an energy source. It can be contained behind dams and channeled through turbines to release energy for the generation of hydroelectricity. Groundwater also contains thermal energy, which can be harnessed as a renewable energy source through ever improving technologies. Moreover, groundwater's potential as an energy source is enormous, particularly in comparison to its current usage.

Our Earth is dominated by two sources of thermal energy: radiation from the sun and heat radiation generated within the interior of the planet itself (this latter source is known as geothermal energy, from the Greek "geo" meaning "earth" and "therme" meaning "heat"). Geothermal energy generated within the interior of the planet migrates along a geothermal gradient towards the Earth's surface, where temperatures are lower. Worldwide geothermal gradients average 25°C/km, although they can be considerably higher in tectonically and volcanically active regions, and lower in areas of stable cratons (12°C/km in the Canadian Shield). Distribution of these thermal variations is depicted in the geothermal maps of Canada provided by Grasby et al. (2009).

The migration of geothermal energy is accomplished by conduction through rock and sediment, and by convection of groundwater circulating within the outer crust. Unless the groundwater is fast moving, it remains in thermal equilibrium with the surrounding rocks and sediments through which it flows. Thus, the ground and groundwater usually have the same temperature. However, when groundwater is fast flowing, it may move out of thermal equilibrium with the surrounding geologic environment, and in such cases, we observe several interesting geothermal features. Groundwater that has been heated within the subsurface can discharge at the Earth's surface as thermal springs (warm or hot), geysers, or the fumaroles associated with volcanic activity. Figure 7.1 pictures thermal waters (with mist rising) discharging between boulders at Nahanni Headwater hot springs near Tungsten, N.W.T.

Temperature fluctuations at the Earth's surface influence shallow groundwater temperatures to depths of approximately 10 m (Figure 7.2). During spring and summer, heat from the sun warms the ground surface, and heat energy migrates downward into the ground. This causes the ground to warm, and its temperature increases progressively into the late summer months. During winter, this heat energy flow is reversed, and the ground loses heat, resulting in a cooling of ground temperatures. Thus, shallow subsurface groundwater experiences a range of temperatures on an annual basis.

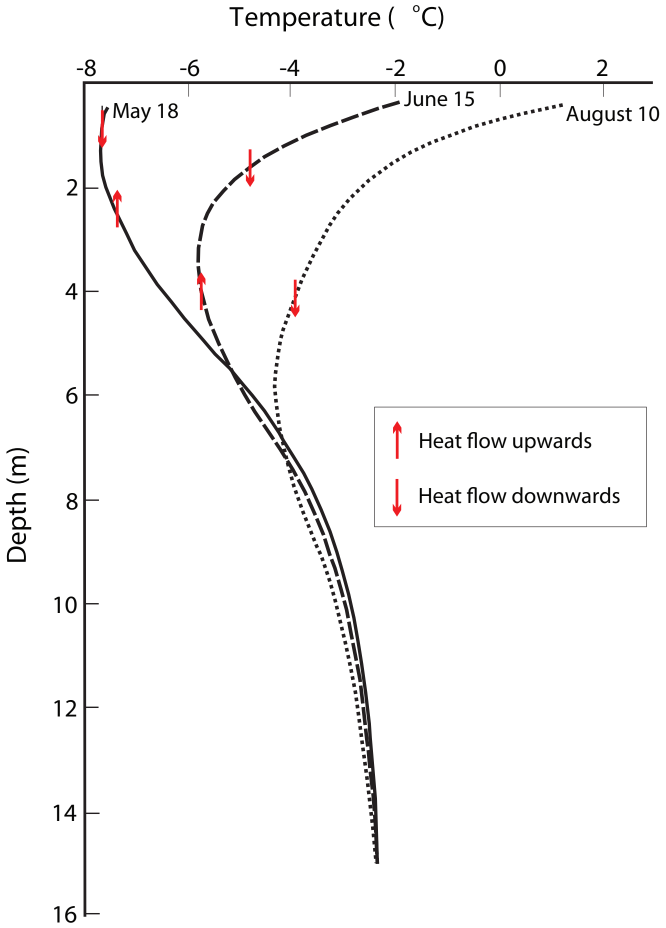


Figure 7.2 Temperature distribution with depth (adapted from Domenico and Schwartz, 1990).

Between depths of 10 m and 20 m, however, ground and groundwater temperatures remain relatively stable year-round. The depth at which this occurs is termed "the maximum depth of annual cyclic variation".

Thermal waters have been defined as those waters with temperatures significantly (> 5°C) above the mean annual air temperature (MAAT) of the local region (White, 1957; van Everdingen, 1972), while "hot" water in the broadest definition has a temperature above that of the human body (37.0°C), although Woodsworth (1997) used 32°C to define "hot springs" in western Canada. Shallow ground and groundwater temperatures in

Canada tend to average nearly 5°C above MAAT, and it may be more appropriate to define "thermal waters" as those with a temperature of at least 5°C above the mean annual ground temperature (MAGT) of a particular area, or as Michel (1977) and Grasby and Hutcheon (2001) suggest, temperatures > 10°C above MAAT. Groundwater with a temperature below this limit would be considered as non-thermal, even though it still contains a certain amount of heat. The relatively low temperature of non-thermal waters might still make them ideal for potential heat/cooling sink applications.

Water's thermal and fluid properties make groundwater an ideal transporter of heat energy within the subsurface, while the rocks and sediments through which the groundwater migrates become the primary heat storage medium. Geothermal resources, and the groundwater associated with the heat flux are considered an important type of renewable energy source because of the constant generation and transport of heat to the Earth's surface. We will focus, in this chapter, on examining the potential to utilize groundwater as a thermal energy source/sink throughout Canada.

7.2 DISTRIBUTION OF THERMAL WATERS

When people think of geothermal water, they often imagine phenomena such as the Old Faithful geyser in Yellowstone National Park, the district heating of buildings in Iceland's capital Reykjavik (meaning Bay of Steam), or the tourist resorts and spas associated with well-known thermal and mineral springs throughout the world. Geothermal waters, however, heated to varying degrees, exist almost everywhere on Earth.

Ground temperatures below the depth of annual cyclic variation rise, in accordance with the local geothermal gradient, as the depth within the Earth

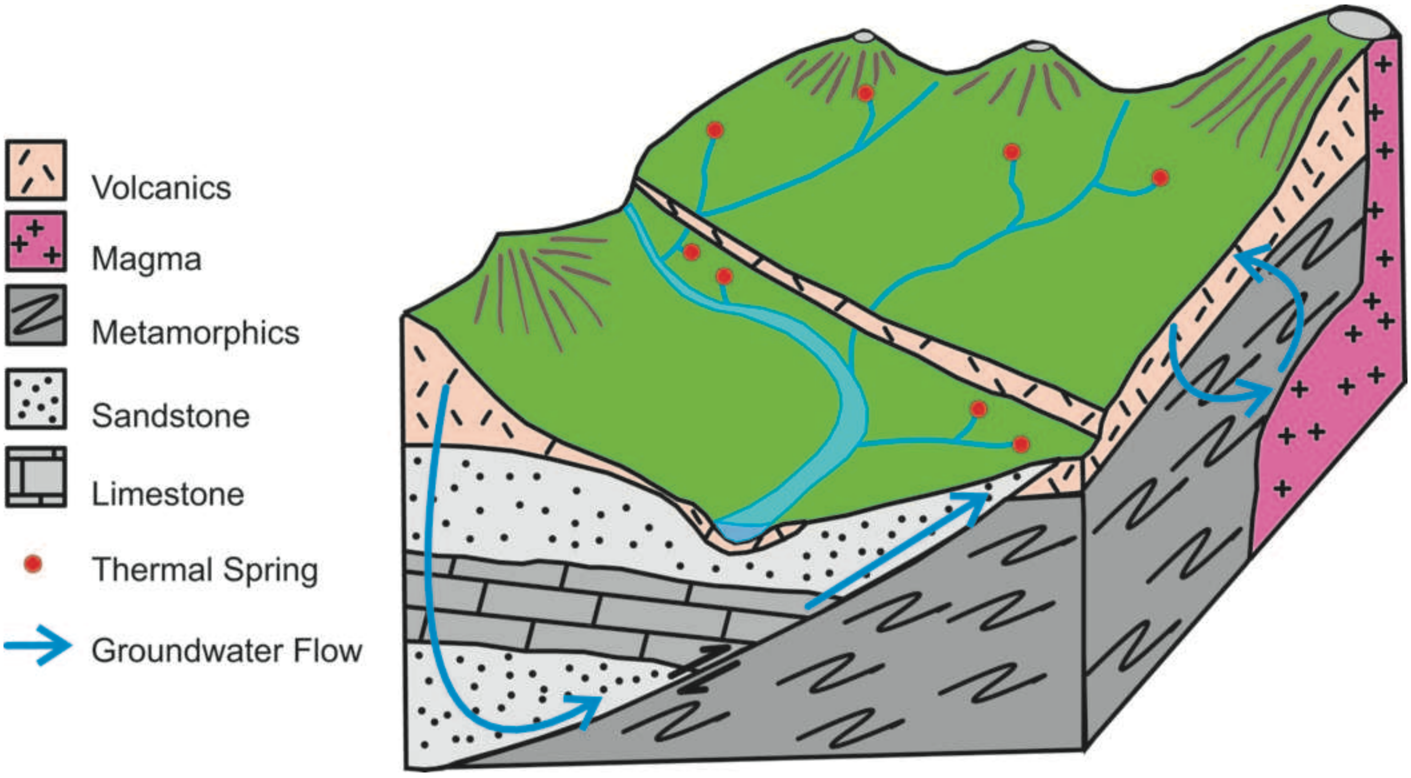


Figure 7.3 Schematic showing thermal springs resulting from deeply circulating groundwater flow discharging along a fault trace and groundwater circulation related to high-level pluton emplacement.

increases. Deep mines often encounter unbearably high rock temperatures at depths exceeding one kilometre, requiring additional ventilation and cooling to allow miners to work with some degree of comfort. Groundwater circulating within the upper 2 to 3 km of the Earth's crust is also heated as it flows through the deeper hotter rocks. The water expands as it is heated, causing a decrease in its density. This heated, lower-density groundwater rises towards the ground surface through fractured or permeable rocks, while colder, denser water migrates deeper: the thermally driven groundwater circulation carries heat towards the ground surface by convection. Depending on the depth of circulation, the local geothermal gradient, and the rate of upward flow once the water is heated, these thermal groundwaters may discharge as warm or hot springs, often along fault lineaments (also see Figure 7.3). Because the groundwater moves quickly up the fault, it falls out of thermal equilibrium with the shallow environment and thus is warm or hot relative to other near-surface groundwater. In those areas where molten magma has risen recently within the crust to form high-level plutons, or erupted onto the surface as volcanoes, the geothermal gradient is very high and groundwater heats up rapidly at relatively shallow depths (Figure 7.3). When the rate of ascent is relatively slow, much of the heat can be dissipated into the rocks through which the groundwater migrates, leaving a cool groundwater discharge. Thermal springs in Canada have been shown to originate as meteoric[1] water (Michel 1977, 1986; Grasby and Hutcheon, 2001; Grasby et al., 2000; Caron et al., 2008) which circulates to depths estimated at 0.2 to 4.8 km.

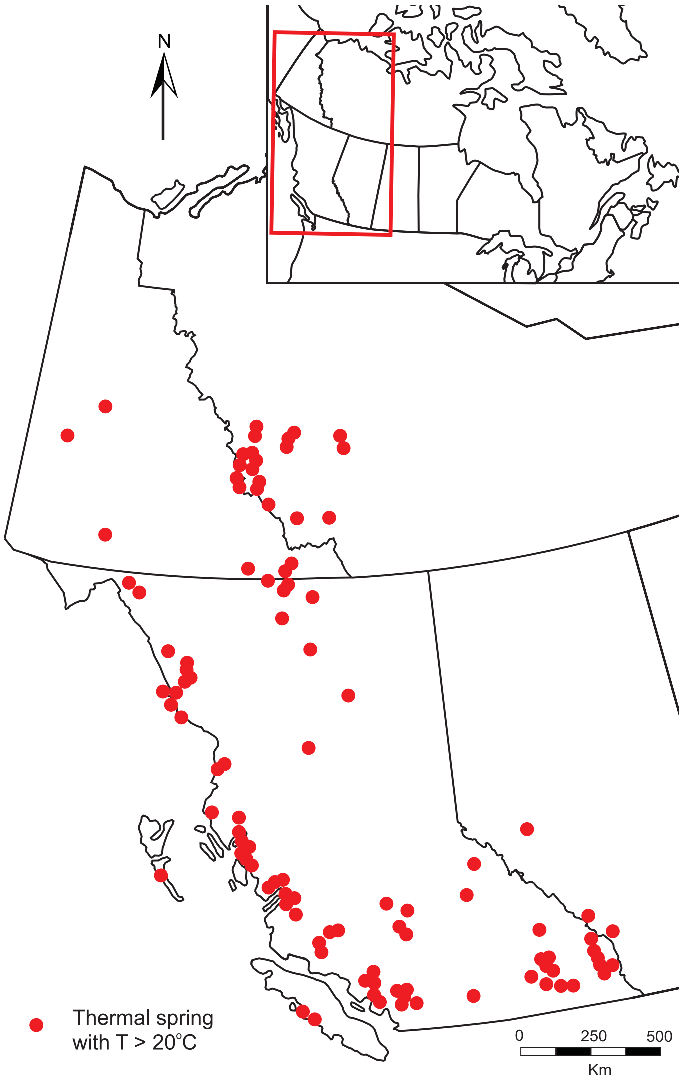


Figure 7.4 Distribution of known thermal springs in Canada with T > 20°C (after McDonald et al., 1978).

Western Canada's Cordillera hosts numerous identified occurrences of thermal springs, wherein water temperatures up to 86°C have been reported (Woodsworth, 1997). (Figure 7.4. See also van Everdingen, 1972, Crandall and Sadlier-Brown, 1977; McDonald et al., 1978; and Woodsworth 1997). Many more thermal springs remain still unidentified. A number of the more accessible springs are enjoyed by hikers, while others (e.g., Banff, Harrison, and Miette) have been developed for tourists, some of whom are attracted by a belief in the therapeutic benefits of these thermal waters. Most spring sites in Canada, however, remain relatively pristine and undeveloped.

The majority of thermal springs in the Canadian

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1. Meteroric water is water that is derived from precipitation.

Cordillera are associated with deep circulation systems within sedimentary rock sequences, with faults providing high permeability conduits which permit the rapid ascent and concentrated discharge of the heated waters. Hot springs near Mount Meager in southern B.C. and Mount Edziza in northern B.C. are associated with recent volcanic complexes active during the past few thousand years, while others, such as those of the Tungsten, N.W.T area, are related to residual heat associated with high-level pluton emplacement during the Cretaceous.

7.3 GEOTHERMAL RESOURCE POTENTIAL

Geothermal resource potential can be divided into three main categories based on the possible application types, which are usually related to subsurface thermal conditions. These three categories are:

1. Electricity generation—with steam turbines where temperatures exceed 150°C, and with binary generation technology where temperatures are > 80°C
2. Direct utilization in space heating or industrial processes where the resource temperature is moderate to high (>60°C)
3. Space heating with or without the aid of heat pumps when the resource temperature is low (<60°C)

British Columbia's Geothermal Resources Act (GRA) defines a geothermal resource, in part, as groundwater with a surface discharge temperature exceeding 80°C. There are only two known spring localities (both in B.C.) that meet this requirement; thus, the GRA is focused on the development of deeper subsurface groundwater reservoirs for high-temperature applications, such as electricity generation. The province of Nova Scotia, on the other hand, has identified several "Geothermal Resource Areas" (as part of the Mineral Resources Act) within sedimentary basins containing flooded former coal mines with groundwater temperatures below 20°C. None of the other provinces or territories formally recognize geothermal resources, although Manitoba is encouraging development of low-temperature resources. Allen et al. (2000) summarized the status of geothermal development in Canada, and Grasby et al. (2011) demonstrated the fact that there is tremendous geothermal energy potential across the country. Future technology developments may also help develop Enhanced Geothermal Systems that could supply a significant amount of Canada's electricity demand (Majorowicz and Grasby, 2010). Additionally, Majorowicz et al. (2009) have described significant shallow heat exchange potential across Canada.

Traditional applications in all three categories have considered only direct utilization of existing geothermal conditions, wherein groundwater at the ambient subsurface temperature is employed as the ground source fluid. Higher temperature groundwater (categories 1 & 2) can be utilized directly for space heating of local buildings and greenhouses, industrial processing, aquaculture, swimming pools and spas. These categories are also an indication of at least localized higher-than-average geothermal gradients that might potentially be tapped as high-temperature energy sources through the drilling of deeper boreholes. For instance, at B.C.'s Mount Meager, recorded bottom-hole temperatures (as high as 270°C) were sufficient to permit the construction of a 20kW test scale geothermal power plant facility designed to generate electricity (Jessop, 1998). Central Alaska's Chena Hot Springs generates electricity utilizing groundwater temperatures as low as 74°C (B. Aho, pers. comm.).

Category 3 usually focuses on shallow boreholes (<200 m deep). These low-temperature resources can incorporate applications for both heating and cooling by employing heat exchangers and heat pumps, where heat energy is either added to or removed from the groundwater during the respective cooling and heating applications. Because of the widespread occurrence of groundwater throughout Canada, the potential for use of groundwater as a low-temperature energy source is similarly widespread.

Higher temperature resources are primarily restricted to the Cordilleran region of the country. Lower temperature groundwaters are more widespread across the entire country, and are still capable of being utilized as energy sources using our current levels of technological development (Grasby et al., 2011).

7.3.1 Direct generation of electricity

Geothermal resources suitable for the generation of electricity require a reservoir capable of providing super-heated hot water and steam at a temperature exceeding 150°C, and preferably above 200°C. The Cordillera Region, as part of the "Rim of Fire", with its young volcanoes and recent high-level pluton emplacement related to ongoing tectonic activity, is the only region in Canada where this very high temperature potential exists.

The primary focus for the development of geothermal electrical generation within Canada has been at Mount Meager, located approximately 170 km north of Vancouver. Mount Meager is the northernmost volcano of the Cascade Mountains and is currently one of only a few Canadian locations leased for geothermal electricity production.

BC Hydro began exploratory surveys at Mount

Meager during the mid 1970s, drilling a total of 18 test holes and 3 deep full-diameter exploratory wells. In 1983, flow from one of the exploratory wells was utilized successfully in the operation of a test 20 kW generator facility, although the facility was subsequently discontinued in 1984 for several reasons, including declining energy prices and infrastructure overcapacity at BC Hydro (Jessop, 1998).

Western GeoPower Corp. undertook additional investigations in 2002 which yielded borehole temperatures of 200°C to 225°C at depths of 600 to 900 m. A follow-up program that included drilling in the period 2004 and 2005 resulted in the company stating in 2007 that the geothermal reservoir covered an area of 4.5 to 7.5 square kilometres and that the reservoir has an average temperature of 220°C to 240°C (maximum of 275°C) at a depth of 1,600 to 1,700 metres, and has a potential development capacity of 100 MW or more. As a result, feasibility for a 100 MW power plant utilizing dual-flash turbine technology with two 55 MW (gross) generating units was explored. Dual-flash turbine technology flashes hot water from the reservoir to steam by suddenly dropping its pressure. The steam is then used to drive a low-pressure turbine. The condensed steam and unflashed water are re-injected to the reservoir for reheating and to maintain reservoir pressure. In 2009, Western GeoPower Corp. was taken over by a U.S. company, Ram Power Corp., and the Mount Meager project has been moved to low priority.

More recently a project examining production of hot water from the Western Canada Sedimentary Basin was proposed to produce electricity for the remote town of Fort Liard, wherein a geothermal system would provide the town's entire electrical needs, removing its reliance on burning imported diesel fuel. The Fort Liard project is being developed by Borealis GeoPower. Discussions began in 2009; an MOU with the town was signed in 2010.

Borealis GeoPower is planning construction of the system during the summer of 2013 with the official start-up set for January 1, 2014. It is expected to generate at least 600 kW of electricity using a binary power plant (Phase 1) to replace the current diesel generators for electricity production. In Phase 2 it will provide up to 6.8 MW of geothermal heating for all 160 homes in the community (1.3 MW) and other commercial uses.

Geothermal potential is also being examined for other remote mine sites in the Yukon, in addition to geothermal leases at Knight Inlet and Canoe Reach in B.C.. At the Chena Hot Springs in central Alaska, two 200 kW Organic Rankine Cycle (ORC) power plant modules, designed and built by United Technologies Corporation (UTC) based on reverse engineering of traditional air conditioning hardware, have produced electricity at less than 20% of the cost for the previous diesel generators (< $0.06/kW). The project has produced a flow rate of 480 gallons per minute (gpm) and flashes a binary fluid (R-134a) to vapour in order to drive the turbine and generate electricity. The binary fluid is recondensed using local cold (4–7°C) groundwater in summer at a rate of 1,500 gpm, and air cooling in winter. The thermal water is re-injected to the subsurface to maintain reservoir pressure. In addition, the geothermal waters are utilized directly for heating of the resort buildings, its swimming pools, and greenhouses, which produce fresh vegetables for the resort (see www.chenahotsprings.com for details).

7.3.2 Moderate- to high-temperature resources

High-heat flow occurs in tectonically active regions, usually related to convergent or divergent plate margins, as evidenced by molten discharges of magma from volcanoes. Upward heat flow, however, occurs everywhere within the Earth's crust. In areas of rapid sediment accumulation, the sediment weight depresses the ground, forming a basin into which sediments continue to be deposited. Deep sedimentary basins have been identified throughout the world as potential targets for exploration of geothermal resources primarily because of the presence of significant quantities of groundwater—a major medium for transferring and transporting heat from rock at depth. Even with an average geothermal gradient of 25°C/km, groundwater at a depth of only 2,000 m will attain a temperature of 50°C. Higher temperatures can be expected when the geothermal gradient is above average, or if one looks to greater depths within the basin. Groundwater that migrates upward, either vertically or toward the basin margins, can carry additional heat closer to the ground surface than would otherwise be expected. Heat can also be trapped in the deeper reservoir rocks when the overlying sediments possess a comparatively low thermal conductivity[2] and are relatively impermeable.

Although the temperature of these deep basin groundwaters can exceed 60°C, they usually do not attain the higher values required for electrical generation. Instead, these moderate- to high-temperature groundwater resources can be utilized for direct heating applications, such as space heating of buildings and greenhouses, industrial processes, drying of agricultural products, aquaculture, and thermal spas and pools. Jessop (1976) described development of 60°C groundwater resources for space heating of apartment buildings in France's Paris Basin. Higher water temperatures provide more heat energy per volume of water extracted a factor that can substantially affect the economics of a project.

From 1976 to 1986, the Earth Physics Branch of Energy, Mines and Resources Canada (now Natural Resources Canada, or NRCan) initiated several investigations across the country to determine the potential for moderate- to high-temperature geothermal resources in deeper sedimentary basins (Figure 7.5). Canada's largest sedimentary basin is the Western Sedimentary Basin of Alberta, Saskatchewan, southwestern Manitoba, northeastern B.C. and southwestern N.W.T., with a maximum depth of nearly 5.4 km. Atlantic Canada's Cumberland Basin, part of a group of Carboniferous basins in the area, contains up to 9 km of sediment. Other smaller Carboniferous sedimentary basins in Nova Scotia and New Brunswick, the Quebec Basin, the Michigan Basin, the Mackenzie Delta–Beaufort Sea Basin, and the Sverdrup Basin in the Arctic Islands have also been investigated. Jessop (1976) provided a preliminary overview of the geothermal potential for all of these basins.

The Western Sedimentary Basin's (WSB) geothermal potential was originally evaluated by Sproule and Angus (1981) for NRCan's Earth Physics Branch: the study involved the compilation of existing data (such as bottom-hole temperatures) from exploratory oil and gas wells drilled throughout the basin. The study paid particular attention to delineating sediment thickness, thermal gradients and bottom-hole temperature distribution, as well as commenting on permeability of potential reservoirs and the geochemistry of groundwater encountered in the formations during drilling.

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[2] Thermal conductivity is a property of a medium (air, water, soil, rock) that describes the medium's ability to conduct heat. For porous media, the bulk thermal conductivity is determined by the thermal conductivities of both the minerals (and organics) along with the fluid (air or water) filling the pore space. Thermal conductivity is analogous to hydraulic conductivity in hydrogeology in that it is the property that governs conduction (heat rather than water). Typical values are: granite (2.5–3.8 W/mK), sandstone (1.5–4.3 W/mK), wet sand (2.5–3.5 W/mK), water (0.598 W/mK at 20°C).

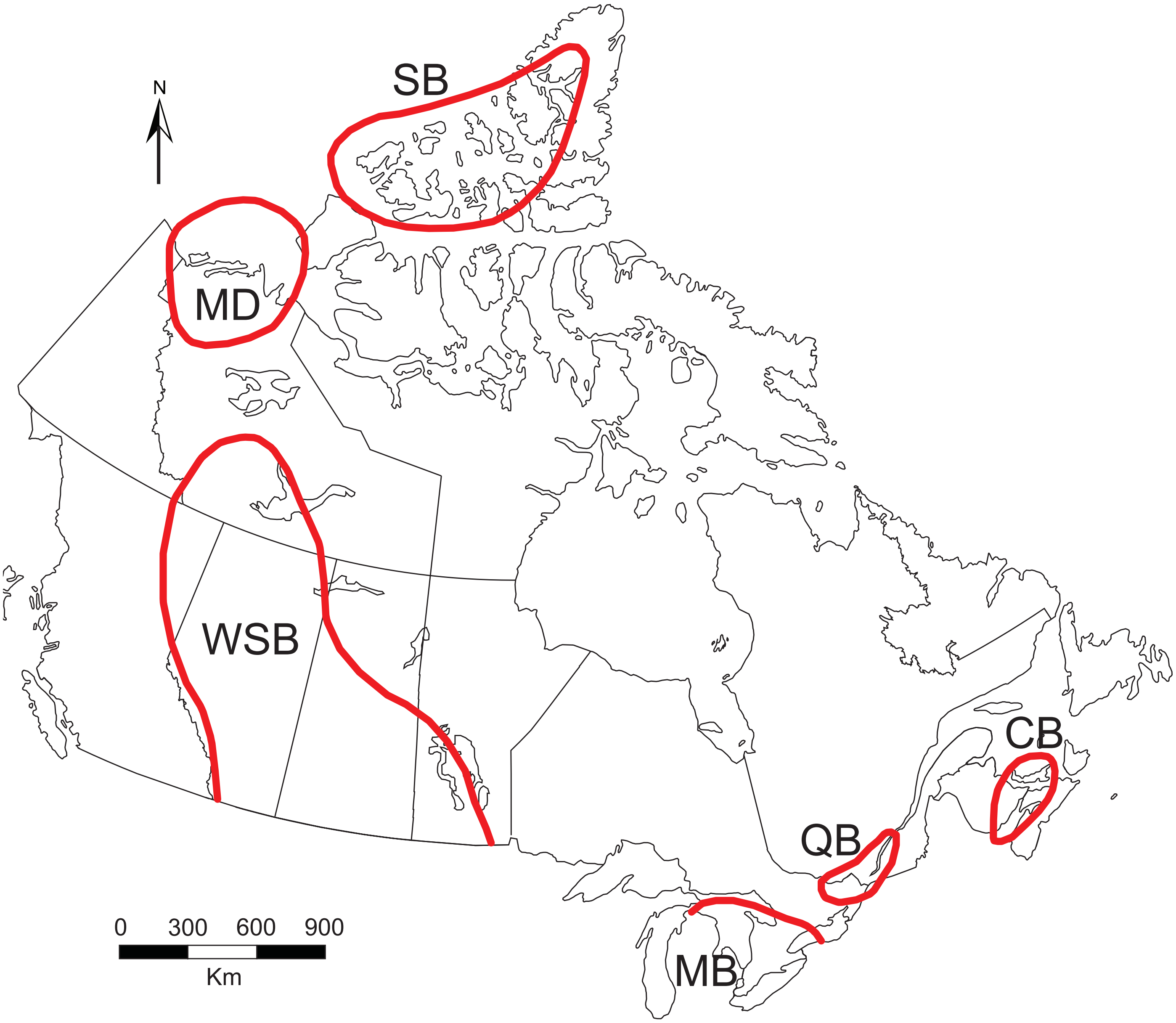


Figure 7.5 Location of major sedimentary basins in Canada discussed by Jessop (1976). Western Sedimentary Basin (WSB), Mackenzie Delta–Beaufort Sea Basin (MD), Sverdrup Basin (SB), Michigan Basin (MB), Quebec Basin (QB), and Cumberland Basin (CB).

The WSB can reach a thickness in excess of 3,000 m in a trough stretching through western Alberta, northeastern B.C. and into the south end of N.W.T. (Figure 7.6). Localized thickening of the sedimentary rocks is also present in southern Saskatchewan. Figure 7.7 depicts the approximate temperature distribution within the basin. The highest temperatures, which exceed 90°C, are found within parts of the trough containing over 3 km of sediments: the highest temperature reported was from a well at the southern end of the Yukon–N.W.T. border, where a bottom-hole temperature of 179°C was measured at a depth of 4419 m (Jessop, 1976). Temperature gradients varied from 20 °C to 50°C per km, and averaged near 30°C/km. Some of the higher gradients were reported from those areas where the basin is less than 2 km deep. The basin east of central Alberta is generally less than 1.5 km thick and temperatures measured below 60°C. In 1983, Acres Consulting Services Ltd. examined the

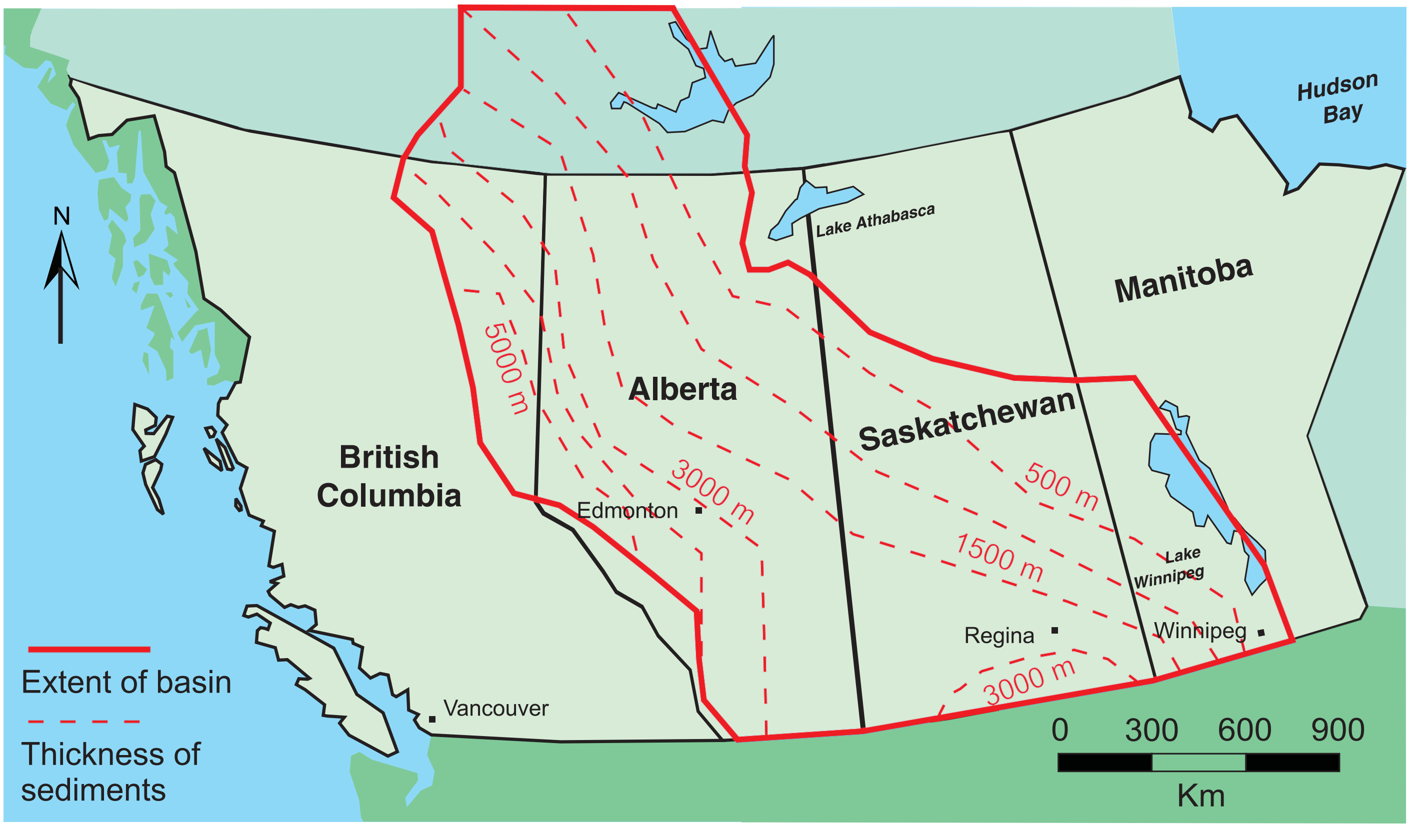


Figure 7.6 Thickness of sediments within the Western Sedimentary Basin overlying Precambrian basement (adapted from Canadian Plains Research Centre Mapping Division, 2008). The western margin of this basin forms a trough with over 3,000 m of sediment.

economic potential for low-temperature geothermal applications for the National Research Council of Canada.

Jessop (1976) reported an elevated geothermal gradient of 30°C/km for both major basins in northern Canada, but since these are not located close to any potential markets they have not received much consideration. Nevertheless, there has been recent interest in the potential to supply electricity to remote northern communities not connected to transmission grids. Additional suggestions for producing electricity from the hot water co-produced from pumping oil and gas wells before being re-injected into the ground are also under discussion.

Geothermal gradients in eastern Canada are consistently low, and average 15°C to 25 °C/km (Jessop 1976; Leslie 1981, 1982; Jessop et al., 1995). A thick sediment accumulation (up to 9 km) and an average geothermal gradient in the Cumberland Basin make this the most likely basin in Atlantic Canada to find moderate- to high-temperature groundwater at depth. Further research is required to identify potentially favorable reservoir formations.

Bottom-hole temperatures do not necessarily correspond to a geological formation which can be considered as a reservoir rock. Only a few stratigraphic formations provide sufficient permeability and storage capacity to be considered as geothermal reservoirs. Drilling represents a significant portion of geothermal system development (capital) costs and, as a result, potential target formations must be well defined early in the evaluation process. Production rates are limited by reservoir permeability, thickness, continuity, and hydraulic pressure, as well as by well design, well diameter, and pump size. Acres Consulting Services Ltd. (1983) estimated that the minimum target flow rate for geothermal systems in the WSB should be

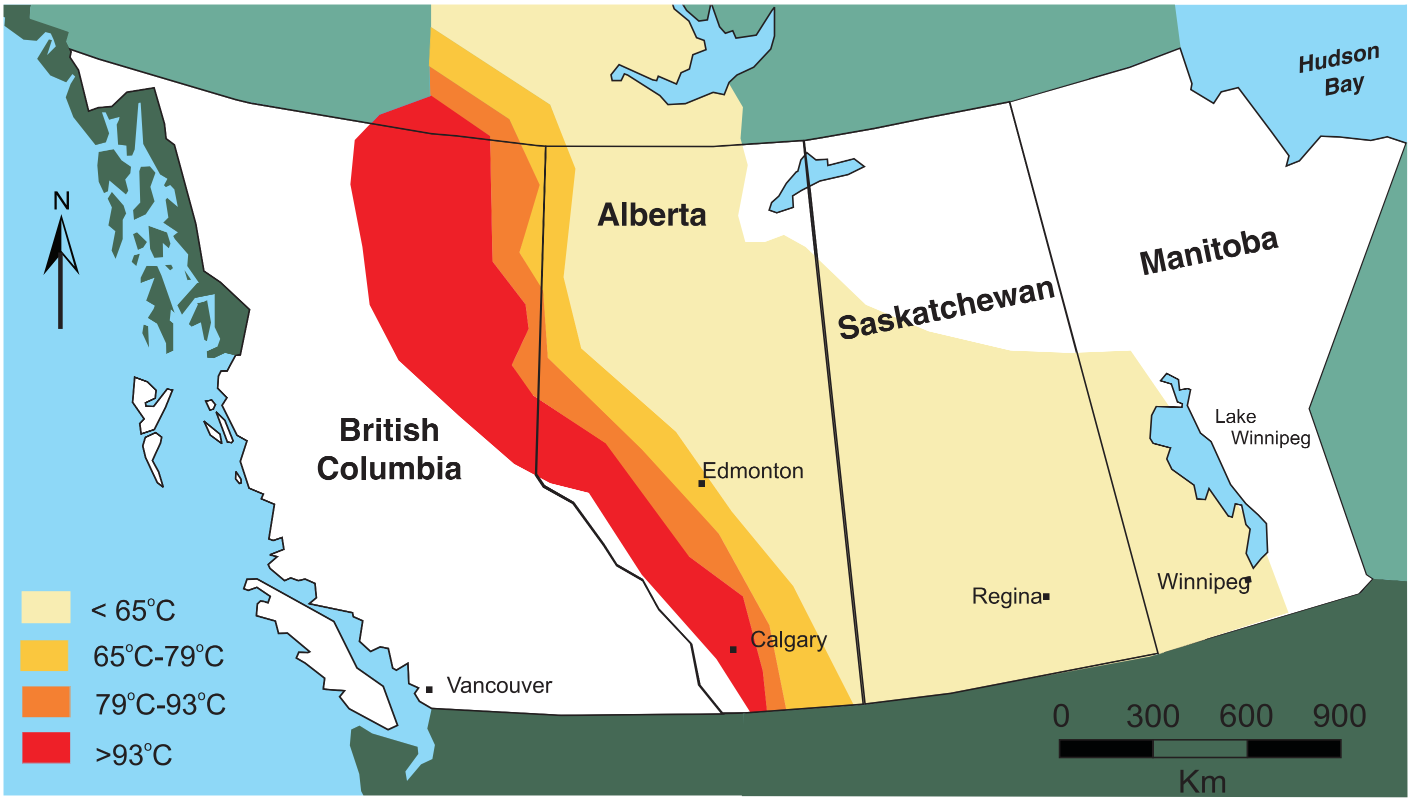


Figure 7.7 Temperature distribution in the Western Sedimentary Basin (from Allen, 2000).

100 m^3/hr. Temperatures must be closely related to potential reservoir formations and their characteristics to develop a proper evaluation for any sedimentary basin.

7.3.3 Low-temperature resources

Much of the worldwide attention for geothermal energy development has traditionally focused on electricity generation and, to a lesser extent, on the potential exploitation of hot water in deep sedimentary basins for direct space heating. In recent years, however, there has been increasing interest in the use of low-temperature resources for heating and direct cooling applications.

Low-temperature geothermal systems, whether used for heating or cooling, or for a combination of both, are known under a variety of names, including ground source heat pump systems, geo-exchange systems, ground-coupled systems, or earth energy systems. Open-loop systems, wherein groundwater is extracted using a water well and used for heating or cooling, are a particular type of low-temperature geothermal system. Closed loop systems, in contrast, involve no direct communication with the groundwater regime: heat exchange occurs through a set of horizontally buried pipes (horizontal loop) or pipe circuits placed in a series of boreholes (vertical loop).

In Canada, low-temperature geothermal resources occur everywhere in the shallow subsurface wherever mean annual ground temperatures are roughly 3°C to 5°C above the mean annual air temperature. Mean annual air temperatures for selected cities across the country are given in Table 7.1, while representative shallow groundwater temperatures across Canada are shown in Figure 7.8. Temperature rises with depth, in accordance with the local geothermal gradient, but is still relatively low even at a depth of a few hundred metres.

Air temperatures fluctuate both daily and seasonally, thus, continuous heating or cooling of buildings is required in order to maintain a constant comfortable room temperature environment. Heating and cooling, which typically accounts for 60% of all energy used for commercial, institutional and residential buildings (NRCan, 2006), represents an important component of the overall energy and greenhouse gas emission picture. Figure 7.9 illustrates the fact that groundwater temperatures remain relatively constant throughout the year, but are generally lower than normal room temperature (20°C). Many low-temperature heating applications employ heat pumps to enhance energy recovery and to make up the difference between ground temperature and room temperature.

Lower ground temperatures also permit direct cooling applications in many instances, thereby considerably lowering electrical consumption compared to standard chillers and air conditioners.

Open-loop geothermal systems extract groundwater from an aquifer using a water well, and pass it across a heat exchanger to allow transfer of energy for direct use in a building's heating/ventilation/air-conditioning (HVAC) system, typically in combination with a heat pump. The majority of open-loop systems dispose of the "used" groundwater either by discharging it to a surface water body or by injecting it back into the aquifer. These types of open-loop systems, known as pump-and-release or pump-and-dump systems, are relatively simple to implement and offer energy efficiencies which

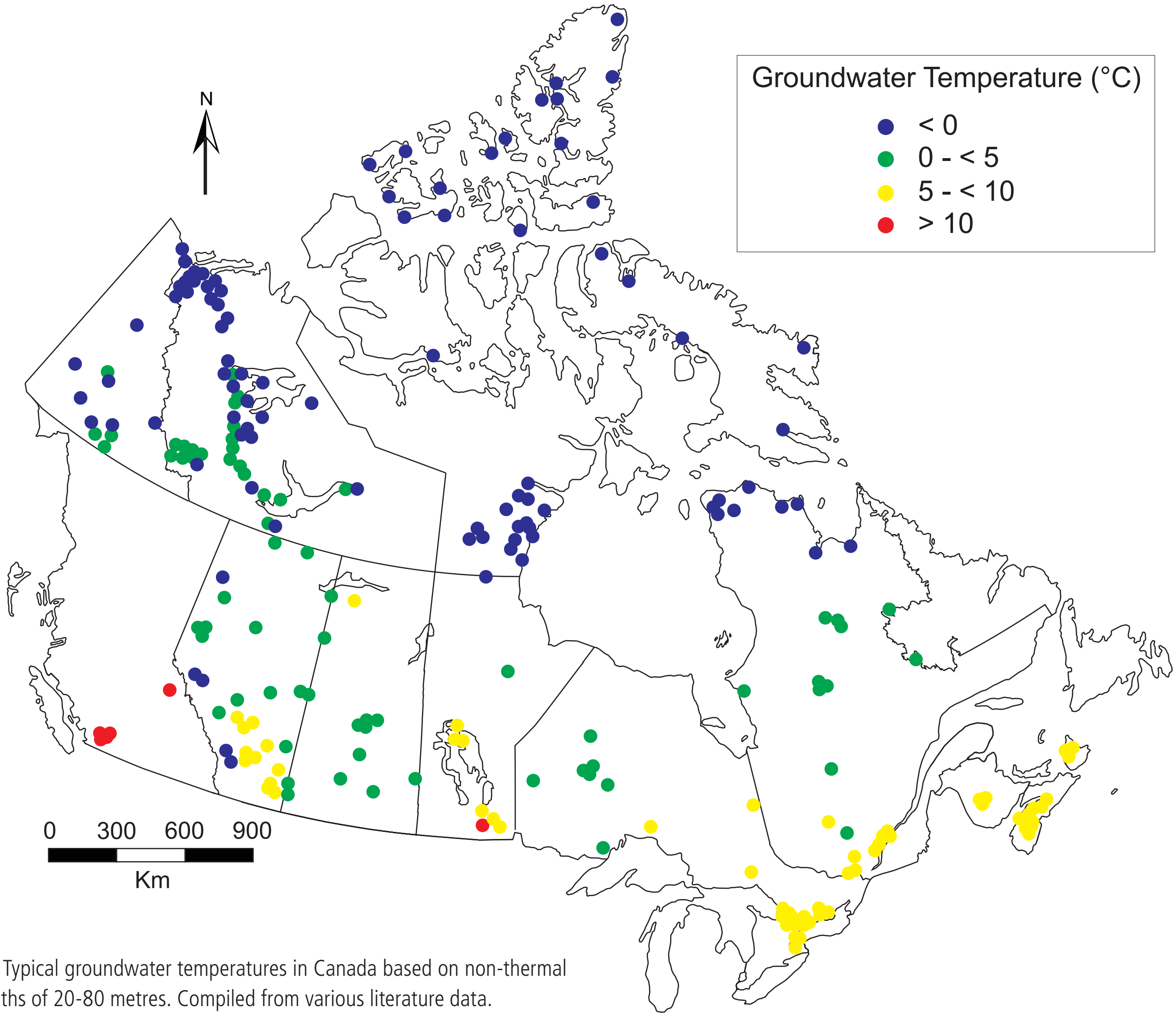


Figure 7.8 Typical groundwater temperatures in Canada based on non-thermal wells at depths of 20-80 metres. Compiled from various literature data.

TABLE 7.1 MEAN ANNUAL AIR TEMPERATURE (MAAT) FOR SELECTED CANADIAN CITIES SHOWING STANDARD DEVIATION. DATA FROM ENVIRONMENT CANADA (2006): 1971–2000 CLIMATE NORMALS

CITY	MAAT (^{o}C)
St. John's	4.7 ± 0.8
Charlottetown	5.3 ± 0.8
Halifax	6.3 ± 0.7
Fredericton	5.3 ± 0.8
Quebec City	4.4 ± 0.9
Montreal	6.2 ± 0.9
Ottawa	6.0 ± 0.8
Toronto	7.5 ± 0.9
Winnipeg	2.6 ± 1.3
Regina	2.8 ± 1.2
Calgary	4.1 ± 1.1
Edmonton	2.4 ±1.2
Vancouver	10.1 ± 0.7
Whitehorse	-0.7± 1.6
Yellowknife	-4.6 ±1.3

are comparable to closed-loop systems, but at substantially reduced capital cost (Rafferty, 2001). Nova Scotia's Acadia University, in Wolfville, currently utilizes an unconfined, unconsolidated sand and gravel aquifer to cool its research greenhouses and the adjacent environmental science building.

Open-loop geothermal systems, however, have a potential for causing environmental degradation due to the long-term warming or cooling of the material surrounding the well(s) which can be coupled with a degradation in system efficiency or system failure due to excessive warming (or cooling) of the aquifer (Bridger and Allen, 2005). This is particularly true in cases where injection of waste heat is not countered by subsequent removal of that heat, a situation which leads to excessive heat build-up. Some areas of an aquifer beneath the City of Winnipeg, for example, have warmed up by several degrees due to continued release of waste heat, largely from industrial cooling applications (Ferguson and Woodbury, 2004; 2005). When waste heat or cold energy is discharged directly into the subsurface (or surface) environment, and is unable to dissipate naturally, open-loop systems may lead to negative environmental impacts.

Depending on system design, the Earth's subsurface can also be considered as a potential store for heat (and cold) energy as discussed in the following section.

7.4 THERMAL ENERGY STORAGE (TES)

The concept of utilizing the Earth's subsurface for energy storage (especially for the purpose of providing space heating/cooling for buildings) means that we need to assess our ability to enhance and upgrade low-grade geothermal resources. A number of underground subsurface techniques utilize the Earth as a warm or cold mass storage medium (Figure 7.10): these forms of thermal mass storage include pit storage, rock-cavern storage, closed-loop pipe, duct or borehole systems in unconsolidated materials or solid rock, and open-loop aquifer or gravel-water pit storage.

Closed-loop systems, including Borehole Thermal Energy Storage (BTES) systems, offer a solid alternative when no suitable aquifers are present on site, or when the cost to determine an aquifer's suitability and the subsequent well drilling exceeds a project's budget.

Open-loop systems, including Aquifer Thermal Energy Storage (ATES) systems, are best suited to those aquifers where in situ permeability provides adequate volumes of groundwater for heat exchange operation. Worldwide use of these various techniques has shown aquifer thermal energy storage (ATES) to be one of the better methods of underground energy storage over longer-time periods (IF Technology, 1995) with respect to the storage volume achievable, the ability to transfer

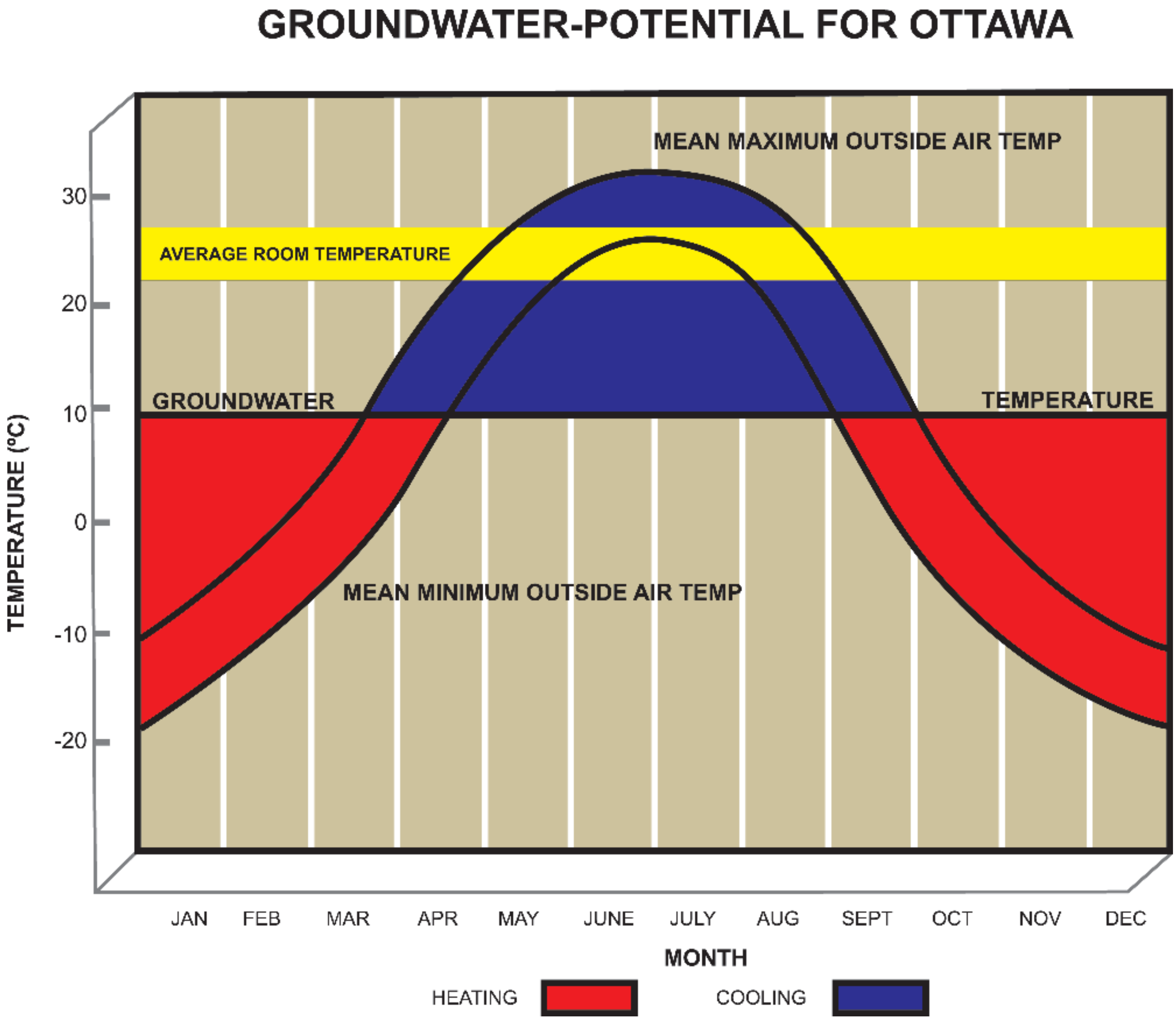


Figure 7.9 Schematic showing heating and cooling seasons superimposed with monthly air temperature range, room temperature and groundwater temperature for Ottawa, Canada.

energy, the temperature range, cost-efficiency and capital cost. Cavern Thermal Energy Storage (CTES) systems, which rely on ambient temperature groundwater stored in large caverns, have been developed at old mine sites in some areas around the world, including Springhill, Nova Scotia. All three approaches (ATES, BTES, and CTES) are being developed and utilized around the world for heating and cooling, in projects ranging from individual homes to large industrial and institutional complexes.

7.4.1 Aquifer Thermal Energy Storage (ATES)

Aquifer Thermal Energy Storage (ATES) open-loop systems offer increased energy efficiency and long-term cost savings over pump-and-dump systems and closed-loop systems because they use an aquifer as the seasonal storage reservoir for waste or excess thermal energy generated in alternate (off-peak) seasons or periods of low demand (i.e., solar energy in summer months, cold air in winter months). During periods of high heating or cooling demand, water is pumped from

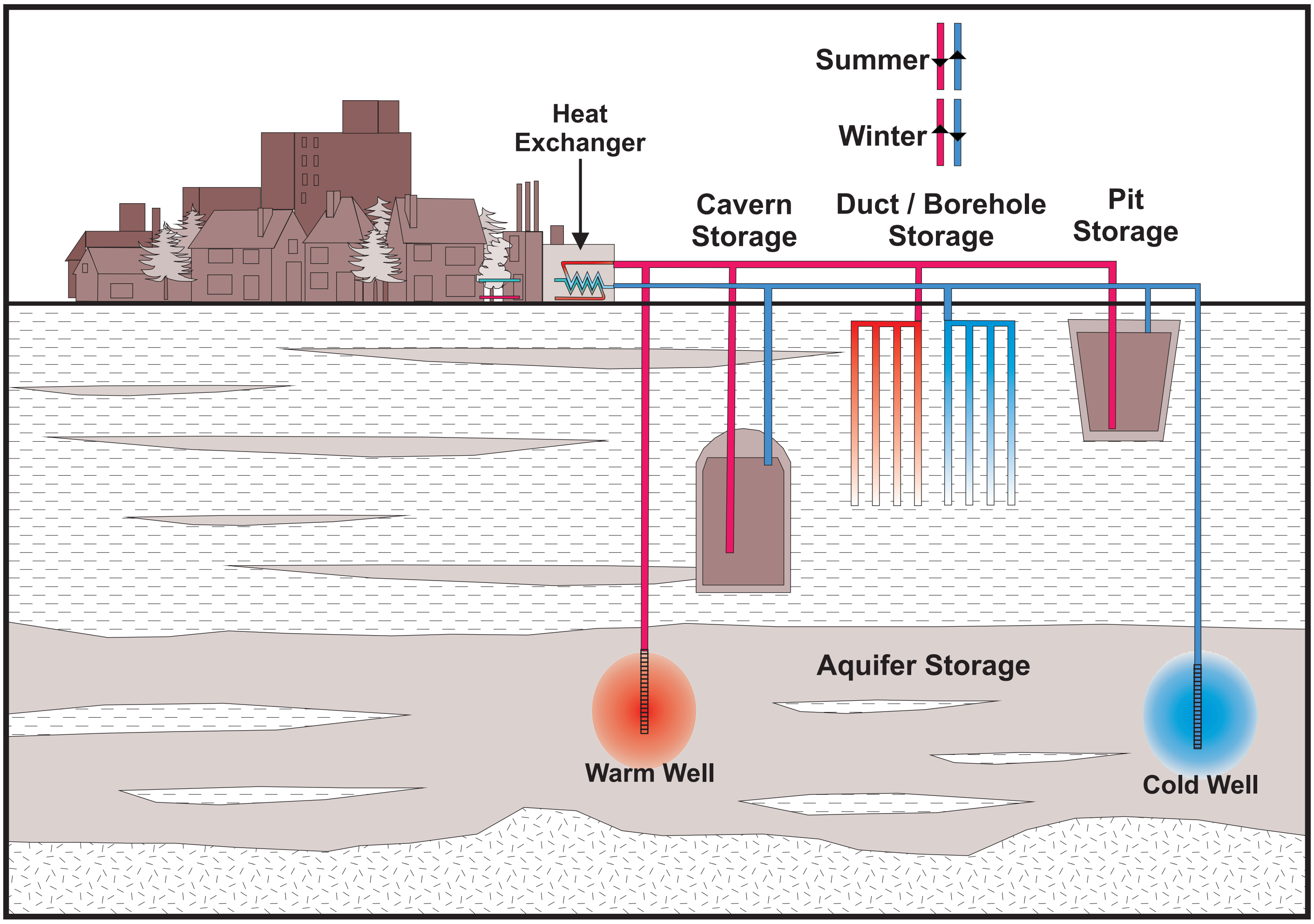


Figure 7.10 Various forms of underground thermal energy storage (adapted from IF Technology, 1995).

the aquifer to be utilized as an energy source or sink. ATES systems operate by transferring waste or excess heat or cold mass to/from groundwater via a heat exchanger. Groundwater injected back into the aquifer is heated (13°C to 120°C) or chilled (6°C to 12°C) (Figure 7.11). This water may retain a temperature higher or lower than the undisturbed ground temperature, depending on the earth's thermal properties within the specific location, and the aquifer's flow characteristics. It is difficult to maintain the thermal stores in high-gradient aquifers, because of the down-gradient drift of the thermal plumes, as illustrated in the shallow, high-gradient aquifer of Figure 7.11. However, plume capture becomes much more efficient when the hydraulic gradient is low, because the thermal plumes do not drift.

Three main ATES system types can be defined on the basis of the energy form being stored: chilled-water systems (normally referred to as cold storage), heat systems, and integrated heat and cold systems.

Cold storage involves the injection, storage and recovery of chilled/or cold water (at temperatures between 6°C and 12°C) in a suitable storage aquifer for periods from several hours to several months. One or more wells are used in this process, depending on energy requirements and the properties of the aquifer. Cold storage applications include air conditioning and equipment cooling (e.g., computers) on institutional (hospitals, universities/colleges, and government

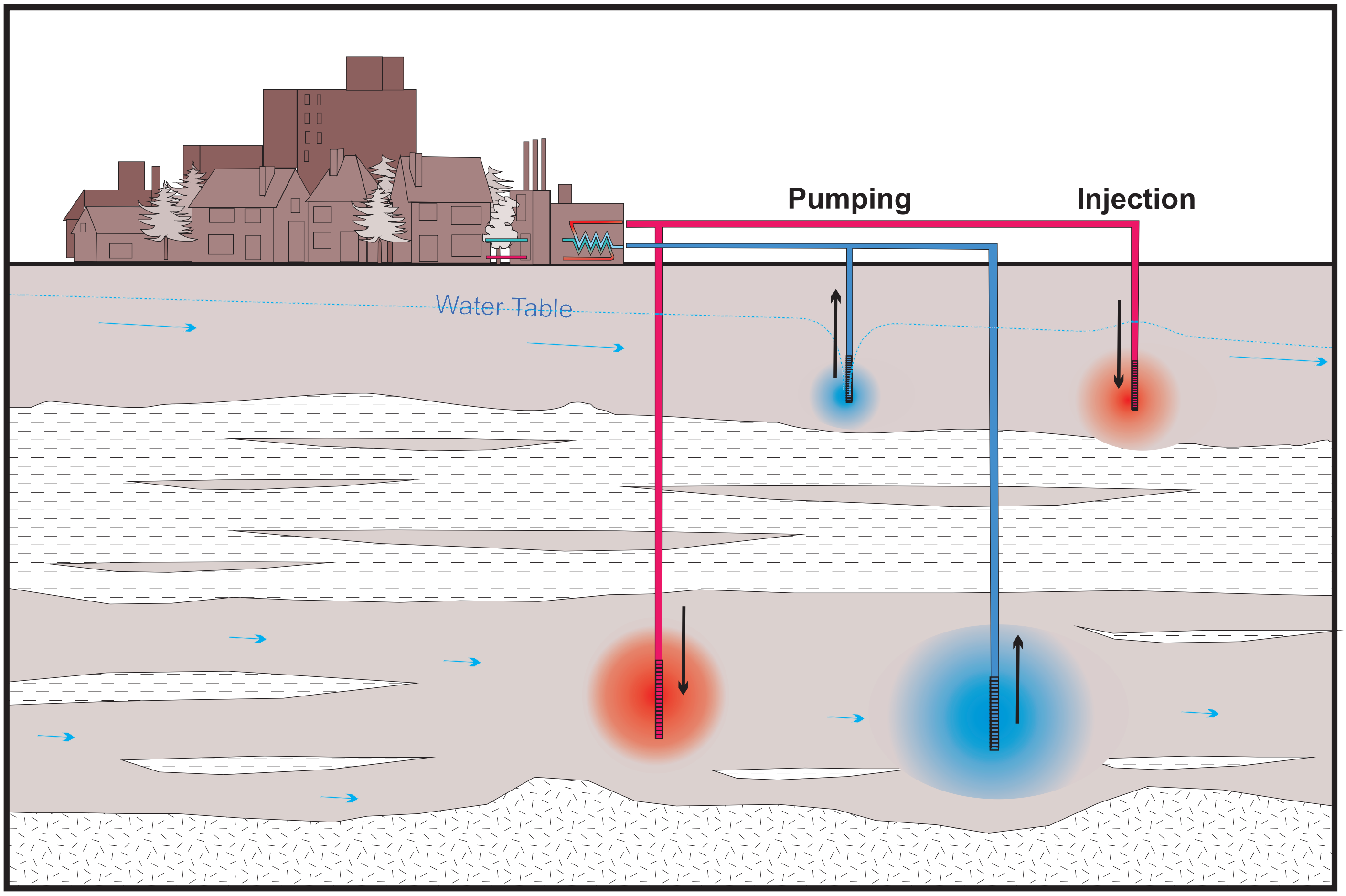


Figure 7.11 Aquifer Thermal Energy Storage (ATES) system illustrating the injection of warm water during the cooling season in a high-gradient (shallow) and a low-gradient deep aquifer. In the high-gradient aquifer, the stored heat and cold energy plumes have drifted down-gradient. In the low-gradient aquifer, the heat and cold energy plumes remain proximal to the storage wells (adapted from IF Technology, 1995).

facilities) campuses and in commercial buildings (office complexes and warehouses), and industrial process cooling (manufacturing facilities). Cold storage systems are best applied in those locations where there is a significant cooling demand for much of the year: there are many cold storage systems in operation today, both in North America and in Europe, particularly in the Netherlands.

Heat storage involves the injection, storage and recovery of heated water into and from a suitable storage aquifer. Heat storage systems are differentiated on the basis of whether they store low- to moderate-temperature heat (10˚C to 40°C) or high-temperature heat (40 ˚C to 150˚C). The components, well configurations, and storage periods of heat storage ATES systems are similar to those of cold-storage systems. Aquifer heat storage is used for space heating, industrial heating, heating for agricultural purposes (e.g., greenhouses), and roadway deicing and/or snowmelting. Convective heat losses (buoyancy effects) are far greater for heat storage than for cold storage, and heat storage efficiency is typically less than that of cold storage, ranging between 50–80% (IF Technology, 1995). Wells for high-temperature heat storage are usually drilled to greater depths in order to counter the effects of higher heat losses resulting from convection currents. This system minimizes losses by using the earth above the storage aquifer as an insulator between the warm aquifer and the cooler ambient air, and through the choice of a storage medium surrounded by warmer materials (due to the geothermal gradient).

Integrated (or combined**) heat and cold ATES systems** offer increased efficiency levels over cold- or heat-only storage systems, particularly for large-scale applications. These systems are usually used in combination with heat pumps to provide heating and cooling in commercial or institutional buildings. Although the components of combined systems are essentially the same as for cold or warm mass storage, the design complexity of above-ground and below-ground components for these integrated systems usually increases dramatically. Well positioning for below-ground components becomes more important because the aquifer is used for both warm and cold mass storage (storage of warm and cold mass results in development of thermal plumes around the wells, thus increased risk of heat transfer between them, see Figure 7.11).

ATES system design ultimately reflects the variability of the local conditions present on-site, and different system configurations exist as a result. The main components of any ATES system include:

- a suitable storage aquifer
- a production well or wells (acting as pumping or injection wells)
- a low-cost or free source, or sink, of thermal energy (such as waste industrial process heat, or solar heat for heating, or cold outside air temperatures for cooling)
- a heat exchanger
- energy demand

Determining the feasibility of an ATES system requires an analysis of an aquifer's suitability to act as a storage medium for warm or cold groundwater. This can be assessed through a characterization of the aquifer's properties. Normally, aquifer characterization for an ATES project entails a detailed assessment of the aquifer's geology, physical properties, flow characteristics, and water chemistry (characteristics which are the same as those assessed for most environmental investigations or water supply studies).

Most thermal storage projects utilize unconsolidated aquifers as storage media although unfractured and highly fractured bedrock aquifers can also be used for thermal energy storage (Allen and Michel, 1997). Mapping of structural features, such as those fractures and faults which strongly influence fluid flow within these aquifers is an important goal for future research.

Bridger and Allen (2005) reviewed basic criteria for the design of ATES systems, with the following results:

First, high hydraulic conductivities are desirable in order for large flow rates of water to be withdrawn or injected from or to the aquifer with the least amount of change to hydraulic and temperature gradients around the production wells.

Second, because water has a higher heat capacity but lower thermal conductivity than rock, the storage of thermal energy in aquifers is best suited to high porosity formations which minimize conductive energy losses and increase the efficiency of the thermal store.

Third, regional groundwater flow is an important consideration in ATES system design as higher groundwater flow regimes may lead to advection or down-gradient "drift" of stored energy beyond potential recovery regions (Midkiff et al., 1992). A lower- permeability storage aquifer is required to minimize convective losses in the presence of a steep regional gradient in hydraulic head, which would correspond to faster groundwater flows. This contrasts, however, with the need for a greater-permeability medium to minimize conductive

transport. Additionally, small-scale vertical and horizontal variations in hydraulic conductivity or heterogeneity within the aquifer (resulting from changes in geology) must be considered as these will affect the thermal plume dispersion (Bridger, 2006).

Several large-scale ATES systems have been installed in Canada. Three of the earliest systems, dating back to the late 1980s, are Carleton University system in Ottawa (Allen and Michel, 1997), the Sussex Hospital in Sussex, N.B. (Cruickshanks and Adsett, 1997), and the Scarborough Centre system (Mirza, 1993).

Carleton University's system became operational in 1990, and operated until 2006. It was to be implemented in phases, which would sequentially bring in line different areas of the campus over a several-year period. Phase 1 (for the residence area) was completed in 1990. A five-well configuration supplied groundwater at a combined rate of 125 L/sec through simultaneous pumping and reinjection. The configuration was designed to be reversed on a seasonal basis, so that winter pumping wells became summer reinjection wells, and vice versa. Well rates ranged from 25 L/sec to 95 L/sec, depending on the individual well productivity. Carleton University took steps during the early 1990s towards further expansion and redesign of the system, as five additional Phase 2 wells were drilled in 1994. Nevertheless, the system continued to be operated only in a small portion of the campus. Disagreements about baseline data used to measure the effectiveness of the new system and length of the payback period caused the project to be officially terminated in 1995, although the small pilot project remained in operation until 2006.

British Columbia implemented a relatively new ATES system at its Agriculture and Agri-Food Canada laboratory facility in Agassiz (Pacific Agri-Food Research Centre, or PARC) (Allen and Bridger, 2003). This system continues to supply both heat and cold energy to a 7,000 m^2 building facility consisting of laboratory, office, industrial, and greenhouse space. In addition to climate control, the ATES system cools several large-growth chambers and freezers. The system's total cooling capacity is about 150 tons: the total heating capacity from the heat pumps is about 1 million btu/hr (1 Mbtu/hr). The building facility has a year-round demand for cooling, and consequently, a load imbalance in favour of cooling. Heating is required from late fall to early spring. The ambient groundwater temperature is roughly 10°C. Agassiz's ATES system was designed with this load imbalance in mind, and consists of four 60 m deep production wells, including two warm wells used to store warm energy (15°C to 16°C), two cold wells used to store cold energy (6°C to 9.5°C), and a dump well that is situated downgradient from the main well field and used as a heat-dissipation well during peak cooling. This system is a hybrid, achieving primary storage through ATES, but with minor pump-and-release capability to handle the annual load imbalance. The estimate of the total water pumped and injected for heating and cooling is around 70 million gallons (265,000 m^3) per year.

More recently, a large-scale $14 million project geo-exchange system has been implemented at the University of British Columbia's Okanagan campus (UBC Reports, 2005). Between 2008 and 2011, an open-loop groundwater system operated for new buildings (Phase 1); however, reliability of the groundwater supply for a larger system delayed the addition of the five original campus buildings (Phase 2). In 2011, the system was converted to a closed-loop campus District Energy System (DES) (Phase 3) with an open-loop geothermal heat exchange system, which provides heating and cooling to ten academic buildings totalling approximately 80,000 m^2. Overall 80% of all the heating and cooling on campus is generated from no to low-carbon emission sources.

7.4.2 Borehole Thermal Energy Storage (BTES)

Borehole thermal energy storage (BTES) systems involve the transfer of thermal energy between a carrier fluid and the subsurface materials into which the boreholes are drilled. Technically, these systems do not concern groundwater because they involve no water exchange. However, both the subsurface geology and groundwater have important implications for the successful storage of heat and cold energy within such systems, and for this reason BTES represents a viable option in aquitards and aquicludes (such as solid unfractured crystalline rock or massive clay).

When no aquifer is present, the Earth's subsurface materials (sediment or rock) form an aquitard through which groundwater movement is very slow and well water yield is minimal. Thermal energy in these settings migrates upward along the geothermal gradient to be transferred by conduction directly via subsurface materials and contained porewater. This subsurface thermal energy is still capable of being exploited through the use of a series of closely spaced closed-loop pipes installed in vertical boreholes or, where space exists, pipes buried as horizontal loops in the shallow subsurface (see Figure 7.10). BTES systems are most effective in such low-permeability geologic units because groundwater flow is low to absent. These types of systems do not involve pumping or reinjection of groundwater, and they operate only through circulation of a carrier fluid within a closed-pipe system, therefore, there is no opportunity to hydraulically control the thermal stores.

BTES systems often require a considerable number of boreholes to achieve sufficient surface area for heat exchange: these systems can be enlarged by the addition of more boreholes to create a store of suitable size for the intended application. Depth, spacing, and design of boreholes are modified according to the thermal properties of local subsurface materials. Thermal energy exchange is by conduction between the subsurface materials and the fluid flowing within the pipes; as a result, it is important to maximize the thermal properties of all backfill material within the boreholes. In those formations with very low permeability, open water-filled boreholes often provide the best thermal connection between the pipes and the surrounding store material. However, since these systems rely on the retention of thermal energy within a relatively confined volume of subsurface material, it is vital to identify and address (seal) any fractures or other similar high-permeability features which might cause fluid excursions. A high-silica clay or clay/cement grout is normally the backfill material of choice when water loss cannot be prevented.

BTES installations require identification of a suitable low-permeability subsurface unit (aquitard). Low-permeability saturated clays, well-compacted glacial tills, or massive poorly fractured bedrock can all be utilized as potential BTES stores. Thus, a thorough understanding of the hydrogeologic characteristics of the subsurface materials is required. National standards for the design and installation of both ATES and BTES systems were approved in 2003 (CSA, 2003). In Ontario, provincial regulations to deal with the proper completion of boreholes associated with BTES projects were implemented in 2012 as a result of drilling into natural gas bearing formations.

BTES installations are becoming more widespread in Canada. The largest system installed to date is at the University of Ontario Institute of Technology (UOIT) / Durham College in Oshawa, where 370 boreholes, 200 m deep, were drilled with a 4.5 m spacing within a current parking lot (Beatty et al., 2006). The subsurface stratigraphy consists of 40 m of silt/clay overburden overlying 14 m of hydraulically tight shale (with a hydraulic conductivity of $K = 10^{-7}$ m/s) and 146 m of massive limestone ($K = 10^{-10}$ m/s). The boreholes were filled with water after installation of the closed-loop tubing was completed.

In Dartmouth, Nova Scotia, there are investigations for a BTES system for a municipal building complex containing offices, library, and recreational facilities on the harbourfront. Temperature of the energy store (in metamorphic rocks) for this application would be lowered to provide additional cooling capacity by charging the store with cold energy from harbour waters during the winter. Buildings for the new Dartmouth campus of the Nova Scotia Community College system are also being designed to utilize BTES for heating and cooling. Extensive instrumentation for monitoring building performance will be incorporated during construction and will also be utilized in instructional coursework.

7.4.3 Cavern Thermal Energy Storage (CTES)

Most subsurface thermal energy storage (TES) applications to date have involved the development of ATES and BTES systems, and both technologies have seen a rapid rise in implementation across the

country over the past several years. However, abandoned mining operations throughout Canada have resulted in the creation of numerous subsurface mine workings that are now flooded with groundwater. Communities located adjacent to these flooded, abandoned mines can benefit from utilizing the groundwater in these subsurface workings for Cavern Thermal Energy Storage (CTES).

The extent and configuration of such workings varies considerably, and some mines extend to depths in excess of one kilometre and contain tens of kilometres of interconnected tunnels (drifts) and stopes at multiple levels. These old workings form large cavernous reservoirs that will fill with groundwater when not continuously pumped. Temperature of this groundwater equilibrates with the surrounding rock, which then represents a potentially large thermal energy resource for the community nearby. Watzlaf and Ackman (2006) reviewed the use of groundwater from old mine workings for the purpose of heating and cooling. Potential utilization of subsurface caverns (mines) as thermal energy stores in Canada was reported by Jessop et al. (1995), Michel et al. (2002), and Grasby et al. (2011).

There are two basic design concepts for seasonal storage of thermal energy in caverns (CTES), either as a single cavern system or as separate hot- (or warm-) and cold-water stores located within different parts of the workings. Theoretically, both hot and cold water could be stored simultaneously in what is known as a stratified layered system (SL system) within large isolated abandoned mine workings, such as salt mines, or deep workings with little perturbation from interconnecting groundwater flowpaths, Hot water in a SL system "floats" above the cold water because of density stratification, similar to lake water in the summer. When there is little or no perturbation of the static condition, this thermal stratification can be maintained over seasonal periods, provided the respective quantities are adequate and the cavern store remains stable. A zone of convection mixing and diffusion will occur at the boundary between the two thermal strata and the cavern depth must be deep enough to accommodate the hot- and cold-water strata, as well as the thickness of the diffuse zone. Because a single large cavern, unless properly designed, would be structurally unstable in most rock types, the store in other mine types normally consists of tunnels on several levels linked vertically by shafts and raises. Boreholes connecting the system to its aboveground infrastructure are completed at different depths for cold and hot water access, in order to minimize thermal convection.

Interconnections between levels in many abandoned mine workings which have subsequently flooded may provide pathways for deeper, geothermally heated waters to migrate upward due to their lower density, and for cooler near-surface waters to sink due to their higher density. The results are the formation of a slowly circulating convection system, similar to water in a pot being heated on a stove. One can expect a certain amount of circulation to develop in deep, well-connected mine workings, whereas isolated shallow workings will contain only cooler near-surface waters. These shallow workings often receive large influxes of snowmelt recharge during the spring, and water temperatures can be close to 0°C. In this situation, groundwater use solely for cooling may be the only consideration.

The second method of cavern thermal energy storage is to capture cold and hot thermal energy in separate water-filled caverns or two isolated sets of abandoned mine workings. Some interconnectivity between stores can be tolerated in such schemes, provided thermal mixing is of limited occurrence. The mine workings employed in this scenario may represent two adjacent mine properties with different owners or a single mine with multiple relatively isolated working levels (such as a coal mine, for instance, where the workings on individual coal seams are separated by barren poorly fractured strata).

Since 1989, Springhill, Nova Scotia has been a world leader in championing the use of groundwater from flooded coal mine workings for heating and cooling of buildings (Jessop et al., 1995). Workings on seven levels were used to extract coal from five seams to depths of 1,300 m between 1868 and 1958. The coal seams subcrop under the western edge of the community and were accessed through stopes running-down dip. Most seams were mined independently with limited connection between seams. Since 1958 the workings have been allowed to flood with groundwater. Jessop et al. (1995) estimated the total volume of groundwater in the mine workings to be approximately 4,000,000 m^3, but a more recent detailed Geographic Information System (GIS) study of mine documents by Herteis (2006) estimated that the No. 2 seam alone contains 5,500,000 m^3 of water. Groundwater temperatures measured at the time of well drilling, and/or testing in the late 1980s and early 1990s, ranged from 9°C to 19°C, averaging 15°C. The western edge of Springhill is an industrial park and most of the current eight users of this system are located in or adjacent to the park.

Jessop et al. (1995) presented data for the original user's first year of system operation from 1989 to 1990 which indicated that the company (a plastics manufacturer) calculated a net energy savings of $160,000 per year and a 50% reduction in CO_2 emissions, relative to the pre-geothermal system. The payback period for the extra capital cost was less than one year. In 2004, a new community centre and arena complex was opened, with mine water providing heating and cooling for the building and the chilling requirements for the arena ice.

Although the total volume of groundwater associated with flooded abandoned mines appears to be immense, the high degree of hydraulic connectivity associated with mine workings requires that the placement of wells be such that interference effects are minimized. This is especially critical when adjacent wells are operating at significantly different temperatures. For large multi-user systems, such as the industrial park in Springhill, it is important to co-ordinate the design, implementation, and usage of all operators in order to avoid problems. Another issue that must be considered over time for abandoned mines is the potential for roof collapse of near-surface workings. It is important to identify these possible hazards early so that buildings and equipment are located on solid ground.

7.4.4 Other considerations

In all of these systems, heat or cold energy is stored in the subsurface. The source of this thermal energy is irrelevant. Solar (heat) energy, for instance, can be transferred to the subsurface for daily or seasonal recovery at a later date. Likewise, cold energy (low temperature) from melting snow in snow dumps can be transferred to the subsurface to create a cold store which can be utilized, when required, for air conditioning. TES system design should be flexible and adapted for local conditions.

One of the key considerations for maximizing the storage potential in any of these types of systems is the efficient balancing of heating and cooling loads. Canadians require both heating and cooling, but often, there is an imbalance in this need. Typically, heating carries the heavier load, particularly for residential units: this creates an excess of cold energy that must somehow be dissipated. Industrial processes and locations where there are significant computing facilities require heavier cooling loads. From an environmental perspective, addition of cold water to the Earth's subsurface environment may not pose as significant a threat as the addition of warm water; however, future research is needed to determine the potential environmental side effects of geothermal development, particularly where there are substantial load imbalances or where cooling-only or heating-only systems are operational.

Another consideration is the potential for adverse effects on aquatic environments, particularly where geothermal waters are directed into surface water systems or where groundwater discharges into streams, lakes, and wetlands. While geothermal technology has significant advantages over other forms of conventional and green energy technologies, there remains the need to exercise caution.

Thermal regimes require information on water temperature, knowledge of the geothermal gradient, and thermal conductivity of subsurface materials. It is important in any system to understand how heat will circulate or dissipate in the subsurface, especially when storage is considered as part of the design. Subsurface materials with high thermal conductivities may enhance storage by readily transferring some heat from water to rock, where it is stored locally rather than being transported further away. When significant water flow is expected, heat will be carried by the water and will affect the thermal distribution. Upward groundwater flow in an area will transport relatively high temperatures to surface, as is the case with many of the world's hot springs. Water flow within boreholes, from one depth interval to another, can also generate false thermal gradients which must be identified during the developmental investigative stage in order to provide for proper evaluation of the resource potential and proper system design. Interference between geothermal systems has not yet become a serious issue here in Canada, but in Malmo, Sweden, there have been reported instances of losses in efficiency of ATES systems due to interference between adjacent landowners. Parts of Winnipeg have experienced subsurface warming on account of the extensive use of groundwater for industrial cooling (Ferguson and Woodbury, 2004), but to date has not resulted in interference.

Multiple aquifer strata in the Netherlands allow the Dutch to specify aquifer usage (groundwater withdrawal or recharge) by temperature.

Chemically, thermal groundwaters can dissolve relatively high concentrations of elements from the rocks through which they migrate: eventually these groundwaters will become high salinity brines when they remain in the subsurface for long periods of time. These groundwaters are also excellent and efficient scavengers of metals, and play an important role in the formation of many types of mineral deposits. We must evaluate and understand the chemical composition of any groundwater in the context of its potential utilization as an energy source. Groundwater chemistry is of interest when evaluating corrosion or scaling issues related to equipment and infrastructure and the quality of water supplyto other users (particularly if there is potential for quality deterioration as a result of mixing with poor quality water, a situation which is often encountered in coastal areas where saltwater intrusion occurs when an aquifer located in close proximity to the ocean is over pumped). Dissolved metals, such as iron and manganese, will come out of solution and precipitate as oxides when oxygen is present, leading to well screen clogging and scaling on heat exchangers. Biofouling of well screens can be particularly problematic in low-temperature geothermal systems, particularly where manganese and iron are present at moderate to high concentrations in the natural aquifer. Biofouling gradually reduces the efficiency of pumping through progressive buildup of slime on the well screen. However, biofouling is not restricted to geothermal systems; it is a pervasive problem in many pumping systems. Treatment technologies continue to improve.

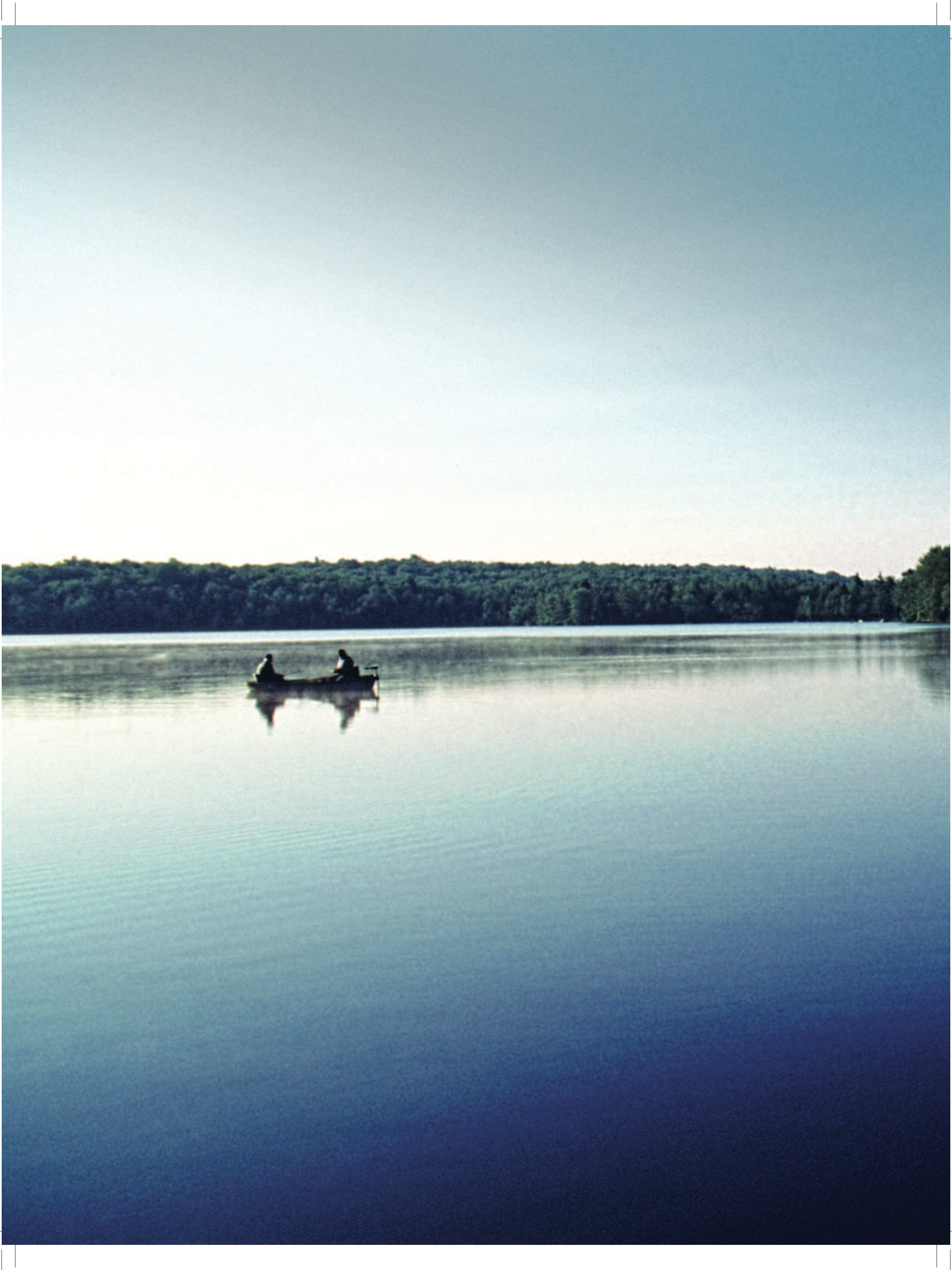
7.5 CONCLUSIONS

The Earth is a major thermal energy store and geothermal represents a large, relatively undeveloped, and renewable thermal energy source. Groundwater is the dominant medium for convective transport of heat in the upper 3 to 5 km of the Earth's crust. Groundwater is generally in thermal equilibrium with the rocks and sediments through which it flows; however, where rapid upward migration occurs, groundwater can discharge at surface as warm or hot springs, geysers, or volcanic fumaroles, with temperatures well above ambient.

Groundwater with temperatures exceeding 150°C has traditionally been targeted for the generation of electricity, although recent technology now makes it possible to lower the minimum temperature to about 75°C. Moderate- to high-temperature groundwater resources (>60°C), associated with regions of high heat flow or deep sedimentary basins, can be utilized directly for space heating and industrial processes. Depending on the groundwater temperature and the potential application, lower temperature resources (<60°C) can be employed for space heating with or without the aid of heat pumps.

Low-temperature resources (5°C to 15°C) associated with productive aquifers or abandoned mine workings can be utilized directly with heat pumps, or enhanced through subsurface thermal energy storage (TES), to provide heating and cooling (thermal energy sink) for buildings. Likewise, poorly conductive aquitards and aquicludes are ideal for TES applications with the use of horizontal or vertical closed-loop Earth energy systems. The advantages of the low-temperature aquifer and non-aquifer systems are that they are very adaptable, they can act as a heat source or heat sink, and at least one type of hydrogeological unit (aquifer, aquitard, or aquiclude) can be found at any site.

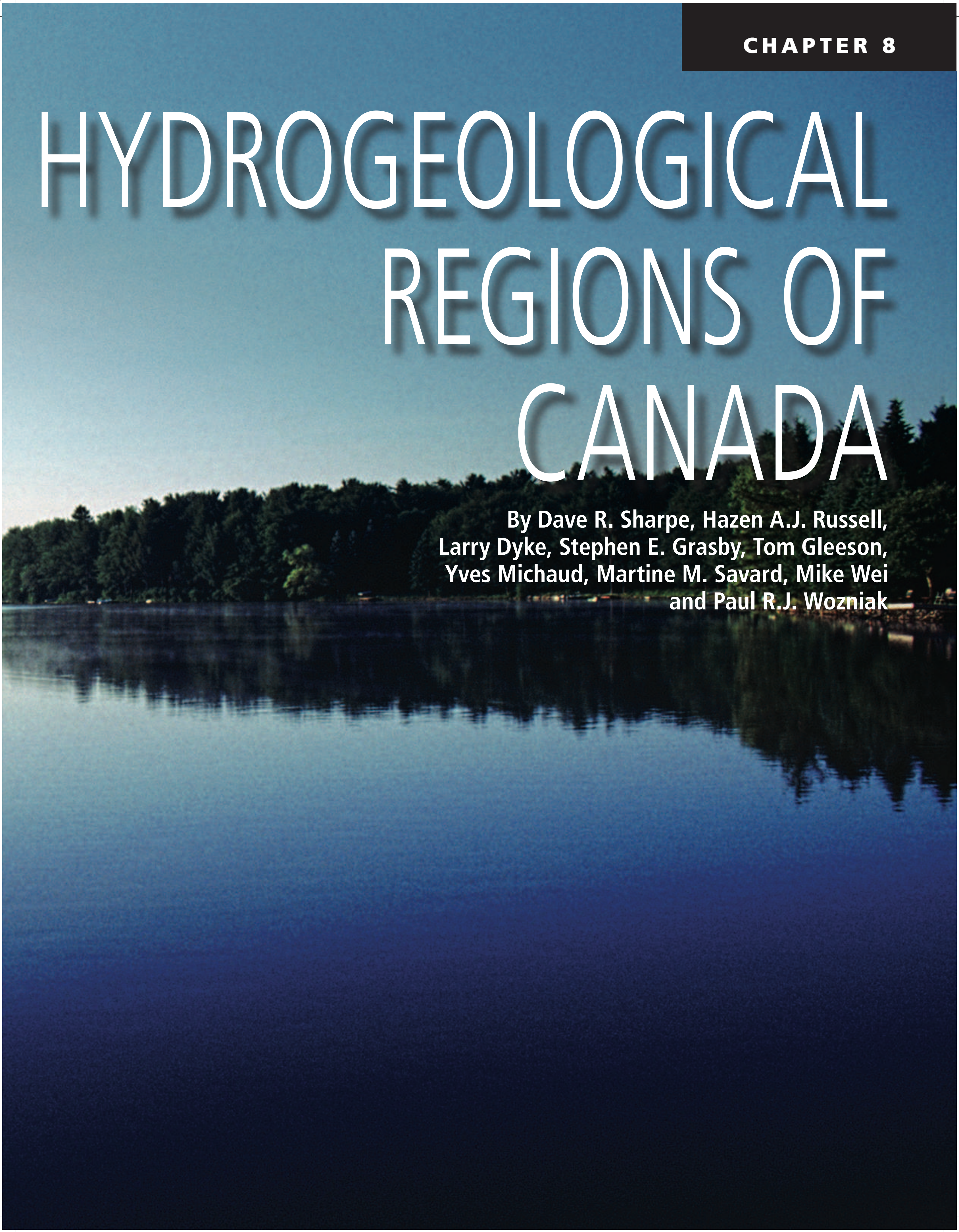
PART IV: OVERVIEWS OF HYDROGEOLOGICAL REGIONS



CHAPTER 8

HYDROGEOLOGICAL REGIONS OF CANADA

By Dave R. Sharpe, Hazen A.J. Russell, Larry Dyke, Stephen E. Grasby, Tom Gleeson, Yves Michaud, Martine M. Savard, Mike Wei and Paul R.J. Wozniak



8.1 INTRODUCTION

Groundwater is important to economic development, ecosystems, and the well-being of Canadians. About one-third of Canadians and close to 80% of the country's rural population relies on groundwater. Groundwater has been routinely surveyed since early 19th century, but has only been mapped at national/regional scales to a limited extent (Brown, 1967). Our understanding of the resource at a national level is hampered by the vast geologic, physiographic, and climatic differences of this country. Current federal-provincial groundwater initiatives are seeking to establish a framework for understanding national, regional, and watershed-scale groundwater resources, and to assist in understanding the range of issues and differences in Canada's hydrogeological systems. Nationally, the country has been divided into nine hydrogeological regions. Each region possesses broadly distinguishable characteristics related to geology, physiography, and climate (e.g., water balance) at the scale of ~1:5,000,000 (Figure 8.1). Although physical features within each of these locations may be comparable, climate variation within each plays a key role in determining water availability. These identified regions provide a physiographic context for the public discourse of groundwater/surface water systems, in addition to outlining a framework for understanding broad controls on water occurrence, availability, flow, and overall groundwater accessibility.

This chapter presents i) a synoptic context for groundwater issues in Canada by developing an improved subdivision of hydrogeological regions; ii) a framework for understanding major differences in groundwater systems using a national-scale map of our nine hydrogeological regions, summary text and conceptual figures; iii) and a vehicle for communication of regional groundwater information related to groundwater usage/sustainability.

8.1.1 Previous work and principal concepts

Brown (1967) presented the most recent work on delineation of groundwater regions in Canada. His counterpart for the United States and North America is Heath (1982, 1984, 1988). Heath provided a detailed description of how hydrogeological regions are defined using five groundwater system features:

i) Geological framework
ii) Nature of the water-bearing openings
iii) Composition of the rock matrix
iv) Storage and transmission characteristics
v) Recharge and discharge conditions

Using this scheme, the United States has been divided into 15 regions and North America into 28 regions (Heath, 1982, 1988). These divisions help guide this discussion.

8.2 DEFINITION OF HYDROGEOLOGICAL REGIONS

Canada's nine hydrogeological regions are defined and described using several regional characteristics. These include formation geometry, architecture, and composition, which are then summarized with conceptual regional block diagrams. The delineation of hydrogeological regions is based on major geological provinces and rock formations (Table 8.1). Fundamental water-bearing openings and rock matrix properties help determine the quantity (storage), flux (transmission), and composition (quality) of formation waters. These same properties, and any overlying sediment cover (Fulton, 1995) not depicted on the map (Figure 8.1), affect recharge and discharge rates. Key features identified by Heath (1982) can be correlated within and across regions with a variety of proxy data.

i) *Geology* addresses control of groundwater quality, water-storage characteristics (i.e., porosity) and water-transmitting characteristics (i.e., pores, fractures or cavernous openings)

ii) *Topography* provides elevation differences that establish hydraulic gradients for regional, intermediate, and local flow systems

iii) *Moisture surplus* charts climate characteristics resulting in regional moisture surpluses or deficits as assessed by a simple water budget or by average total annual runoff (discharge); moisture surplus can also be expressed as the inflection point in an annual groundwater hydrograph

iv) *Frozen ground* or permafrost defines those areas where temperatures in rock or soil remain at or below 0°C through the summer

Six of the nine regions in our discussions here (Sharpe et al., 2008) are similar to the regions identified by Brown (1967) and Heath (1988). Significant differences relate to recognizing the hydrogeological importance of sedimentary basins and basin analysis principles (Sharpe et al.,

Figure 8.1 Hydrogeological regions.
Map of nine colour-coded hydrogeological regions, identified by major geological domains, draped on a digital elevation model of Canada (see relief features). Moisture deficit or surplus is indicated by generalized dry (red) and moist climate regions (green) in inset map.

2008). Hence, the Maritime sedimentary basin is acknowledged as a distinct hydrogeological terrain from the Appalachians, and the Southern Ontario and Hudson Bay Lowlands defined as elements distinct from the St. Lawrence Lowlands despite some geological affinities. Population base and the range of hydrogeological issues present in the area particularly warranted the inclusion of the Southern Ontario Region as a distinct entity in our discussions.

8.2.1 The hydrogeological regions map as a framework for analysis

Digital coverage of these hydrogeological regions, such as geology, topography, moisture regimes, and frozen ground (Sharpe et al., 2008) can be combined with other data in Geographic Information System (GIS) to provide a framework for analysis of the entire Canadian landscape (see National Atlas of Canada). Five principal GIS layers were used to develop regional boundaries; these consisted of

Figure 8.2 Canada's land cover.

This map shows a simplified distribution of the main land cover types across the country as interpreted from 1995 satellite data. Land cover primarily represents vegetation patterns across the country; these have an important influence on the water cycle, particularly with respect to precipitation and evapotranspiration. The map complements Figure 8.1 as it illustrates important patterns: tundra vegetation (light green) is linked to permafrost; prairie cropland cover (yellow) is linked to moisture stress in the Plains Region (prairies); mixed vegetation cover (brown) helps define the Southern Ontario and St. Lawrence Lowland Regions; forests and large lakes mark the Canadian Shield. The land cover map used NOAA AVHRR 1-km data from 1995; Canada Centre for Remote Sensing, Natural Resources Canada.

three geology maps (Wheeler et al., 1997; Stockwell, 1970; Mossop et al., 2004), a permafrost map (Natural Resources Canada, 1995), and a digital elevation model for topography (Natural Resources Canada, 2000a). Moisture surplus and deficit were derived from the National Atlas of Canada using Thornwaite estimates of evapotranspiration. A national land cover map from the National Atlas illustrates the movement of water on the land surface and a link to regional climate.

8.2.1.1 Land cover

Canada's land cover (Figure 8.2), interpreted from 1995 satellite data, is largely represented by vegetation patterns across the country; these have an important influence on the water cycle. Vegetation and its distribution have significant impact on evapotranspiration and the amount and means by which water leaves a watershed. Evapotranspiration is the sum of evaporation and transpiration, both of which are affected by land cover types. Plants, such as broadleaf trees, with larger surface areas, intercept precipitation, and the moisture usually evaporates rather than infiltrating the soil. Areas where water does infiltrate the soil, that is areas where plants have active, deep-root systems, experience greater transpiration.

Precipitation and temperature are key determinants of long-term patterns of vegetation land cover across Canada. The transition from evergreen to mixed, to broadleaf forest common to the Shield Region for example, relates to the precipitation-temperature gradient across this geological region, and not to geological variation. This map also illustrates the major surface water cover as lakes, or water storage as ice and perennial snow banks (Figure 8.2).

A land cover map adds hydrogeological understanding to the broad geologically based hydrogeological regions (Figure 8.1), and illustrates the role of cross-country climate, through vegetation patterns, to geological and topographical variations highlighted on the hydrogeological regions map. Recharge within any geological basin is a function of precipitation, geology (soil and rock permeability), absorption of water in the soil by plant roots, and evapotranspiration. As such, land cover data (Figure 8.2) can be useful for national, provincial, and local water resource inventory, and water supply planning, as well as other hydrogeological analysis.

8.2.1.2 Evapotranspiration

The GIS framework of the hydrogeological regions map aids countrywide analysis and comparisons. Because evapotranspiration is difficult to estimate on land (Fernandes et al., 2007), a map of mean annual discharge, or total runoff, helps depict regional comparisons of water availability to the land surface (Figure 8.3a). Mean annual stream discharge, for example, is highly variable in the Cordillera where climate and diverse topography change quickly over short distances (Figure 8.3a). Discharge in the Prairies is low because of low precipitation and high evapotranspiration fluxes; Maritime and Appalachian Regions show mainly high to intermediate discharges due to high precipitation input. Other regions either evidence variation due to more local terrain conditions, or are poorly gauged. Here we have examples of mapping resolution drawbacks when charting broad hydrogeological regions with available data, and of scaling difficulties from subregion to regions.

8.2.1.3 Baseflow and groundwater storage

The primary controls on groundwater regimes

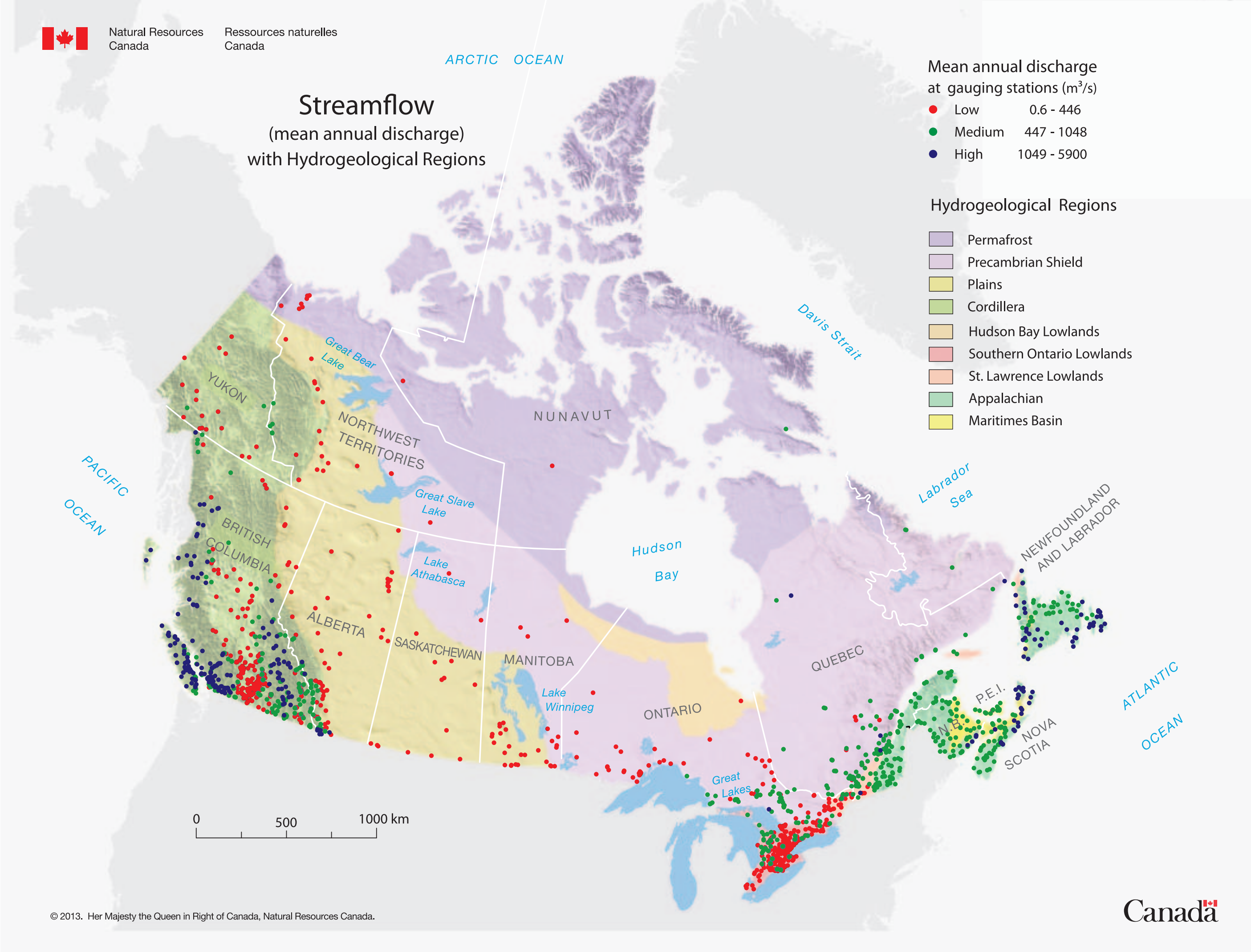


Figure 8.3a Mean annual discharge.
This map of mean annual streamflow discharge (m³/s), or total streamflow runoff, which is limited by sparse stream gauge coverage (6,049 small coloured dots shown in aggregated form). In some regions, depicts regional comparisons of water availability to land surfaces. The hydrogeological region boundaries provide the background.

(climate, topography, and geology) are integrated by baseflow, wherever it represents groundwater discharge; baseflow provides an awareness of the shallow groundwater storage and flow systems across Canada where stream gauging occurs (Figure 8.3b), although groundwater discharge does not always move to streams. In the Plains, for example, groundwater discharge often flows to wetland areas (sloughs). There seem to be regional baseflow differences, which can be identified in each hydrogeological region, although other factors, including uneven distribution of stream gauges, may explain this component of streamflow[1]. Other processes besides groundwater discharge can affect "baseflow" or "low flow" stream flux (see chapter 4 for more details); these include

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1. *Baseflow* is the more slowly varying component of streamflow through wetlands, lakes, and rivers and is most apparent between precipitation and snowmelting events. The baseflow component of streamflow is frequently estimated using streamflow data and separating hydrograph trends. *Baseflow index* is a long-term summary of baseflow relative to total streamflow. In some settings, baseflow is primarily the result of groundwater discharge to surface water and baseflow index can therefore be used, with caution, as an indicator of the contribution of groundwater to streamflow at a watershed scale. Natural processes (such as snow accumulation and melting in alpine areas) and similar human processes (such as flow regulation using dams and reservoirs) that store and then slowly release water generate a component of baseflow that is not due to groundwater discharge. This complicates the interpretation of baseflow in terms of groundwater recharge, flow, and discharge. Streamflow data collected by Environment Canada's Water Survey of Canada, in partnership with provinces and territories, enables interpretation of baseflow across Canada using consistent data and methods.

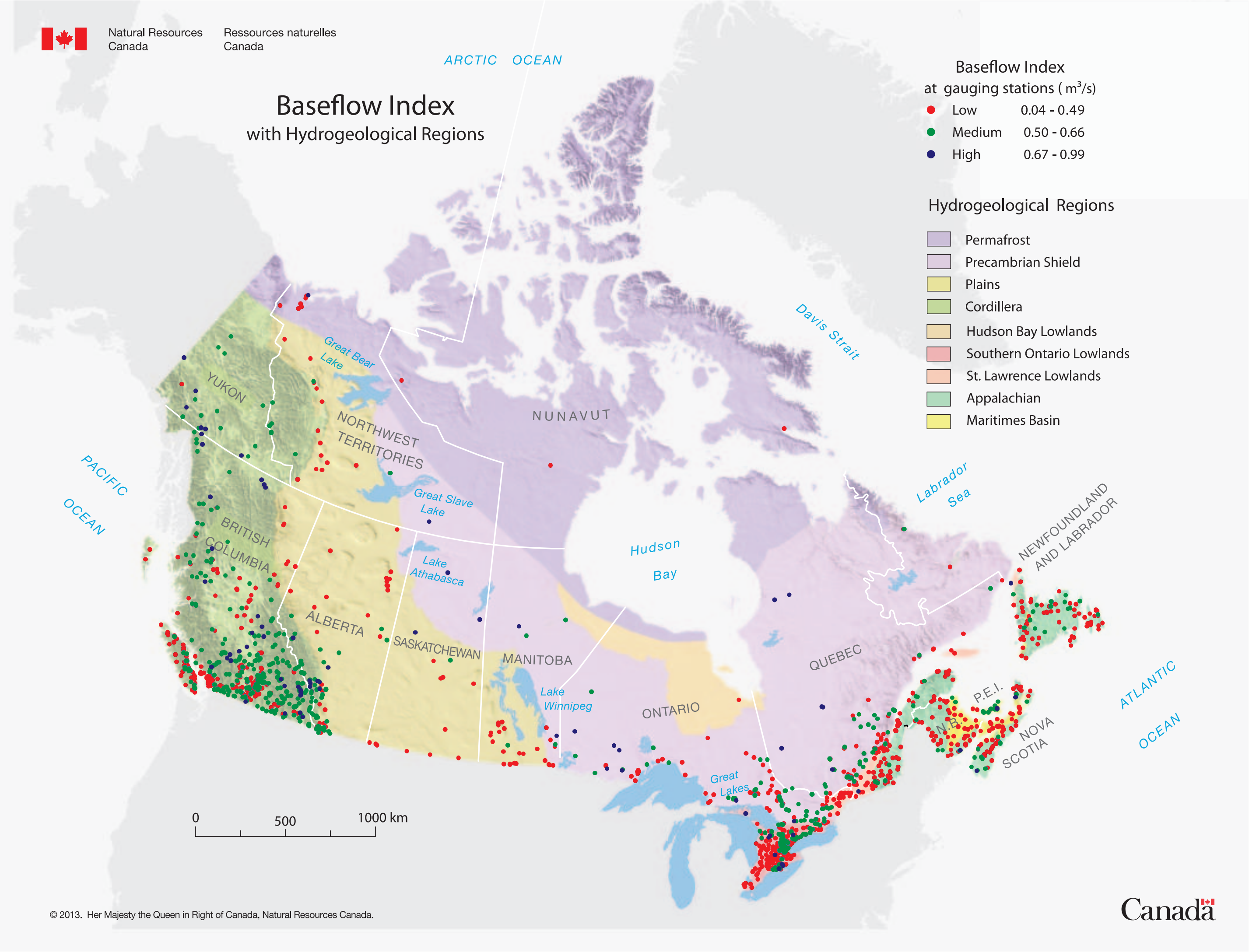

Figure 8.3b Baseflow.
Streamflow data can be used to estimate baseflow across Canada using 1,432 streamflow gauges (coloured dots). These gauges (6,049 total gauge symbols shown in aggregated form) monitor small watersheds with year-round observations for at least three years. Gauges are classified as having low, intermediate, and high values of an index of long-term baseflow (Neff et al., 2005). Baseflow index varies greatly across hydrogeological regions.

lake and channel storage, bank storage, snowmelt, vegetation losses, and freezing (Burn et al., 2008).

Although geology helps determine the overall capacity of rock formations to store and release water, not all available rock openings contribute to storage that is accessible, potable, and renewable. The magnitude of seasonal water table fluctuations to available water and baseflow discharge is also strongly governed by this effective storage. Seasonally, the water table tends to fluctuate most in areas of fractured, low-porosity rock formations, which are typical of several regions across the country.

8.2.1.4 Permeability and water table

Regional-scale geological maps are also analyzed to quantitatively map parameters which provide understanding of the hydrogeology of different regions at a national scale. Recent maps of near-surface permeability, or the ease of fluid flow through porous rocks and soil, coupled with water table type, provide useful information on the relative values and their controlling processes within the different hydrogeological regions across the country.

Regional-scale geology maps have also been coupled with regional-scale permeability in order to map permeability of the near surface (100 m depth) over North America (Gleeson et al., 2011a). Permeability patterns in Canada reflect largely homogeneous low permeability in the Canadian Shield, generally very low permeability in the Western Canada Sedimentary Basin, and heterogeneous permeability in the Cordillera and Appalachian Regions. Permeability maps quantify the spatial distribution of permeability which controls how water flows through hydrogeological systems. Permeability varies by many orders of magnitude and it is the most difficult hydrogeological property to estimate and map. Permeability maps are also useful for modelling regional hydrogeological systems, sustainable groundwater resources and how groundwater relates to national systems such as climate.

Permeability maps can also be coupled with other regional data such as recharge, topography, and watershed size in order to map water-table type (Gleeson et al., 2011b). A water-table type can be mapped using a dimensionless parameter, i.e., the water-table ratio, to differentiate water-table types across the country. At the regional scale, the water table can be differentiated into two types: i) topography-controlled water tables, where the water-table elevation is closely associated with topography, and ii) recharge-controlled water tables which are largely disconnected from topography (Haitjema and Mitchell-Bruker, 2005). Recharge-controlled water tables are expected in arid regions with mountainous topography and high permeability, such as interior Cordillera areas. Topography-controlled water tables are expected in humid regions with subdued topography and low permeability, such as Southern Ontario and the St. Lawrence Lowlands. Water-table type is a simple first-order characteristic of regional groundwater systems, one that helps characterize Canada's hydrogeological regions.

8.2.1.5 Effects of glaciation

Virtually all of Canada was glaciated several times during the Quaternary Period (the last two million years). This glaciation resulted in extensive, but variable, surficial sediment thickness across the country (Fulton, 1995). While glacial sediment is not depicted on the national hydrogeological regions map (Figure 8.1), sediment thickness has an important influence on the hydrogeology of most regions, particularly as regarding runoff, infiltration, storage, and discharge of groundwater. Sedimentary basins, such as in the Prairies, Southern Ontario, St. Lawrence and Hudson Bay Lowland regions, have thick glacial sequences. The Shield, Cordillera and Appalachian Regions generally have thin and discontinuous sediment cover. More details on the importance of glacial sediments are presented in our descriptions of each hydrogeological region.

Quaternary glaciations and related climatic conditions also appear to have had a large impact on groundwater flow systems across Canada (Lemieux et al., 2008). Complex flow processes occurred during glaciation and affected regional-scale groundwater flow systems. Key processes that affected groundwater flow during the last glaciation (~120 ka ago to present) included brine-basin flow, subglacial infiltration, loading-induced land depression and uplift, and permafrost development. Glacial advances and retreats likely altered the evolution of regional groundwater flow

systems, affecting surface-subsurface recharge and discharge fluxes over the Canadian landscape. Infiltration of subglacial meltwater occurred during ice sheet advance, while groundwater was mainly discharged to the surface during ice sheet retreat.

Lemieux et al., (2008) estimated that almost half of all glacial meltwater infiltrated into the subsurface as recharge. While meltwater-induced recharge rates vary according to bedrock type and rock properties, fresh glacial meltwater was injected as deep as several hundred metres below land surface, displacing basin brines in the Prairie and Southern Ontario sedimentary basins. Permafrost, on the other hand, acted as a barrier to groundwater flow, modifying these surface-subsurface interactions. Present-day groundwater flow and quality is still responding to these ice age stresses and fluxes.

8.2.2 Vignettes

These vignettes briefly summarize each hydrogeological region and include i) setting, ii) climate, iii) vegetation, iv) physiography, v) geology (bedrock and surficial), and vii) general hydrogeological elements. Information for the regional overviews was largely obtained from summary publications e.g., climate (Environment Canada, 2000), ecoregions (e.g., Marshal and Schut, 1999), physiography (Bostock, 1970), geology (Stott and Aitken, 1993; Fulton, 1995); and hydrogeology (Betcher et al., 1995; MacRitchie et al., 1994; Pupp et al.,1990; Pupp, Maathuis, and Grove, 1991; Pupp, Stein, and Grove, 1991; Lennox, 1993). A more complete list of bibliographic sources is available in regional chapters and in Sharpe et al. (2008).

Conceptual block models and a cross section for

TABLE 8.1 CHARACTERISTICS OF THE HYDROGEOLOGICAL REGIONS OF CANADA

REGION (AREA) KM^2	GEOLOGICAL CHARACTER	CLIMATE/ MOISTURE SURPLUS	MAJOR AQUIFERS	GROUNDWATER USE/ ISSUES
Cordillera (~1.4 million km^2)	High-relief mountains. Surficial deposits overlying fractured sedimentary, igneous, and metamorphic rocks of ancient to younger ages. Intermontane valleys are underlain by glacial, alluvial fan and river deposits. Northwest-southeast trending mountains intercept west-east weather systems and control moisture patterns. Ice-fields, glaciers, and snow packs discharge water in the summer.	Precipitation is >1,000 mm/year near coasts and uplands (high surplus); as low as<300 mm/ year in dry interior valleys (deficit); runoff is mainly high.	a) sand and gravel along narrow coasts, terraces, and valleys; abundant but small; may be vulnerable; b) fractured and faulted bedrock.	Industry use, ~55%; agricultural use, ~20%; municipal use is ~25% due to low cost and high quality. Significant stream-aquifer interactions in valley alluvial aquifers.
Plains(Western Sedimentary Basin (~1.7 million km^2)	Region-wide basin of low-relief, subhorizontal, multi-aged sedimentary rocks. Carbonate and ancient fluvial rocks set mainly in mudstone units. Overlying thick glacial deposits may be extensive and contain buried valleys. Incised postglacial valleys provide local relief. Shallow gas, coal, and brines may occur.	Mean precipitation is <300 mm/year in the SW and ~600 mm/ year in Manitoba; prairie areas have water balance deficits and little runoff.	a) Potable in shallow fractured basin rocks; b) thick muddy glacial sediment host buried valley / inter-till aquifers.	Groundwater availability is limited due to overlying aquitards, dry climate, and high concentrations of dissolved solids.
Canadian Shield (~2.9 million km^2)	Undulating region of complex deformed, fractured Precambrian-age igneous, metamorphic and sedimentary rocks, with discontinuous cover of glacial sediment. Region contains several hydro-structural terrains: sedimentary basins, volcanic belts, and low-relief, glacial-lacustrine basins.	Mean precipitation is ~400 mm/year in the west and ~1,000 mm/ year in the east; surplus high in east with higher relief. Runoff is variable.	a) Widespread low-yield fractured crystalline rocks; b) clay basins have protected thick sand/gravel units.	Plentiful lakes and decreased water quality with depth limits well use; local mining can impact water quality.
Hudson Bay Lowlands Region (240,000 km^2)	Ancient marine sedimentary basin contains younger subhorizontal carbonate and sandstone rocks; some karst permeability; thick sediment cover consists of glacial and related mud deposits. Low relief, fine-grained sediment and poor drainage results in large wetland terrains.	Mean precipitation varies: ~400 mm/ year in northwest and ~800 mm/year in the southeast; runoff is linked to wetlands.	a) Peat-sediment boundary; b) limestones are prominent aquifers; c) buried valleys.	Low population and abundant surface water limits groundwater use and knowledge.
Southern Ontario Lowlands (~72,000 km^2)	Low- to moderate-relief terrain underlain by gently-dipping, carbonate, clastic and gypsum-salt strata. Near-surface karst is widespread and creates recharge in Niagara Escarpment uplands. Glacial sediment covers 90% of region and is up to 200 m thick in stratified moraines and buried valleys in sediment and rock. Shallow gas and basin brines are also important.	Mean precipitation is ~700–1,000 mm/year and is affected by Great Lakes; runoff varies from 200–400 mm/year.	a) Shallow bedrock with marine reefs; b) thick sediment in moraines and buried valleys; c) sediment-rock contact zones.	Great Lakes water use is replacing groundwater where demand is high; renewed analysis of groundwater due to new legislation.
St. Lawrence Lowlands (Platform) (~45,000 km^2)	Low-relief, terrain underlain by shallow-dipping ancient sedimentary rocks and thick glacial sediment in glacial-marine basins. Appalachian and Canadian Shield uplands discharge water to valleys. Shallow gas, fault-controlled flow, and saltwater intrusion are possible.	Mean precipitation is ~800–1,100 mm/year. Runoff varies from ~300–450 mm/year.	a) Significant carbonate bedrock aquifers; b) sand and gravel aquifers buried below marine clay.	High population, urban/agricultural growth is creating high water demand and land use conflicts.
Appalachian (~249,000 km^2)	High-relief upland to mountainous region of ancient folded sedimentary and igneous rocks, with thin sediment cover. Range of rock types results in varying yields and water quality. Glacial sediment is thick in valleys; sand and gravel deposits may be protected by clay beds.	Mean precipitation is ~800–1,200 mm/year; runoff is variable ~300–500 mm/year.	a) valley fills have high-yield sand and gravel aquifers b) Upland rock aquifer yields vary mainly in fractures.	Surface water use is very common; groundwater is used, yet large yields are difficult to find.
Maritimes Basin (~59,000 km^2)	Carboniferous lowlands with flat-lying, alternating sandstone–mudstone sequences. Coal, salt, gypsum and minor shallow gas can occur locally. Glacial sediment cover is thin and discontinuous. Saltwater intrusion is generally balanced by high recharge fluxes.	Mean precipitation is ~900–1,500 mm/year; Runoff may exceed 600 mm/year.	Fractured red sandstone forms key aquifers; some inter-granular flow. Coal, salt, and gypsum may affect water quality.	PEI relies 100% on groundwater; land use conflict and saline sea pushing landward are concerns.
Permafrost (~2.9 million km^2)	Arctic islands and most areas north of 60º contain frozen ground that hampers groundwater flow. Diverse topography, relief, and geology define subregions of sedimentary basins and crystalline rocks. Glacial sediment is thin, discontinuous; local peat accumulations are significant.	Mean precipitation is ~100–300 mm/year; runoff is very low and poorly gauged.	Continuous and semi-continuous frozen ground acts as a barrier to most groundwater flow.	Groundwater flow is restricted and little is known about these systems in permafrost areas.

each region illustrate key features of the respective hydrogeological systems. Each conceptual model helps elucidate and enhance portrayal of the elements within the regional flow systems, and the principal aquifer/aquitard settings. While our focus is on aquifers in the regional discussions that follow, the groundwater flow pattern in any flow system is primarily controlled by the occurrence of low-transmission units or aquitards.

8.3 HYDROGEOLOGICAL REGIONS OF CANADA

8.3.1 Cordillera

The Cordilleran hydrogeological region covers ~1.4 million km^2, including most of British Columbia, and southwestern Alberta. The region has dramatic physiography, geology (Figure 8.4) and climatic diversity. Population, agricultural and industrial, pressures on water resources are focused along narrow coastal zones, lowlands (e.g., east coast of Vancouver Island, Fraser Lowland), alluvial terraces, or in drier interior valleys (e.g., Okanagan Basin, Nicola Basin). As a result of competing demands for water between these user groups, there is potential for water use conflicts or water quality impacts in these areas.

Cordilleran climate varies from mild, humid conditions along the southwest coast to subarctic conditions in high mountains in the north and in dry interior valleys. Climate is dominated by Pacific Ocean air masses and orographic effects (Figure 8.4, O). In general, coastal areas have milder wetter conditions, whereas interior valleys (Figure 8.4b) have larger temperature fluctuations and are dryer. Precipitation is highly variable and can exceed 4,000 mm/year along the Pacific Coast; locally it can be as low as 600 mm/year (Gulf Islands). Eastward from the coast, annual precipitation decreases from 1,200–1,500 mm/year in mountains to as low as <300 mm/year in some intermontane valleys (Okanagan; Figure 8.4a, b, IM). Climate above treeline (>2,000 m), is cold, windy, and snowy, with areas of perpetual ice and snow cover (Figure 8.4, SP). Hence, vegetation ranges from temperate rainforest on the coast to extensive coniferous forest in the interior, shrub vegetation in the arid south, and tundra in high-elevation areas. Compare this altitudinal vegetation trend with national north-south vegetation trend (Figure 8.2).

This mountainous region consists of a series of northwest-southeast trending mountain ranges and intervening interior plateaus and intermontane valleys (Figure 8.4, IM). Plateaus are most extensive in the north, whereas larger intermontane valleys are more prominent in the south. Mountain relief is ~1,000–3,000 m. Physiography reflects underlying geology, such that eastern mountains are dominated by deformed, folded, and faulted sedimentary rocks whereas coastal mountains have more volcanic and massive plutonic rocks. Late plutonic intrusions affected the coast range. Some north central plateaus are predominantly underlain by large shield volcanoes and lava flows. Surficial deposits are thick (100 m) in intermontane valleys and along major river valleys (Figure 8.4). These deposits include extensive glacial-fluvial, glacial-lacustrine, and glacial-marine sediment. Alluvial fans and aprons occur in mountain areas and intermontane valleys.

8.3.1.1 Hydrogeology of Cordillera

Aquifers occur in restricted valley-bottom, alluvial settings and upland bedrock (Figure 8.4). In valley-bottom and alluvial aquifers, groundwater flow occurs in inter-granular openings. These aquifers exist as either deeper confined or shallow unconfined sediment aquifers: they are generally small (discontinuous) but are very common and important. Extreme artesian conditions can exist in confined aquifers in intermontane valleys where connection to adjacent elevated bedrock systems provides substantial hydraulic head (Figure 8.4). Shallow unconfined glacial-fluvial or fluvial (alluvial) aquifers may have direct connection with surface water when located adjacent to rivers and streams (Figure 8.4): these unconfined aquifers may be vulnerable to contamination. Groundwater flow in bedrock is typically through secondary fractures, such as bedding planes, joints, or faults (Figure 8.4, see arrows). Groundwater flow in karstic and volcanic lava-flow rocks may also occur in dissolution channels and in inter-bedded zones, respectively. Numerous thermal springs occur in the region (e.g., van Everdingen, 1972; Foster and Smith, 1988); these are typically localized along major, crustal-scale faults or found in association with high-heat flow areas within western volcanic belts.

Groundwater recharge is seasonal. Recharge in coastal areas occurs in winter and early spring when precipitation is greatest. Recharge in interior regions occurs in late spring to early summer, and is related to snowmelt. Warm temperatures, wind, and vegetation promote high evapotranspiration losses throughout summer across most of the region. Most Cordillera baseflow values are high, although lesser intermediate and low values do occur. Strong topographic gradients which enable groundwater flow, combined with baseflow due to glacial meltwater and snowmelting, may contribute to higher values in this region. Studies on Vancouver Island suggest low bedrock storativity may be the limiting factor in recharge to fractured bedrock aquifers in coastal regions, not the amount of available precipitation (Kohut et al, 1984; Lapcevic et al, 2006).

Groundwater quality is generally very good across the region, with local occurrences of elevated nitrate, arsenic, fluoride and boron, and saline water. High salinity affects coastal aquifers, and deep salinity may occur inland. Water quality can be poor in mining areas due to naturally occurring or mine-related high levels of metals in this and other regions.

Groundwater use is highest in the industrial sector, while lesser agricultural use is strong in alluvial deposits of the intermontane basins such as the Okanagan Valley. Municipal supply is about 25% of use due to low cost and high quality. Groundwater is also used for geothermal heat exchange, both for energy and for cooling.

8.3.2 Plains (Western Canadian Sedimentary Basin)

The Plains Region is a sedimentary basin covering ~1.7 million km^2 (~18% of Canada's land) bounded by the Cordillera to the west and Canadian Shield to the east and north (Figure 8.1). The region is sparsely populated with a few large cities. Predominant land use is agriculture. The semiarid south is dominated by dry land farming along with significant areas of irrigation in southern Alberta. Hydrocarbon exploration and development, potash and coal mining are the dominant resource extraction industrial activities across the region. Oil sands production may impact groundwater systems in northern Alberta as about three barrels of water are required to produce one barrel of oil. Allocation of additional surface water rights is no longer possible in southern Alberta; thus, demand has increased on groundwater systems. This may be subject to quantity, quality, and sustainability issues.

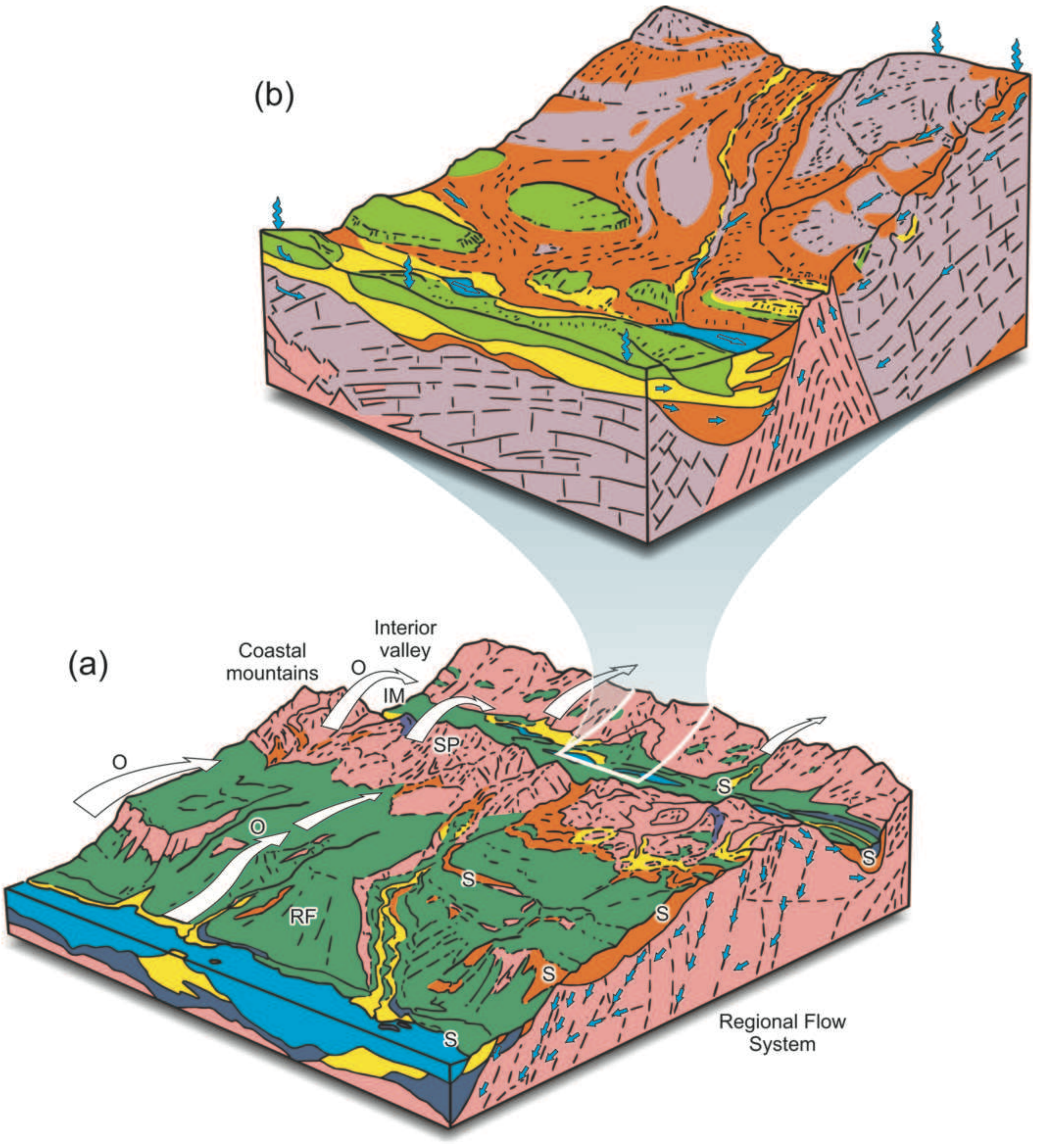

Figure 8.4 a) Cordillera hydrogeology region.
Key elements include: coastal mountains with orographic effects (O), complex geology with fracture flow systems (arrows) and intermontane valleys (IM). Note regional flow systems driven by high hydraulic heads and gradients. Orographic effects (O) generate extreme contrasts in precipitation, moisture availability, and vegetation between temperate rainforest (RF) in coastal mountains, alpine snowpacks (SP), and arid interior intermontane valleys (IM). Sediment cover (S) is variable but thickest in intermontane and coastal valleys; **b)** Intermontane valleys are less vegetated, show fracture flow in sediment-poor rock slopes, and collect thick, complex glacial and alluvial fan sediments in the valley. There is significant aquifer potential in such sediment-thick valleys.

The Plains climate is a cool continental regime, dominated by semiarid conditions. Pacific or Arctic air masses and variations in solar radiation result in regional climate being zoned from south to north and from west to east. Moisture-bearing Pacific winds are blocked by the Rocky Mountains and rain-shadow-effects result in subhumid to semiarid conditions. Summers are short and warm; winters are very cold. Precipitation is lowest and evapotranspiration highest in the western prairie cropland area with precipitation increasing from 250 mm/year in southwestern Alberta to ~700 mm/year eastward in Manitoba. Periodic Chinooks blow warm, dry winds from the Rockies (Figure 8.5a) bringing dry, spring-like temperatures to a semiarid region across southern Alberta, and to a lesser extent, across southern Saskatchewan. Evapotranspiration losses are high enough to produce moisture deficits in some areas. Natural vegetation of tall, mixed, and short grasses with sagebrush gives way northward to aspen-poplar parkland, then to slow-growing open spruce forests (Figure 8.2). Thousands of small wetlands, which characterize the Prairie Pothole Region, are critical elements in local recharge-discharge systems in grassland prairies.

Topography of the region trends from 1,200 masl in the southwest to 200 masl along the northeast edge of the basin and 280 masl in the Manitoba Lowlands (Figure 8.5a). Two prominent "prairie steps" disrupt a landscape characterized by flat to gently rolling and hummocky terrain (Figure 8.5a). There are two key drainage systems: the Saskatchewan-Nelson River drains to Hudson Bay, and the Mackenzie River drains to the Arctic Sea. The Saskatchewan-Nelson River drainage originates in rain, melting of annual snowpacks and ice fields of the Rocky Mountains; very little surface runoff, or groundwater discharge is contributed from the dry interior of the region. Geology of the Western Canada Sedimentary Basin (WCSB) is characterized by a sedimentary wedge that thickens from the Shield edge to ~6 km in the southwest (Figure 8.5a). The WCSB is divided into the Alberta Basin and the Williston Basin by a northeast-trending arch. Basal carbonates are only exposed in the east, in addition to the Rocky Mountains (Figure 8.5a,b). Overlying marine sandstone and thick shale are incised by valleys (Figure 8.5b) and overlain by younger fluvial sandstone (e.g., Paskapoo). Almost the whole area was repeatedly glaciated, resulting in a thick, clay-rich glacial sediment cover, which controls much of the active groundwater flow within the region (Figure 8.5c). Unconsolidated sediment thickness is variable: thin across Alberta and thickest along buried valleys and till uplands in Saskatchewan (Figure 8.5c). These may consist of till, sand and gravel, and/or silt-clay. Buried valleys and inter-till sediments form important aquifers across the region.

8.3.2.1 Hydrogeology of Plains

The distribution of potable water in the Plains is controlled by depth and the nature of shallow units that overlie the aquifers; many of these units are confining aquitards such as glacial till and widespread shale (Figure 8.5b). These low-permeability units determine recharge and shallow groundwater flow across the region. The Plains Region is best divided into bedrock and unconsolidated sediment dominated terrains (Figure 8.5a). Bedrock hydro-stratigraphy can be categorized into three divisions: i) lower sedimentary rocks, ii) middle carbonates and evaporites (M), and iii) upper sedimentary bedrock (L) (Figure 8.5a). Deeper, older units that form aquifers (Figure 8.5a) where salinities can far exceed 600 g/L are too

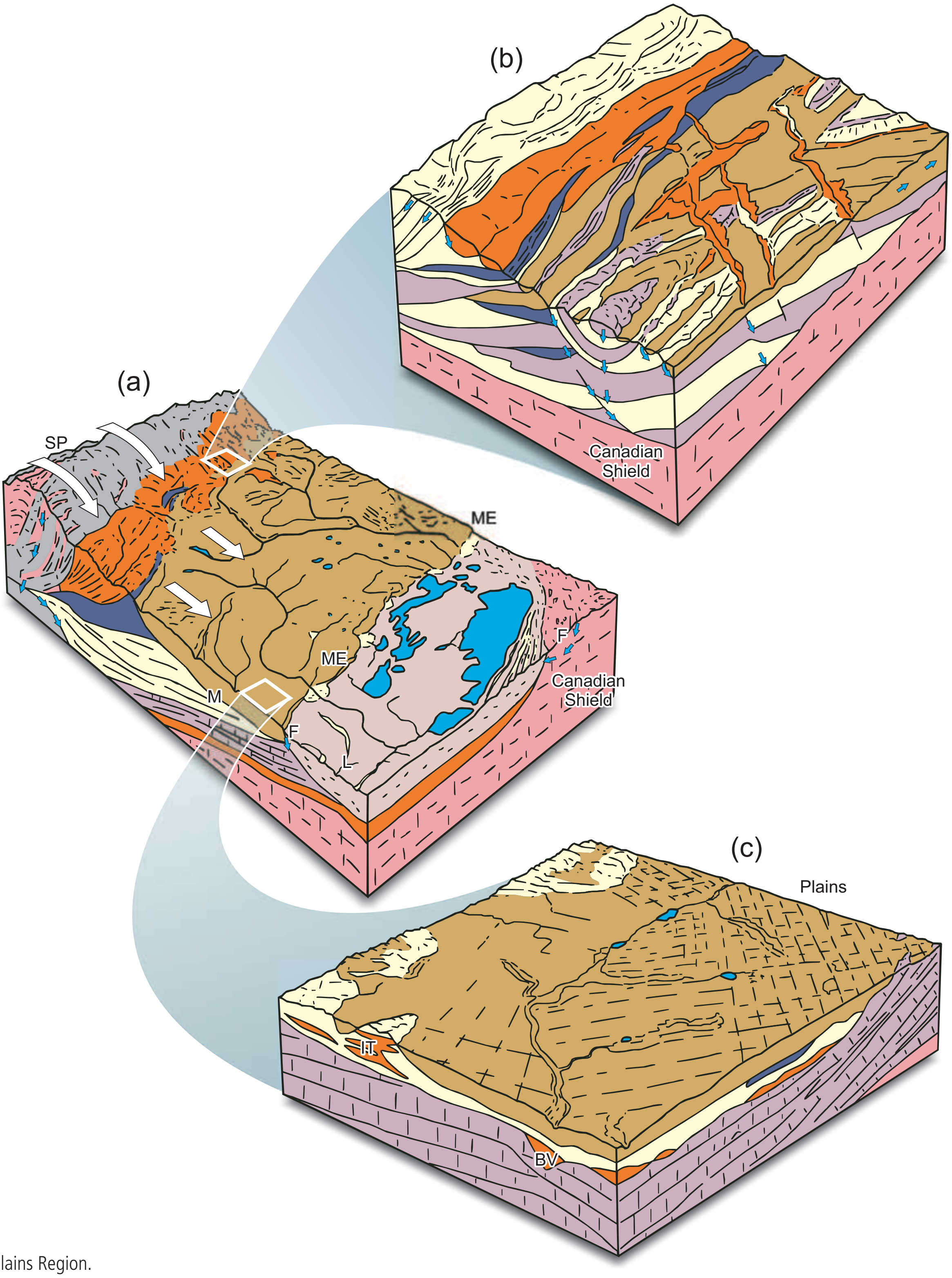

Figure 8.5 Plains Region.

a) view of extensive Western Canadian Sedimentary Basin with gently-dipping, mainly undeformed, marine sedimentary rocks that thin from the Rocky Mountains in the west to the Canadian Shield in the east. Note that warm Chinook winds (white arrows) help induce dry conditions. Snowpack (SP) groundwater and glacier melt provide sustained flow to major rivers. Basin scale, surface terrain features, and dry conditions produce groundwater flow systems at various scales. Deep aquifers in basin-wide flow systems are recharged at basin margins. Within region, recharge, for example, along the Manitoba Escarpment (ME) competes with deeper saline groundwater flow below the escarpment. Local climate controls local flow systems. **b)** Note significant regional fracture flow in structurally-controlled foothills; flow also occurs in fractured rock, sediment, and bedrock-sediment interfaces in foothill areas (block **b** cut out from **a**); **c)** block of Plains Region (see **a** for location) shows thick glacial sediment over basin rocks (particularly in Saskatchewan and Manitoba), local sediment and regional-scale flow systems occur as well as buried valley (BV) and inter-till (IT) aquifers. Inter-till (IT) aquifers provide shallow potable water within unconsolidated sediment cover. Slopes in hummocky terrain drive local flow.

saline (sodium chloride) for potable water. Eastern, basin-edge topography influences regional flow systems as fresh glacial meltwater was introduced during glacial times, and modern meteoric water as recharge from isolated uplands (Figure 8.5a, F). Unconsolidated aquifers, across the region, particularly inter-till and buried valleys (Figure 8.5c), are important, however groundwater in regional glacial sediment, particularly poorly connected inter-till aquifers (Figure 8.5c), is hard and high in sulphate. Surfacial deposits are thin in western Alberta, , and shallow aquifers occur only in hummocky terrain (Figure 8.5b). Near-surface bedrock aquifers dominated by marine and fluvial sandstone are important. Shallow fluvial sandstone aquifers occur with inter-bedded mudstones and isolated channel sands that provide variable yield and quality. Low and hummocky topography, flat-lying strata, and bedrock variability result in prominent local-scale flow systems across the region (Figure 8.5). Plains regions show low to modest baseflow as some discharge goes to ponds and sloughs as well as to streams (Figure 8.3b). In summary, groundwater recharge is limited by the semiarid climate and the presence of confining aquitards. Most groundwater supplies draw on shallow aquifers which are recharged locally. Deeper confined aquifers generally receive very little recharge, and high pumping rates may not be sustainable in the long term, as was shown near Estevan (van der Kamp and Maathuis, 2002). Although groundwater availability is limited due to overlying aquitards, dry climate, and high concentrations of dissolved solids, groundwater use is important for agriculture and industry where major rivers are not close by (Maathuis and Thorleifson, 2000). Rural groundwater use is very high, particularly from shallow inter-till aquifers.

8.3.3 Canadian Shield

The Canadian Shield is the largest physiographic region in Canada with ~31% of the land (2.9 million km^2) and ~10%, by area, of its fresh water. It is a vast region that extends from the Northwest Territories to Labrador, including northern Saskatchewan and much of Manitoba, Ontario, and Quebec (Figure 8.1). The region has low population density with population centres in areas of mining and forestry. The Shield is rich in timber, mineral, and natural resources which attract recreational use, and have some impact (resource extraction) on water resources.

Regional climate is continental with long cold winters and short warm summers. Areas bordering large water bodies tend to be warmer in winter and cooler in summer with the exception of those water bodies that are ice covered during the winter. Mean precipitation is low to moderate, ranging from ~400 mm/year in the west to 1,000 mm/year in the east. Precipitation and temperature both decrease from south to north. Forests of spruce, balsam fir, and pine predominate while broadleaf trees occur in more southern areas. Open, permafrost-stunted black spruce forest occurs in northern terrains. Wetlands are prominent across the Shield terrain.

Regional landscapes consist of a series of bevelled uplands between ~200 and 1,000 masl, with relief of 50–100 m (Figure 8.6a). Greater relief, 150-300 m, occurs along river valleys incised into uplands and plateaus. A series of large lakes occurs along the southern border of the Shield in contact with sedimentary basins, and below northeast-facing escarpments (e.g., Great Lakes, Great Slave Lake).

The Shield consists of Precambrian igneous, metamorphic, and meta-sedimentary crystalline rocks formed during several phases of mountain building, volcanism, and related tectonic events (Figure 8.6a). It is subdivided into geological

provinces according to deformation style and age; each province comprises banded or foliated rocks that have been metamorphosed, deformed, and fractured to various degrees as greenstone-sedimentary terrains and adjacent gneissic belts. These have been intruded by granitic rocks and regional dyke systems. Much of the area has a discontinuous cover of thin glacial sediment. Thicker surficial deposits occur in areas of glacial landforms such as drumlins, eskers and moraines. Extensive glacial-lacustrine deposits occur in parts of Quebec, Ontario, and Manitoba, and form clay basins with underlying sand and gravel deposits (Figure 8.6b).

8.3.3.1 Hydrogeology of Canadian Shield

The Shield's ubiquitous crystalline rocks, characterized by consistently low primary porosity, permeability, and variable fracture patterns (Figure 8.6b), usually have low water yields. Major structural zones support higher groundwater fluxes in connecting systems and in regional flow systems, although fracture zone may have diminished flow (Gleeson and Novakowski, 2009). Fracture zones yield potable water to depths of ~100 m; at greater depths, groundwater becomes progressively saline, reducing, and old. High total dissolved solids, 50–100 g/L, occur in sparsely fractured deeper rocks. Elevated heads remain in Shield rocks due to surface loading from the last glaciation (Clark et al., 2000; Sykes et al., 2003).

Thick unconsolidated sediment aquifers are locally prominent, particularly the high-yield glacio-fluvial aquifers which provide most of the municipal drinking water supply from groundwater. Agricultural areas, in thick clay basins on

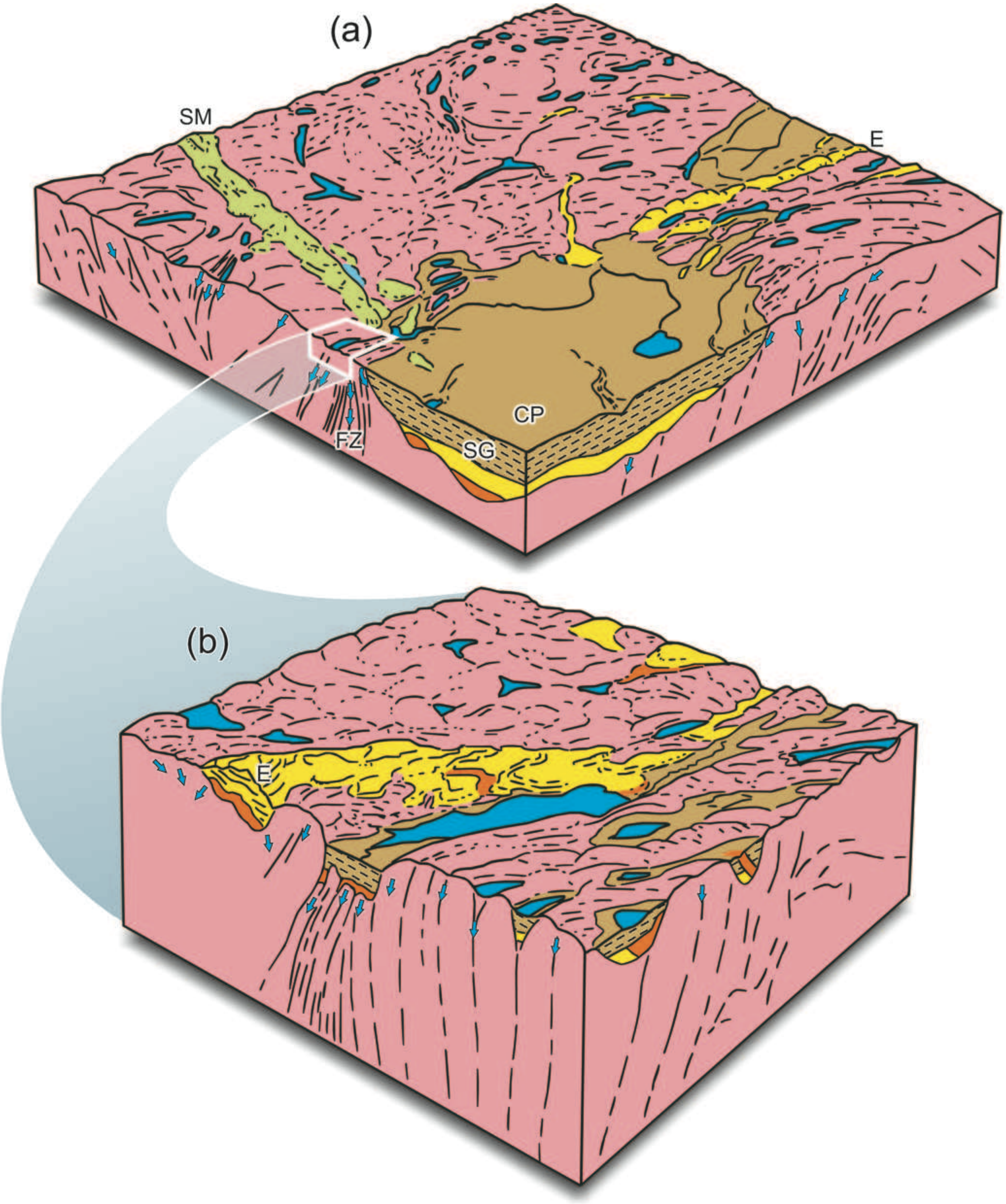

Figure 8.6 Canadian Shield Region.

a) This undulating low-relief terrain is dominated by fractured crystalline rocks, fault zones (FZ), and thin sediment cover except for eskers (E), stratified moraines (SM), and clay plains (CP). Sparse fracture density and clay basins on the land surface limit groundwater recharge. High yield aquifers occur in eskers and sand and gravel (SG) buried beneath clay basins (e.g., Dryden and Abitibi regions of Ontario and Quebec). **b)** Highlighted area west of the clay plain shows groundwater flowpaths for fresh water are generally short and shallow due to low driving gradients. Storage capacity in fractured-faulted rocks is also low.

the shield, rely on sediment aquifers (Figure 8.6b). Recharge and discharge patterns are localized due to fracture patterns and are modest in size from those in porous media aquifers (Gleeson and Novakowski, 2009). Regulation and attenuation of runoff by lakes and wetlands may contribute to intermediate to high baseflow discharge in this region; baseflow may otherwise be limited by lower storage, permeable materials and low topographic gradients. The modest undulating relief on the Shield provides a low driving force for slow groundwater movement and reduced mixing at depth (Figure 8.6a). Water quality can be compromised in bedrock fracture systems due to bedrock mineralization (which may contain uranium and radon gas), and around mining areas where mill discharge may occur.

Groundwater for municipal water supply is drawn largely from aquifers below clay basins such as the Waibigoon clay plain in Dryden (Sharpe et al., 1992). Rural supply, when surface water is not used, is often from fractured rock.

8.3.4 Hudson Bay Lowlands

The Hudson Bay Lowland is the southern expression of a sedimentary basin focussed on Hudson Bay. The terrestrial extent is ~240,000 km^2 and is bounded by Precambrian Shield rocks to the south and west. It is most extensive in Ontario with a minor extent in Manitoba and the James Bay region of Quebec (Figure 8.1). Permafrost bounds the northern extension of this region. The area is very sparsely populated with hydrogeological information mainly available from studies of hydroelectric and mine sites.

Climate is continental and strongly influenced by cold, moisture-laden Hudson Bay and Polar air masses. It is characterized by short cool summers and cold winters. Mean annual temperature ranges from -4°C to -2°C, but is closer to -7°C in Manitoba. Annual precipitation averages from 400 to 800 mm/year, increasing from northwest to southeast. The region supports a very large organic terrain (~75% of area) with open water in wetlands (Figure 8.7a). Poorly drained areas support dense sedge-moss-lichen covers, and less frequent and better-drained sites support open woodlands (OW) of black spruce and tamarack. Raised beaches are vegetated by black spruce and depressions are filled with bogs and fens (Figure 8.7a).

Hudson Bay Lowland rises gently from sea level to ~120 masl, and is an area of low relief with poor drainage (Figure 8.7a). Precambrian Sutton Hills rise 150 m above the surrounding landscape (Figure 8.7a). A series of beach ridges occurs inland from the present shoreline and forms a prominent element of the region. Isolated bedrock knolls penetrate the surficial cover. The low relief is a reflection of the subhorizontal sedimentary strata of the Hudson and Moose River basins, which are up to 1,500 m and 900 m thick, respectively. Both basins are dominated by carbonate bedrock (Figure 8.7a) with anhydrite, gypsum, and lesser halite inter-beds. Karst solution weathering is prominent in portions of the basin (Figure 8.7b). Locally these units contain bituminous limestone beds. Sedimentary rocks in the Moose River Basin consist of poorly consolidated sandy sediment and local kaolinite mudrock and lignite. The sedimentary succession is cut by a number of more recent intrusions, some of which are kimberlitic, such as at the Victor mine. Mud-rich till occurs as a semi-continuous cover (Figure 8.7c) and is considerably thicker than in the Canadian Shield Region. Broad pre-glacial valleys have been filled with more than 60 m of surficial sediment, and a thickness of 145 m has been recorded. Surface sediment is commonly glacial-marine clay, which inhibits drainage and sand.

8.3.4.1 Hydrogeology of Hudson Bay Lowlands

There is little hydrogeological data for this region as there are few water wells and little development. Basal carbonate and evaporite rocks form key hydro-stratigraphic units in Hudson Basin and southern Manitoba and likely have equivalents in the Moose River Basin. Glacial-lacustrine marine, silt-clay, and till units form regional aquitards (Figure 8.7a,b). Kaolinite-rich mudstones and lignite form local aquitards in Moose Basin. Groundwater flows principally along joints, faults, fractures, bedding planes, and solution features in carbonate-evaporite units (Figure 8.7b). Where solution features (karst) are well developed, high bulk-rock hydraulic conductivities may occur and carbonates can form productive aquifers. Massive, fine-crystalline carbonate may have low hydraulic conductivity and form aquitards locally between fractures and solution enhancement. Groundwater interacts with surface water in two key watershed settings where shallow groundwater discharges: i) at peat-sediment interfaces (P), and ii), where peat is underlain by sand and gravel. At intermediate depths, flow discharges along bedrock-sediment interfaces, and deeper groundwater flows from bedrock aquifers to large rivers (Figure 8.7b,c). Holocene karst also affects groundwater flow through shallow flow zones in limestone and sinkholes, on or next to limestone reefs beneath peat cover (Figure 8.7b). Groundwater chemistry may have elevated sodium and chloride concentrations, which can be attributed to marine waters in sediment and bedrock units, as well as dissolution of evaporite units. High chloride levels (10, 000 mg/L) are reported at depths below 200 m.

Groundwater use is modest due to lack of population, industry, and the presence of abundant surface water.

8.3.5 Southern Ontario Lowlands

The Southern Ontario (Lowland) Region is a sedimentary basin covering ~72,000 km^2 located predominantly south of 45 degrees north latitude. It is bounded by Canadian Shield to the north and east, and three Great Lakes to the south (Figure 8.1). The area is the industrial heartland of the country and has the highest population density. Mild climate and fertile soils support an extensive agriculture industry. Even with the proximity of abundant surface water in the Great Lakes (Figure 8.8a), groundwater continues to be a pivotal resource for agricultural and potable use. A particular issue, affecting a number of urban areas (e.g., Greater Toronto Area), is the increasing use of surface water supply, lakes, over groundwater. Potential water diversion, the taking of water from one Great Lake and the return to a different lake, may affect other cities (e.g., London).

Southern Ontario has a temperate continental climate strongly influenced by adjacent Great Lakes. Here climate is characterized by warm summers, mild winters (mean temperature range: 5°C to 8°C), and 720–1,000 mm/year of precipitation. Precipitation is highest east of major lakes. Evapotranspiration ranges from ~600 mm/year in the south to <500 mm/year in the north. Available moisture for runoff to streams or groundwater recharge varies from ~200–400 mm/year. The original mixed coniferous-deciduous stands cover <10% of the region with the remainder having been cleared for agriculture.

This region is part of the Great Lakes watershed

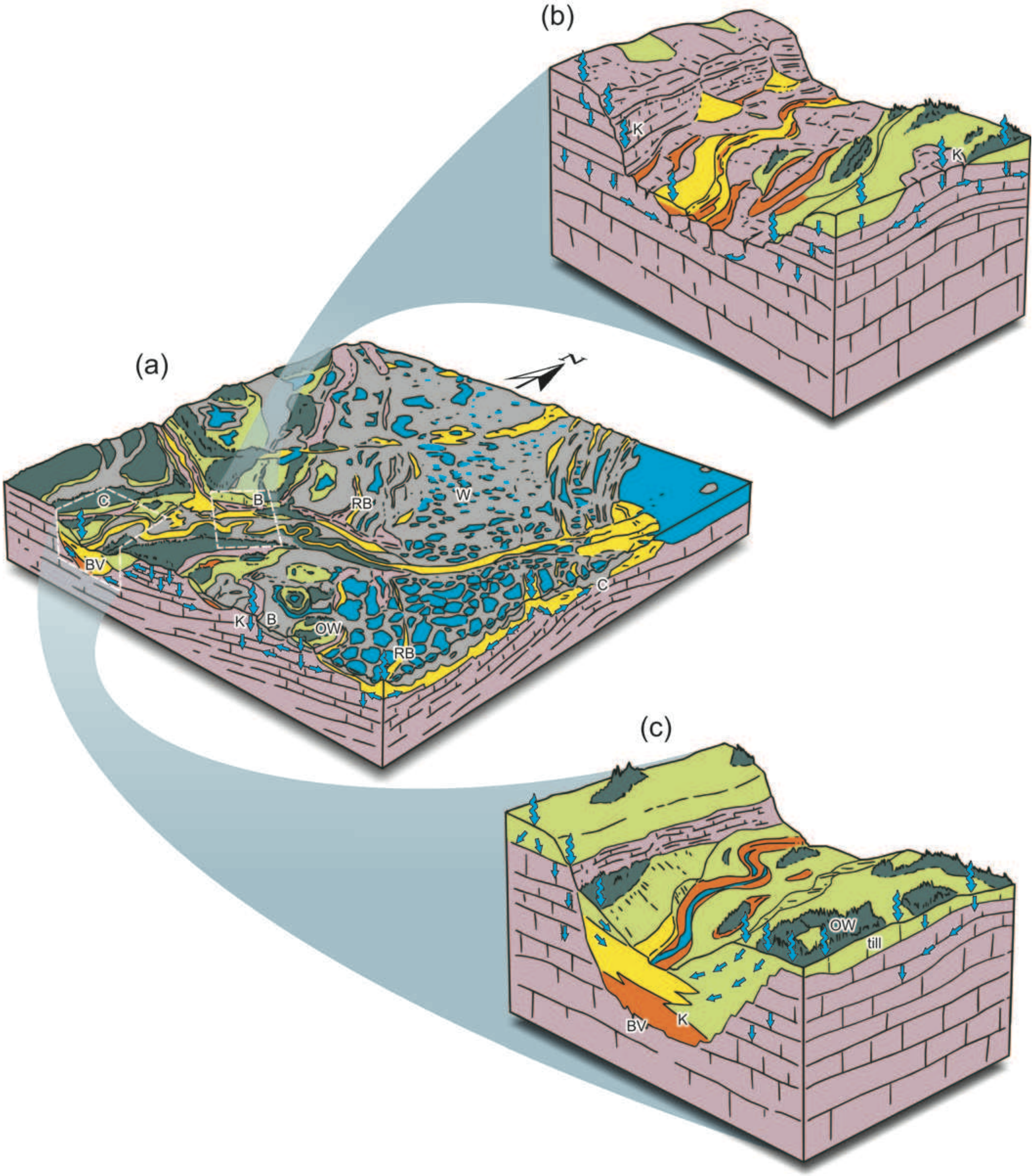

Figure 8.7 Hudson Bay Lowland Region.
a) dominated by subhorizontal sedimentary rocks (carbonate), incised valleys (BV) in low-relief terrain, extensive wetlands (W), open woodlands (OW) and raised beaches (RB) adjacent to Hudson Bay. **b)** Incised valley with karst (K) where enhanced flow can be significant in interfluve settings. **c)** Thick sediment covers or drapes other buried bedrock valleys (BV); buried valley aquifers can contain up to 60 m of saturated sediment.

which drains low-relief terrain of the Canadian Shield and adjacent sedimentary basins. Bedrock scarps (e.g., Niagara Escarpment) of < 100 m relief are the prominent areas of bedrock outcrop (Figure 8.8b). Escarpment uplands rise to 550 masl and slope gently southwest on inclined rock strata (Figure 8.8a). Secondary topography, with ~50 m local relief, such as the Oak Ridges Moraine (Figure 8.8c), rises up to 300 m above Lake Ontario to form an important drainage divide between Lake Ontario and Georgian Bay.

Paleozoic sedimentary rocks of the Michigan and Appalachian basins are separated by a northeast-trending structural arch. Strata east of the Niagara Escarpment are predominantly shale, siltstone, and sandstone with secondary amounts of carbonate rocks. To the west, the carbonate rocks of the Niagara Escarpment predominate in three formations, Amabel-Lockport, Guelph, and Salina, extending from the Niagara Peninsula to Lake Huron. Southwest of the Onondaga Escarpment (OE; Figure 8.8a), the succession is progressively dominated by carbonate rocks, shale and evaporites. Ancient tectonic events likely influenced deposition and sediment changes within strata, and controlled fracture and fault orientations, which in turn, control basin fluid migration (Figure 8.8b). Natural gas and oil is produced in these same rock formations beneath Lake Erie and northward to London (Figure 8.8a).

Predominantly glacial sediment, up to 200 m thick, buries most bedrock and is thickest above buried bedrock valleys and in major stratified moraines (BV, M; Figure 8.8d). Regional silty sand till aquitards (e.g., Newmarket, Catfish Creek tills) and inter-till sand and gravel control groundwater flow patterns. Steep-sided, deeply-incised, buried valleys eroded into thick older sediment truncate regional aquitards and form important hydraulic connections from surface to subsurface valleys by way of extensive gravel, sand, and silt fills (Sharpe et al., 2002). Sand and gravel is also prominent in stratified moraines (e.g., Waterloo, Oro and Oak Ridges moraines).

8.3.5.1 Hydrogeology of Southern Ontario Lowlands

Bedrock and unconsolidated sediment both serve as important aquifers as does the contact or interface between the two. Most water east of the Niagara Escarpment is extracted from thick sediment aquifers located in buried valleys and stratified moraines (the Alliston, and Oak Ridges Moraine aquifers, for example, Figure 8.7c). Wells in these settings can yield > 60 L/s; however, yields of 16 L/s are more typical. Thick sediments contain multiple aquifer-aquitard systems with local and intermediate-scale flow systems, some with transmissive, preferential flowpaths (Figure 8.8b). West of the Niagara Escarpment, shallow bedrock aquifers are more prominent (these include Guelph-Gasport, Amabel-Lockport, and the escarpment caprock aquifer), although sediment aquifers are also predominant in moraines (as with Waterloo). When sediment cover is thin, upland carbonate aquifers have karst openings receptive to significant groundwater recharge and flow (Figure 8.8c). Southwest along the basin flow system, intercalated limestone, evaporite, and shale yield variable quantities and quality of water, primarily along the regional sediment-bedrock interface (Figure 8.8b). The Guelph-Gasport formations yield from ~1 to 4 L/s with increasing yield proportional to enhanced secondary porosity, most likely from solution-

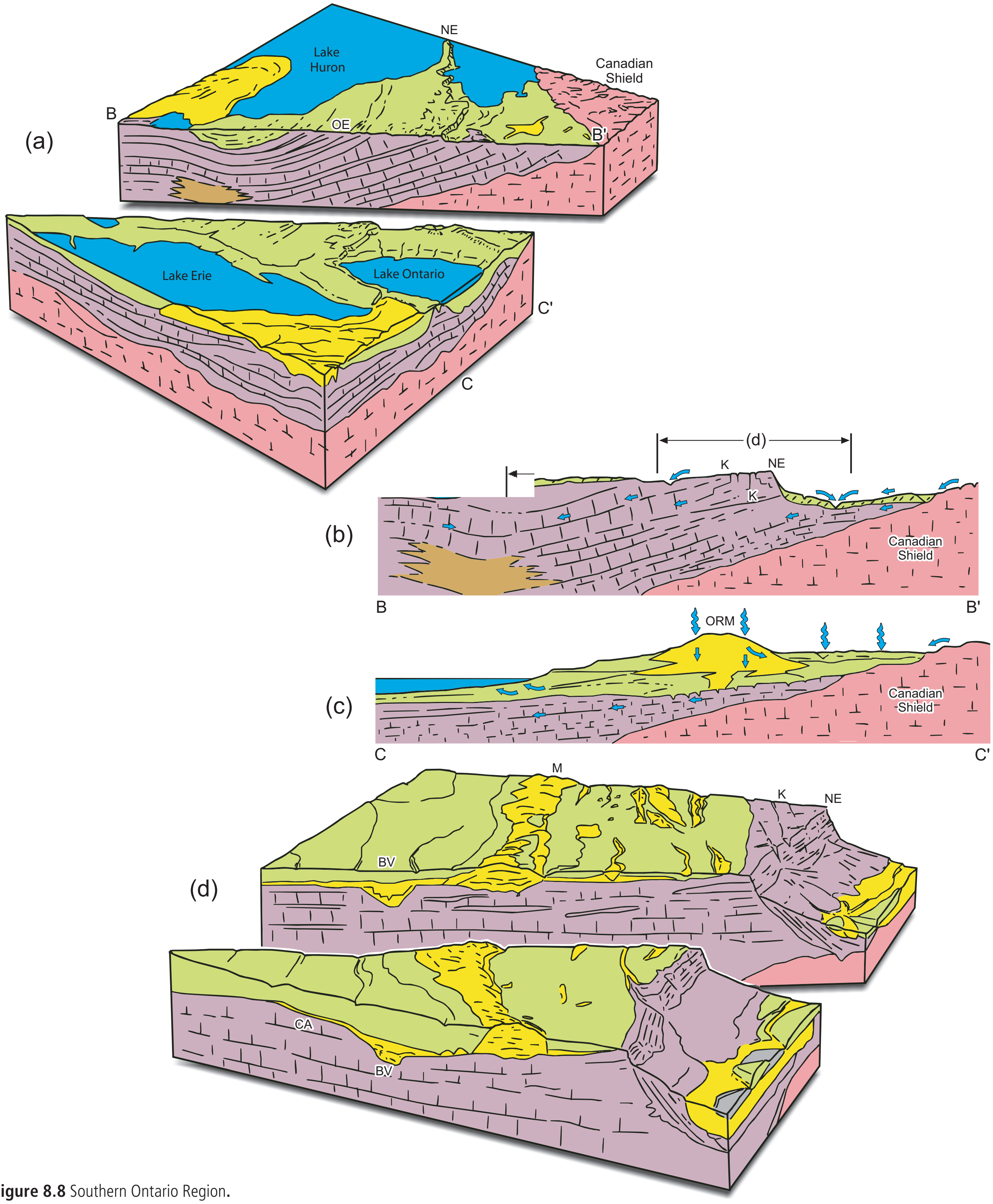

Figure 8.8 Southern Ontario Region**.**
a) bounded by three Great Lakes yet groundwater is significant for most water supply; **b**) regional cross section shows flow in thin shallow sediment covering thick rock strata conducting slow deep basin flow. Prolific regional aquifers, recharged through sediment, occur in shallow, southwest-dipping carbonate strata, likely influenced by karst (K), particularly along the Niagara Escarpment (NE). Regional bedrock-sediment contact aquifers are important; **c)** thick stratified moraines (e.g., Oak Ridges Moraine, Oro, Waterloo) are key recharge areas for lower-sediment and rock aquifers**; d)** extensive glacial sediment controls recharge and hosts significant aquifers in eskers, moraine (M), and buried valleys (BV). Regional bedrock-sediment contact aquifers (CA) are illustrated. Note section **d** is located along section **b**.

enhanced fractures and reef structures (Brunton et al., 2007). The Salina Formation has similar yields, yet flow is of lower-quality calcium sulphate waters. Further west, water quality declines away from escarpment freshwater recharge; also, shale rock yields low quantities of poor-quality water from the upper few metres of weathered and fractured sediment-bedrock contact zone. This sediment-bedrock contact zone is not well known but forms an important aquifer across the region (Figure 8.8d). Most baseflow values (a general estimate of groundwater discharge) for the Southern Ontario Region are low, although some intermediate and high values can be found in sand and gravel areas. This variability may be the result of both distribution of exposed and shallow bedrock and sediment deposits, and, differences in storage, permeability, and thickness of the overlying, mainly glacial sediments.

Groundwater use in Ontario shows that ~1.3 million people use groundwater from private wells, mainly from sediment-rock contact zone aquifers, and 1.9 million people use municipal supplies from stratified moraines and carbonate rocks. Much groundwater use is for agriculture (livestock and irrigation), although industrial use may be up to 35%, in sand and gravel producing areas.

8.3.6 St. Lawrence (Platform) Lowlands

The St. Lawrence Lowlands (Platform) extends along the St. Lawrence River and Ottawa valleys covering an area of ~45,000 km^2 (Figure 8.1). Shallow flat-lying marine strata of the lowlands are bounded by Precambrian Shield rocks of the Laurentian Highlands (Canadian Shield) to the north and east, and the Appalachian Mountains to the south (Figure 8.9a). This region includes the Ottawa valley, Anticosti Island, and archipelagos in the Gulf of St. Lawrence and Newfoundland coastal lowlands (Figure 8.1). The region has very high population density and is industrially active in the Quebec-Ottawa corridor. These facts, plus intense agriculture in the western terrain, creates a setting for potential water use pressures and conflicts.

Climate ranges from continental in the west to maritime in the east. The northeastern areas are notably cooler because of the effects of the Labrador Current. Mean annual temperatures range from 2.5°C to 5°C, while mean annual precipitation ranges from 800 to 1,100 mm/year. Spring arrives in the west in April, and snow may linger in the east into May. Mixed forests of sugar maple, yellow birch, eastern hemlock, and eastern white pine form the most stable vegetation in western areas but have been severely reduced in extent by extensive agriculture. Agricultural land practice has increased runoff from lands (e.g., tile drainage) that were once natural forests. Eastern areas have boreal forest cover.

The Lowlands are part of an ancient rift valley that is partially filled with ancient marine sedimentary rocks which rarely rise above 150 m elevation. Granitic intrusions of Monteregian Hills near Montreal region and Precambrian Shield inliers near Oka provide abrupt local relief, as well as bounding slopes to the margins of the area (Figure 8.9a). Low-relief physiography is inherited from subhorizontal Paleozoic sedimentary strata, mainly calcium carbonate and clastic rocks of the Appalachian basin (Figure 8.9a, b). These strata are up to 2,300 m thick and were deposited along a passive continental margin prior to Appalachian mountain building. Broad, gentle folds affect most formations whereas along the rift margins, extensive normal faulting offsets bedrock units by tens of metres. Fractures are solution-widened (karst weathering) in limestone carbonate rocks, most

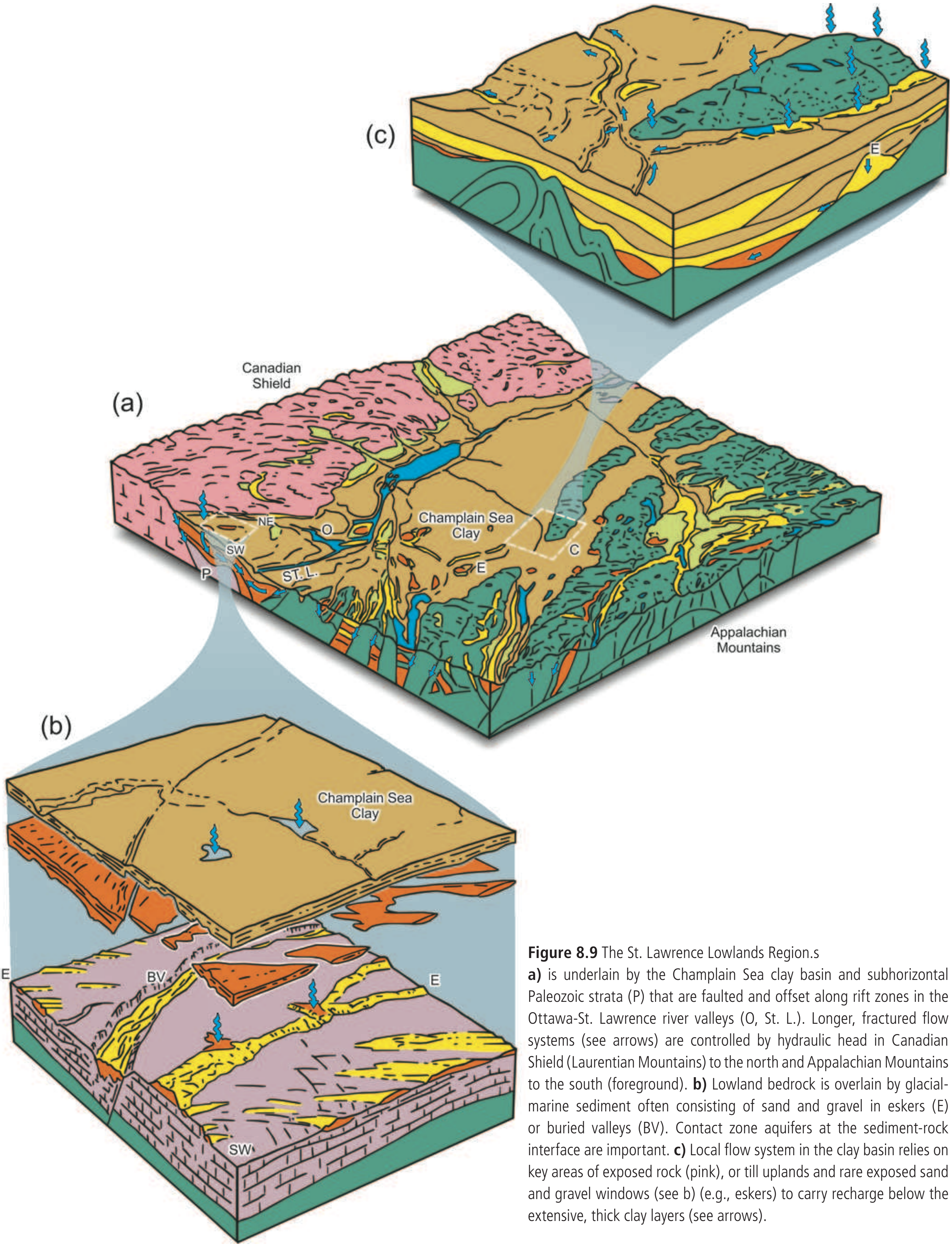

Figure 8.9 The St. Lawrence Lowlands Region.s **a)** is underlain by the Champlain Sea clay basin and subhorizontal Paleozoic strata (P) that are faulted and offset along rift zones in the Ottawa-St. Lawrence river valleys (O, St. L.). Longer, fractured flow systems (see arrows) are controlled by hydraulic head in Canadian Shield (Laurentian Mountains) to the north and Appalachian Mountains to the south (foreground). **b)** Lowland bedrock is overlain by glacial-marine sediment often consisting of sand and gravel in eskers (E) or buried valleys (BV). Contact zone aquifers at the sediment-rock interface are important. **c)** Local flow system in the clay basin relies on key areas of exposed rock (pink), or till uplands and rare exposed sand and gravel windows (see b) (e.g., eskers) to carry recharge below the extensive, thick clay layers (see arrows).

notably where sediment cover is thin, and along major rivers or escarpments. There is natural gas production in Southern Quebec from dolomite rocks and shale gas. The region experiences seismic activity, particularly from Saguenay Fjord to Quebec City.

Glacial marine and glacial sediment covers much of the area to < 20–30 m thickness, with maximum thicknesses of 150 m in bedrock lows (Figure 8.9b). Aquifers are hard to find but they are well-protected in this clay basin. An idealized stratigraphic succession from bedrock includes sub-till stratified sediment, till, glacial-fluvial sand and gravel, marine mud, then littoral/alluvial sediment. Thick, coarse sediment occurs as glacial-fluvial infill in buried valleys or in eskers (Figure 8.9b). The hydrological system is dominated by Ottawa and St. Lawrence rivers and tributaries incised into Champlain Sea muds.

8.3.6.1 Hydrogeology of St. Lawrence Lowlands

Bedrock aquifers are widely used, although fracture-controlled flow in bedrock (Figure 8.9b) results in decreasing yield with depth (Savard et al., 2013). Water quality also decreases with depth in these aquifers. In some areas, local natural gas occurrences can compromise groundwater quality and safety. Water yield from bedrock is often low, therefore most well drillers target the contact zone aquifer (Figure 8.9b), where water is drawn from the weathered, fractured and eroded interface between unconsolidated sediment and bedrock strata. Most shallow bedrock aquifers have poor aquifer yields and poor quality. This is partly due to common fracture systems in this seismically active rift basin which aid inter-formational water flow. This vertical flow may increase yields, but often lowers water quality due to flow from low-quality shale formation waters.

These formations often have chloride, sodium and sulphate well above provincial limits, and water is considered corrosive in some shale formations. Although shallow, Nepean sandstone, March sandy dolostone, and Oxford dolostone formations can have good water quality and locally can yield >50 L/s, comparable to glacial-fluvial esker aquifers (Figure 8.9b). Esker aquifers, confined by Champlain Sea mud, are important municipal aquifers (e.g., Vars-Winchester, Figure 8.9b); these aquifer systems may have lateral gravel sheets that extend the aquifer zone. Muddy marine sediment and local till also confine regional aquifers (Figure 8.9b, c). Widespread mud protects sediment and rock aquifers in the region. However, widespread low-permeability mud makes it difficult to recharge these aquifer systems except in small, porous upland settings (Figure 8.9b), or in a few intrusive bedrock settings (Figure 8.9c), where a larger upland terrain captures recharge and redirects it deeper into the clay basin along the sediment-rock interface. Groundwater is important in the western part of the region for maintaining summer streamflow in an area with net moisture deficient for four months of the year. Baseflow in the St. Lawrence Region is low with few intermediate and high values. Variability may result from the distribution of exposed and shallow bedrock and sediment deposits, as well as differences in storage, permeability, and thickness of these sediments.

A significant rural supply of water is drawn from the sediment-bedrock contact zone aquifer in the clay plains, and from fractured systems near uplands. Municipal supply is often from esker sand and the clay plains gravel below.

8.3.7 Appalachian Region

The Appalachian Region comprises the island of Newfoundland, Nova Scotia, New Brunswick and Quebec south of the St. Lawrence River (Figure 8.1). The ~249,000 km^2 area has a low population density and forestry operations are widespread. Extensive lakes, rivers, and high levels of precipitation ensure that surface water is the principal source of potable water, outside of agricultural areas.

The latitudinal range of the region and the continental and island components bordering the north Atlantic ensure a diverse climatic regime from east to west. Ocean water temperatures moderate climate of the eastern maritime region. In winter, extensive ice cover of the St. Lawrence can contribute to a more continental realm for bordering terrain. Temperatures vary between two distinct climatic regimes: i) maritime climate temperatures range from -2°C to 17°C; whereas ii) continental climate averages winter lows of -7°C and summer highs of 25°C. Highest precipitation values are in excess of 1,600 mm/year along Newfoundland south coasts and Cape Breton highlands. By contrast, continental areas have precipitation maximum of 1,200 mm/year. Mean annual precipitation is 800–1,200 mm/year. Frequent thaws and rainstorms in maritime area during mid-winter contribute to early season groundwater recharge. Other complex hydraulic events relate to large, late winter run-off/ recharge events triggered by moisture laden snow packs.

Continental forests are generally comprised of mixed conifers and deciduous stands of spruce, balsam fir, yellow birch, and maple. In Newfoundland, vegetation is diverse, ranging from moss-heath of the Avalon barren to stands of balsam fir and black spruce on steep, moist, upland slopes; wetlands cover >25% of the area. Much of coastal regions and raised domed bogs are dominated by open patches of dwarf white spruce, black spruce and tamarack. Sphagnum peat bogs are a significant part of the landscape.

The Appalachian Region can be divided into three broad physiographic regions: highlands, uplands and lowlands. The region is dominated by highland erosion surfaces (Figure 8.10a) that are highest in the northwest and slope southeastward to the ocean, from 1,500 masl in Gaspe to less than half that in Cape Breton and Newfoundland. Upland areas are most extensive in this region and form lower levels of the regional erosion surface. Large river valleys in New Brunswick (the Saint John and Restigouche river valleys, Figure 8.10a) are entrenched into the eroded uplands and produce significant local gradients. Lowland areas correspond with the Maritimes Basin.

Geology of the Appalachian Region represents an old, extensively eroded mountain belt (Figure 8.10a). Rock types reflect paleo-geographic and tectonic evolution, and include deformed fractured, metamorphic, volcanic, carbonate, and clastic strata (Figure 8.10a). Granite intrusions occur across the region and make up one third of all exposed rocks, particularly uplands. Sediment cover varies by physiographic region with the thickest sediment occurring in inter-upland valleys (Figure 8.10b). Highland areas are predominantly bedrock with thin discontinuous till cover, whereas the till cover in upland areas is more extensive (Grant, 1989). Eskers and other glacial landforms are common. Lowlands have thicker sediment cover as do buried bedrock valleys (Figure 8.10b). Buried and large river valleys

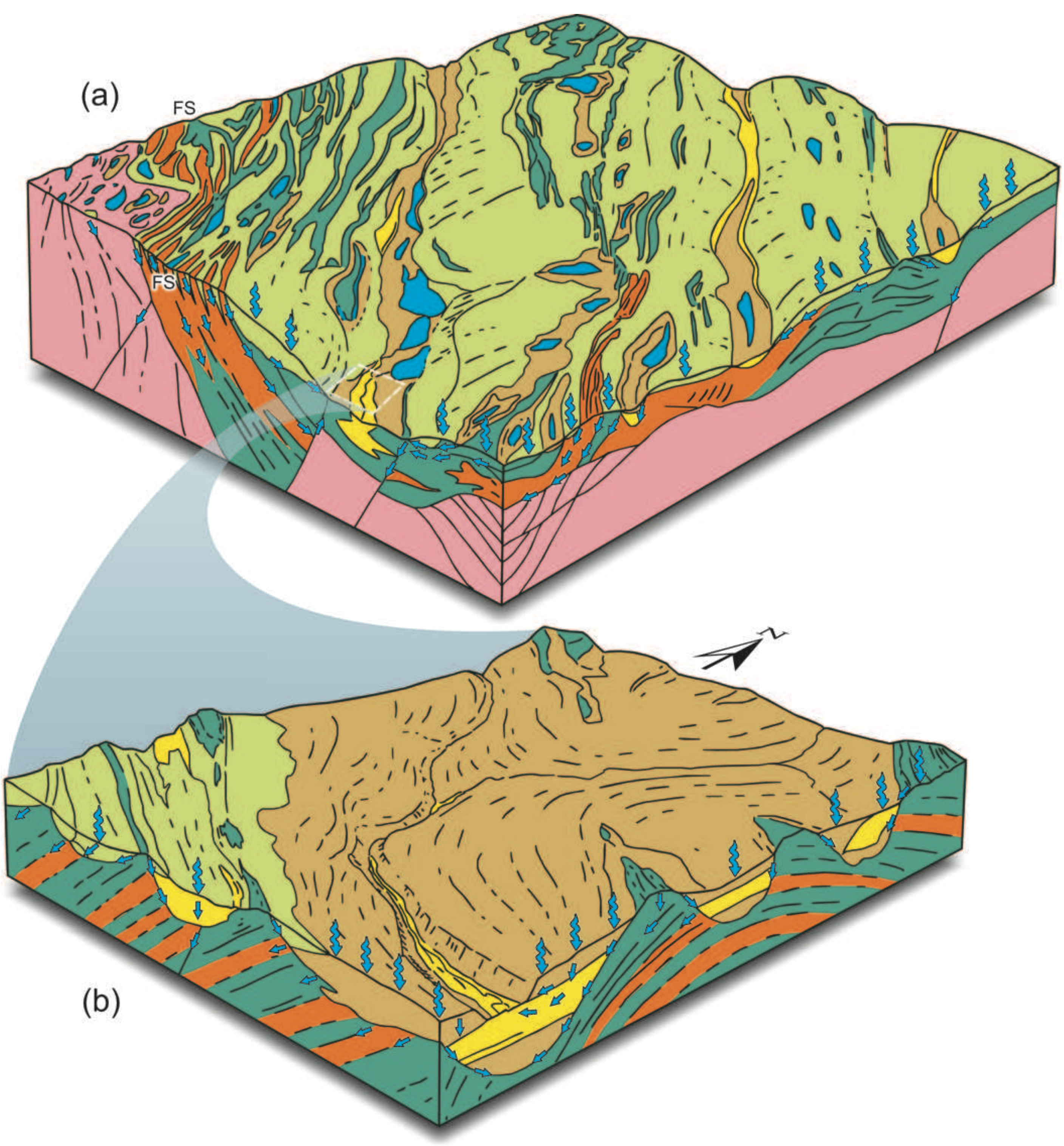

Figure 8.10 The Appalachian Region.
a) consists of uplands of folded, fractured sedimentary (FS), volcanic rocks (green) and plutonic rocks that provide hydraulic gradient, with thin sediment cover and structurally controlled NW-SE valleys. **b)** Thicker sediment occurs in valleys occupied by modern rivers and on slopes with thick glacial sediments; these are important areas for recharge in addition to infiltration into these fractured rock (see arrows).

may contain complex stratigraphy, but sediment often trends upward from gravelly, sandy to silty sediment. Terraces and fluvial incision mark main valleys (Figure 8.10a).

8.3.7.1 Hydrogeology of Appalachian Region

Despite receiving more rainfall than most regions in Canada, this area captures only a modest portion as recharge to groundwater (~10–20% of precipitation) due to the sloping, fractured-rock terrain with its discontinuous sediment cover. Recharge, as in most areas of the country, is seasonal with most occurring in late winter–early spring and in the fall. This region has a diversity of baseflow from groundwater with few high values, reflecting the influence of high slopes and overland runoff. Nevertheless, bedrock aquifers are the most significant source of groundwater in the Appalachian Region and are part of regional, intermediate, and local-scale flow systems (Figure 8.10a; see arrows). The water table is typically within 5 m of the surface. Typical seasonal variation in groundwater levels is usually less than about three metres. In Newfoundland for example, >90 % of water wells extract water from shallow bedrock units. Similar trends are present across the region. In general, the groundwater quantity available is variable because the rocks have low permeability and storage. Fracture permeability provides the primary groundwater storage and solution permeability is important locally. Groundwater yield from fractured bedrock aquifers (Figure 8.10a, b) is generally low, having average yields of 7.2– 64.8 m^3/day in Nova Scotia and Newfoundland. Bedrock yields of >1,440 m^3/day are not uncommon in some sedimentary bedrock aquifers (e.g., Annapolis Valley and Truro) and in the granitic rocks of Nova Scotia.

Monitoring and mapping of groundwater quality is being conducted from water sampling programs and by using regional bedrock geochemistry. Natural geochemical elements of concern include arsenic, uranium, fluoride, barium, iron, and manganese. Newfoundland has mapped potential areas of arsenic concern using lake sediment geochemistry and bedrock lithology, based on the close correlation that occurs between geology and water quality as water flows slowly through the rocks. Well yields in areas of thick sediment can be significantly higher than those from rock aquifers. Sediment valley fills often have high yields, and aquifers in some Nova Scotia wells, located in sand and gravel, may yield >7,200 m^3/day.

8.3.8 Maritimes Basin

The Maritimes Basin Region of Atlantic Canada covers ~59,000 km^2 in numerous structural basins. All of Prince Edward Island and Isles de la Madeleine occur within this zone (Figure 8.11a). Isolated elements occur in Newfoundland, Nova Scotia, New Brunswick, and along south shores of Gaspésie, Quebec (Figure 8.1). In Prince Edward Island and Isles de la Madeleine, groundwater use approaches 100%; elsewhere groundwater is used less than surface water.

Climate of the Maritimes Basin is humid continental with long winters and warm summers. It is one of the wettest parts of Canada with ~25% of precipitation occurring as snowfall. Because of low basin relief, distance to the sea is the major influence on weather. Indeed, coastal areas of the Northumberland Strait are cooled in summer and warmed in winter by the ocean. Prevailing circulation of continental air masses from the west allows much wider fluctuations in temperature than would be expected in a purely maritime climate. Daily average air temperature varies between 17°C and 24°C in summer and between -12°C and -4°C during winter. Average precipitation is ~900–1,500 mm/year; highest values occur along the Bay of Fundy. Mean annual evapotranspiration varies from 345 to 440 mm/year and results in a large water surplus. Mixed forests are composed largely of red, white, and black spruce, balsam fir, maple, hemlock, and white pine. Sugar maple and yellow birch are found on larger hills. Wetlands support white elm, black ash, and red maple, whereas bogs favour open black spruce, and tamarack.

The Maritimes Basin is part of the Lowland Appalachian physiographic region, and the relief is commonly <150 masl (Figure 8.11a); locally it rises to 300 masl in New Brunswick and Nova Scotia. Coastal areas in eastern portions of the basin are dominated by beaches to the north and by peat bogs and salt marshes to the southeast. Lowland plains are characterized by a series of subparallel structural ridges. Rivers occupy ancient valleys that broaden over extended flood plains as they approach the coast.

The Maritimes Carboniferous Basin consists of a series of sedimentary sub-basins (Figure 8.11a), which overlie older eroded Appalachian terranes. Sub-basins generally trend northeast to east and are separated by basement uplifts along large regional faults. The central part of the basin, termed "Maritimes Rift", features a thick sequence (<12,000 m) of mildly deformed and reworked sedimentary rocks. Main rock types are continental sedimentary and volcanic, with minor evaporites. Coal deposits are widespread in the basin and there are minor quantities of gas. Unconsolidated surficial sediment consists of till and glacial-fluvial deposits with small areas of marine clay (e.g., Rampton et al., 1984). Sand and gravel occur as narrow zones near major streams and glacial-fluvial corridors (e.g., Petitcodiac River, Sussex, New Brunswick). Muddy to sandy tills are common and can be up to 20 m thick.

8.3.8.1 Hydrogeology of Maritimes Basin

Groundwater is available in large quantities in the Maritimes Basin with flow mostly in bedrock fractures (Figure 8.11b). Cyclic sedimentary facies sequences mean that some layers act as aquifers, whereas others, within the same formation, act as aquitards. Groundwater flows mainly through fractures, yet significant quantities of water in sandstone and conglomerate are stored in matrix pores. The density of fractures means much of the bedrock can behave as equivalent porous media with mean hydraulic conductivities on the order of those of fine sand. Well yield can be high: Pictou Group red sandstone aquifers, for example, can produce municipal yields of 5–10,000 m^3/day. Groundwater quality is generally good except for high levels of iron, manganese, and calcium sulphate and sodium chloride in evaporitic rocks.

Till is thin, but widespread and adequately transmits water to permit significant recharge to bedrock aquifer systems since bedrock outcrops are rare. Potential recharge rates are ~100 to 400 mm/year. Baseflow discharge values are low in shallow bedrock and sediment deposits, and higher in thick sediment covered areas. Unconsolidated sediment aquifers, particularly glacial-fluvial sediments are important and can yield municipal supplies of 4,500 m^3/day of high-quality groundwater (e.g., in Sussex and Fredericton). Of concern in Prince Edward Island and the Isles de la Madeline is saltwater intrusion which, even in the absence of extraction, can migrate landward ~500 m beneath a thin surface freshwater lens because land to sea gradients are low (Figure 8.11b). In addition, sea levels have been rising for thousands of years, and fresh groundwater may occur in deeper aquifers, essentially trapped beneath intruding seawater in shallower aquifers (Van der Kamp, 1981).

Groundwater is used 100% as water supply in Prince Edward Island and Magdellan Islands (MI) from fractured sandstone aquifers. It is also used for irrigation in PEI agricultural areas.

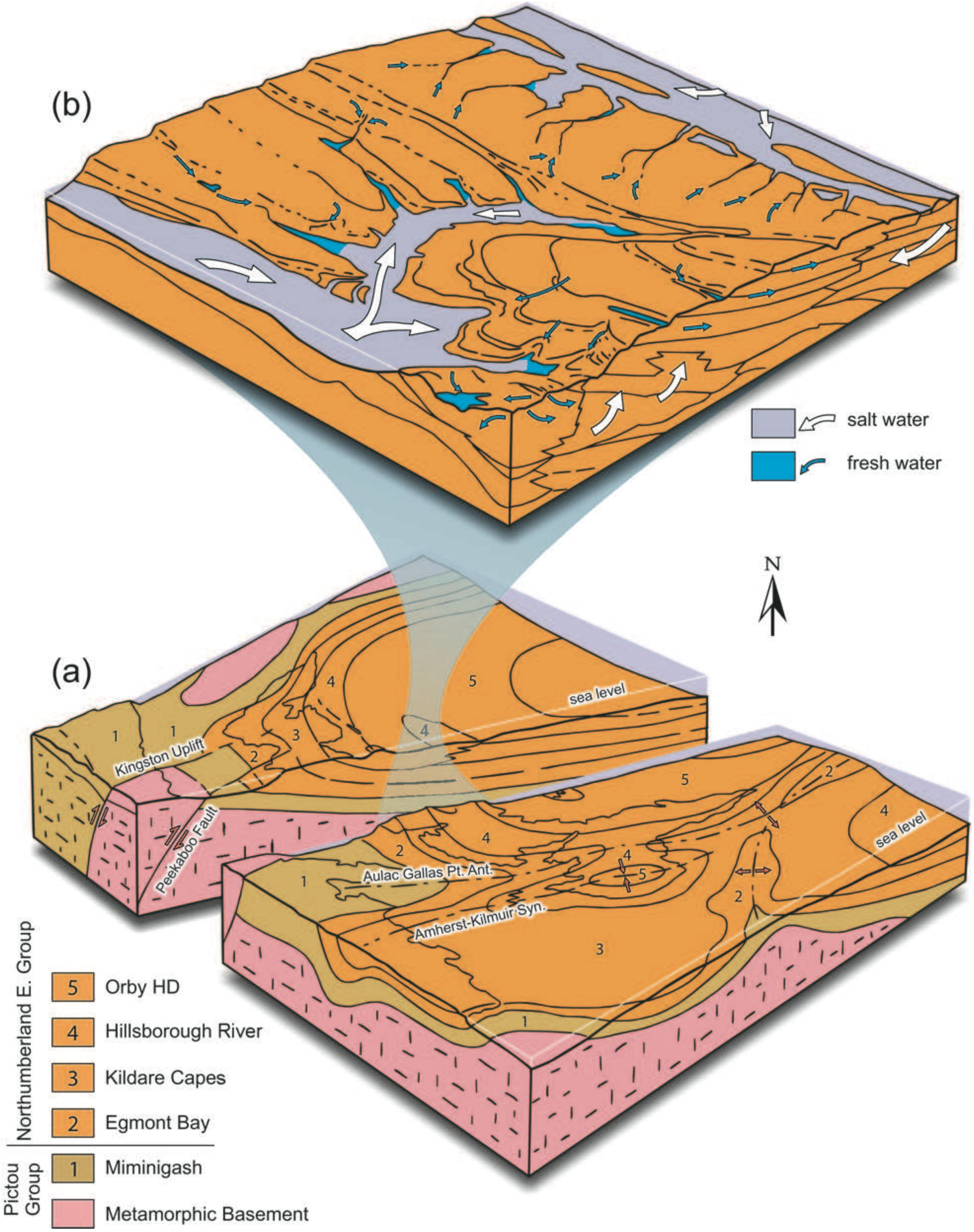

Figure 8.11 The Maritime Basin Region is an **a)** extensive, low-relief (< 150 m) region of small, fault-bounded basins (Amherst-Kilmuir syncline and Kingston uplift, for example) of predominantly sandstone with minor evaporite strata, centred on Prince Edward Island (PEI). Fracture systems control most groundwater flow and flow systems are shallow due to low-relief gradients. **b)** Low gradients may allow saltwater intrusion (sub-surface white arrows), induced by tides (offshore white arrows) along coastal regions. Prince Edward Island (PEI) and Magdellan Islands (MI) residents rely completely on groundwater for their water supply.

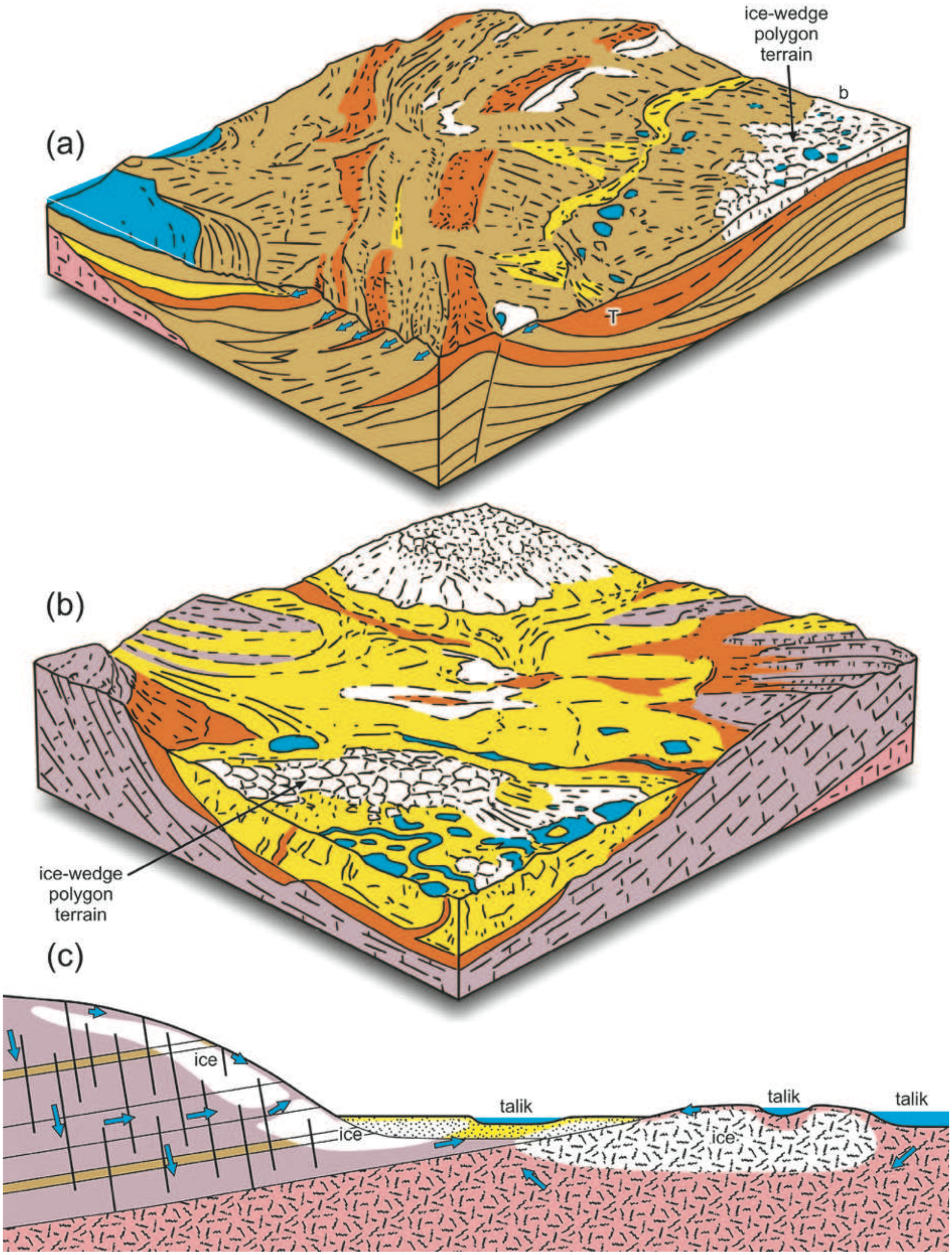

Figure 8.12 The Permafrost Region.

a) Diverse range of geology, topography and climate regions of northern Canada, as exemplified by this low-to-moderate relief, gently-inclined structural ridge and slope with scattered vegetation corridors and ice-wedge polygon terrain in muddy overlying sediment found in low moist areas. Taliks (T) occur beneath rivers, lakes and ponds with windows through permafrost. **b)** Lowland sedimentary basin with unconsolidated sediment cover shows more patterned ground typical of permafrost effects on groundwater flow and storage. **c)** Schematic cross-section shows that groundwater flow is controlled by sub-zero temperatures that maintain most water as bonded ice in a semi-permanent frozen state. This ice acts like aquitards that inhibit groundwater flow. Locally, taliks are important windows to groundwater flow within or below permafrost.

8.3.9 Permafrost

The permafrost region, 2.84 million km^2, covers the northern part of Canada exhibiting temperatures in rock or soil that remain at or below 0°C through the summer. Water in pores and fractures is normally frozen. This region includes all of Canada's Arctic area and parts of Nunavut, the Northwest Territories, Yukon, Manitoba, Ontario, Quebec, and Labrador north of the treeline (Figure 8.1). The southern margin is irregular because secondary features such as vegetation cover or snow depth begin to control where permafrost occurs due to the influence on heat exchange exerted by these factors (Figure 8.12a). Consequently, in the southern Yukon, upper Mackenzie valley, the northern prairie provinces and northern Quebec, permafrost occurs further south in particular settings such as peat bogs or on north-facing slopes (Figure 8.12b). On the land cover map of Canada (Figure 8.2), the vegetation break between tundra and the boreal forest is equal to the permafrost line on the hydrogeological regions map (Figure 8.1).

The climate of the permafrost region is dominated by continental and polar maritime (influenced by the ocean) subtypes. The main constant is that climate is affected by the extreme solar radiation conditions of high latitudes. Mean annual temperature ranges from -20°C on Ellesmere Island to -6°C along the southern boundary. Mean annual precipitation varies from 100 mm in the north to 600 mm in the southeast. Precipitation of the high arctic is the lowest in Canada, and this area is often referred to as a polar desert. Southern permafrost regions are characterized by dwarf shrubs that decrease in size and composition to the north where vegetation becomes dominated by herb and lichen; pattern ground such as ice-wedge polygon is typical permafrost terrain (Figure 8.12a, b).

The region covers the northern part of rugged terrain of the Canadian Shield and the gently undulating regions of the Mackenzie valley and Arctic Archipelago and mountainous areas. Mountainous terrain in the northern Cordillera is important because of the possible restriction of permafrost to lower elevations where atmospheric inversions in winter lower the mean annual air temperature.

The permafrost region contains a diverse array of geological elements, including igneous and metamorphic rocks of the Canadian Shield, subhorizontal sedimentary rocks of the central Arctic and folded and faulted sedimentary rocks of the northwest Arctic Islands. Evaporites are found in the subsurface both in the Mackenzie valley and central to northern Arctic Islands. Surficial sediment consists of regional till sheets, localized glacial-lacustrine and marine deposits, and glacial-fluvial deposits. In the Yukon, large valleys are filled with coarse glacial outwash and finer lacustrine sediment. Pattern ground is common on these sediments in permafrost terrain (Figure 8.11a, b).

8.3.9.1 Hydrogeology of Permafrost

The primary hydrogeological function of permafrost is to act as a barrier to groundwater flow (Figure 8.12c). This role as an aquiclude depends on permafrost being ice-bonded, i.e., having the pores or fractures of the water conducting medium filled with ice. Thus permafrost can act as the cover for a confined aquifer or it can form the base of an unconfined aquifer (Figure 8.12c). The permafrost active layer functions as a thin (<1 m) unconfined aquifer during the time the active layer is thawed in summer (Figure 8.12c). Unfrozen ground within permafrost or connecting the ground surface with unfrozen ground beneath permafrost is referred to as a

talik (Figure 8.12c). Taliks occur beneath larger surface water bodies (rivers and lakes) because the presence of (unfrozen) surface water precludes freezing of the underlying formations. These taliks represent recharge/discharge connections with the deeper groundwater beneath the permafrost. Discharge of groundwater from taliks can also result in icings, accumulations of ice on the ground surface that often occur along rivers or valleys. Large spring systems are also known to occur in regions of thick permafrost. As expected, most values of baseflow as groundwater discharge for the permafrost region are low.

Relatively little is known about the permafrost control on groundwater flow. Within the permafrost zone, groundwater is utilized most extensively in the southern Yukon. A number of communities draw their municipal supply from coarse valley fill aquifers which are likely confined beneath permafrost; however, little documentation for this exists. Confined aquifers beneath permafrost may exist on north-facing slopes in the southern parts of the permafrost zone. Permafrost becomes thicker in the northern regions of the zone, extending to depths >500 m, and precluding sub-permafrost aquifers.

8.4 SUMMARY

Delineation of hydrogeological regions provides a regional framework that links groundwater mapping to conceptual hydrologic patterns, and to land-water attributes across Canada. This framework promotes recognition of common and differing synoptic groundwater elements from area to area and within regions, allowing for water resource comparisons between regions, as well as for the transfer and exchange of hydrogeological knowledge across the country. The Cordillera, Shield and Appalachian regions, for example, are dominated by secondary permeability features and flow in fractured/ faulted, karstic and jointed rocks, and although this is the case, relatively thin, discontinuous unconsolidated sediment cover in these terrains produces significant water yields not apparent at regional scales. Hence, delineation of simple hydrogeological regions can effectively aid public discourse and knowledge of water occurrence, availability and its sustainable use.

Hydrogeological regions provide a framework to introduce the regional hydrogeology of Canada and to connect apparently disparate studies into a broader framework. The hydrogeological regions are first order areas used to capture and summarize the data which will help develop more detailed profiles of each region. Comparison of findings within and between regions allows scalable extension to subregional and watershed scale mapping. A GIS data model helps capture and exchange available digital map coverage (e.g., land cover map of Canada and subregions) and other data, while linking to all scales of groundwater information (see also Chapter 3). Groundwater census estimates at regional, provincial, and national scales require this type of basic resource identification.

ACKNOWLEDGEMENTS

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CHAPTER 9

CORDILLERAN HYDROGEOLOGICAL REGION

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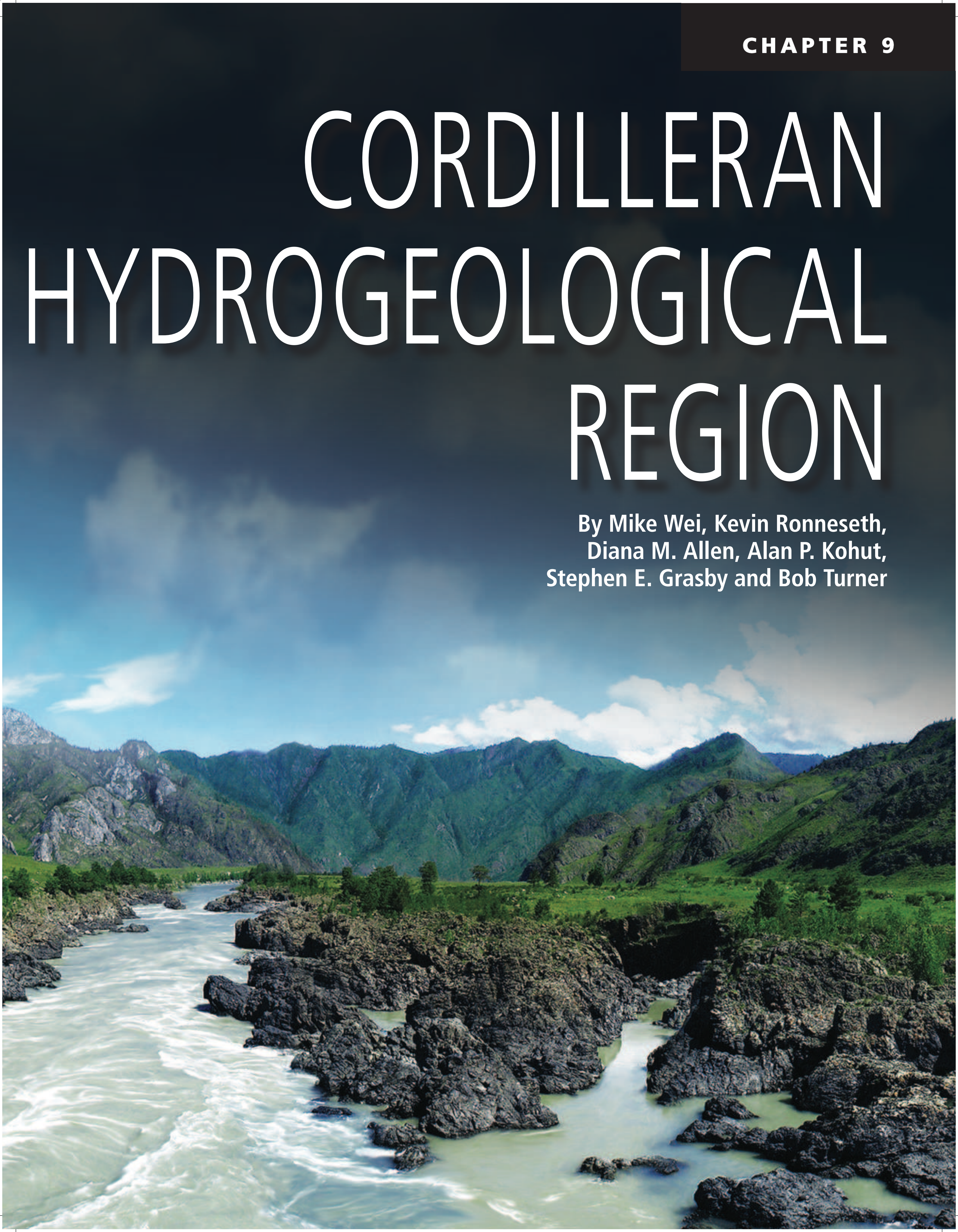

9.1 INTRODUCTION

9.1.1 Previous studies

The Cordilleran Hydrogeological Region (referred to as the "Cordillera" or the "Region" in this chapter) was first described by Halstead in *Groundwater in Canada* published by the Geological Survey of Canada (Halstead, 1967a). Subsequently, it was discussed as part of the Cordilleran region of North America, published by the Geological Society of America (Back et al., 1988). The Canadian Cordillera covers an area of ~1.4 million km^2 and includes parts of two provinces and two territories: most of the Province of British Columbia (except the Peace River region of northeastern British Columbia), part of the Yukon, the Rocky Mountains and Foothills of western Alberta and the western part of the Northwest Territories (Figure 9.1). The Region is vast and physiographically and geologically diverse.

The information and understanding of aquifers in the Cordillera presented in this chapter is based mostly on available local (and a few regional) studies in British Columbia (BC) and on the existing inventory of aquifers classified by the province of BC. BC began conducting groundwater studies in the Region during the 1950s, mostly to support development of groundwater supplies in local communities, and, within the last two decades, to assess local groundwater quality issues. Many of these groundwater reports can be accessed through the Ministry of Environment's Ecological Reports Catalogue—EcoCat http://www.env.gov.bc.ca/ecocat/. In 1994, *Groundwater Resources of British Columbia* provided a region-by-region overview of groundwater conditions in the various physiographic regions in BC (BC Environment and Environment Canada, 1994). The Federal government has also conducted groundwater studies in the Cordillera since the mid-1950s. These early studies focused mainly on describing groundwater conditions of parts of Vancouver Island (Halstead and Treichel, 1966; Halstead, 1967b), the Lower Fraser Valley, east of Vancouver (e.g., Halstead, 1957; Halstead, 1959; Halstead, 1961; Halstead, 1964; Halstead, 1986; Armstrong and Brown, 1963), other locales (Lawson, 1968; Brandon, 1964) as well as on thermal and mineral springs (van Everdingen, 1972). In the 1990s the Geological Survey of Canada characterized the aquifer at Langley (Ricketts and Makepeace, 2003). Recent regional groundwater studies, including many completed by Simon Fraser University in partnership with federal, BC, and local governments, have focused on aquifers at Abbotsford in the Lower Mainland (Liebscher et al., 1992; Hii et al., 1999; McArthur and Allen, 2005; Scibek and Allen, 2005; Scibek and Allen, 2006a; 2006b, Chesnaux and Allen, 2007; Chesnaux et al., 2007), Grand Forks in the southern interior, along the Canada-USA border (Allen, 2000; Allen, 2001; Allen et al., 2004a; 2004b; Scibek and Allen, 2003; 2004; 2006c; Scibek et al., 2004; Scibek et al., 2007; Wei et al., 2004), the Gulf Islands between Vancouver and Vancouver Island (Allen, 2004; Allen et al., 2003; Allen et al., 2002; Allen and Suchy, 2001a; 2001b; Allen and Matsuo, 2001; Dakin et al., 1983; Denny et al., 2007; Mackie, 2002; Surrette and Allen, 2008; Surrette et al., 2008), and most recently, in the Okanagan Basin (Carmichael et al., 2008; Liggett, 2008; Liggett and Allen, 2010, 2011; Liskop and Allen, 2005; Neilson-Welch and Allen, 2007; Toews, 2007; Smerdon et al., 2009, 2010; Voeckler and Allen, 2012). These study areas are heavily dependent on groundwater and have ongoing quality and quantity concerns.

In 1994, the Province of British Columbia developed the *Aquifer Classification System* to identify and classify *developed*[1] aquifers as a means of providing summary information to assist with groundwater management in BC (Kreye and Wei, 1994; see Box 9-1). Aquifers were identified and classified on the basis of available well records, geologic mapping and groundwater reports on file at the time. 888 aquifers were identified and classified in the BC Cordillera, as of December 31, 2007. This work has resulted in a numbered inventory of developed aquifers and their basic characteristics for a large part of the Cordillera where groundwater is being used. These aquifers can be viewed at the BC Water Resources Atlas website http://webmaps.gov.bc.ca/imf5/imf.jsp?site=wrbc. Although numerous developed aquifers exist in the Region, only a small percentage have been sufficiently studied. As a result, our discussion of aquifers in the Cordillera does not follow a region-by-region approach: instead we decided to present and discuss them based on aquifer type, profiling a few of the better studied examples within these type categories. For discussion, the Cordillera's 888 classified aquifers can be grouped according to lithologic, morphologic, stratigraphic, and structural criteria. Each aquifer type is expected to have unique hydrogeological characteristics: nature of its origin, size and location, depths, yields, permeability and vulnerability and potential connection to surface water.

9.2 PHYSICAL SETTING AND CLIMATE

The Cordilleran Hydrogeological Region comprises massive mountain ranges, highlands, foothills, plateaus, basins, and lowlands. The region extends westerly to the Pacific Ocean, from an eastern boundary with the Interior Plains region of Alberta and northeastern British Columbia, and is bounded by the international border with the United States of America to the south (Figure 9.1). The Cordillera has the highest relief in Canada—5,959 m (from sea level at the coast to Mount Logan in the Elias Mountains of the Yukon Territory). The Region includes three major physiographic areas (Holland, 1976) from west to east:

1. Western system of northwesterly-trending coast mountain ranges, coastal lowlands and basins
2. Interior system comprising several major and minor mountain ranges, plains, plateaus, and basins
3. Eastern system of northwesterly-trending Rocky Mountain ranges, foothills and the Liard plateau

The climate of the Cordillera varies from semi-Mediterranean conditions along the southern west coast to polar conditions at high mountain elevations in the north. Mean annual precipitation (Environment Canada, 2006) generally decreases from west to east (following the general movement of the weather fronts), varying, for example, from 1,403 mm at Sandspit in the Queen Charlotte Islands to 293 mm at Kamloops, to 472 mm at Banff Alberta (refer to the graphs in Figure 9.1). Annual precipitation generally increases with elevation in any given area, due to orographic effects. Figure 9.1 includes a graphical summary of average monthly precipitation and, where available, groundwater level data for several long-term climate stations and observation wells. Average monthly climate data for other locations is available from Environment Canada's website: http://www.climate.weatheroffice.ec.gc.ca/index.html.

Seasonal climatic variations control the annual amount and form of precipitation (i.e., rain or

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[1] *Developed* aquifers are aquifers wherein wells have been completed to utilize groundwater.

snow) falling in drainage areas, thereby affecting runoff and the amount and timing of groundwater recharge. Coastal regions experience highest precipitation during the winter months. Much of this precipitation falls as rain (temperatures are above freezing), except at higher elevations where it generally falls as snow (temperatures below freezing). Much of the groundwater recharge in these coastal regions tends to occur during the winter months when the rate of transpiration is at its seasonal lowest. Consequently, natural groundwater levels in aquifers located within coastal regions show a seasonal high during winter or early spring, and generally decline from spring to late fall (see the average monthly groundwater levels for Nanaimo and Abbotsford in Figure 9.1). In contrast, interior stations have their highest precipitation during the summer months (mostly as rain). Much of this precipitation is not available for recharge because evaporation and transpiration are highest during the summer months (when the mean daily air temperature is highest). As well there is no excess water available to infiltrate past the root zone for aquifer recharge (e.g., Liggett and Allen, 2010; Toews and Allen, 2007; Smerdon et al., 2009, 2010). In these interior regions, snow accumulations during winter months, and at higher elevations, are important for recharge during spring and early summer months when snowmelt occurs. Natural aquifer groundwater levels in the interior are generally at a seasonal high in late spring or early summer and then decline over the summer and early fall. The groundwater level usually reaches a seasonal low during the winter months in these areas because precipitation at the land surface is frozen and not available for recharge (see the monthly groundwater levels for Kelowna and Cranbrook in Figure 9.1).

9.3 GEOLOGIC SETTING

9.3.1 Surficial geology

Despite their geological and physiographical diversity and complexity, aquifers in the Cordillera can be grouped into two broad types: *unconsolidated* or *surficial* aquifers, and *bedrock* aquifers. Most unconsolidated aquifers in the Region are formed by deposition of sand and/or gravel in moving water under a *fluvial* or, if by moving water during glacial times, a *glaciofluvial* environment. Surficial geology and glacial history have a major influence on the *lithology*, form or *morphology*, and *stratigraphic* location of sand and gravel deposits (location of the geologic deposit in relation to other geologic deposits). Therefore, the occurrence and characteristics of unconsolidated sand and gravel aquifers. The *lithology* of the sands and gravels—e.g., the grain size, sorting, and porosity—affects its primary permeability and storativity, while the mineralogical make-up can influences the natural chemical quality of the groundwater. The morphology of the sand and gravel deposit influences its thickness, shape, and extent and its stratigraphic location (relative to other less permeable, surficial deposits, such as clay, till) determines whether a particular deposit will be shallow or deep, confined or unconfined, vulnerable or not vulnerable, and directly influenced by or connected to surface water or not.

The Cordillera has experienced several periods of glaciation (BC Environment and Environment Canada, 1994; Armstrong, 1981; Fulton, 1975). The surficial geology and unconsolidated aquifers of the Region, however, mostly reflect the last glaciation period (Fraser Glaciation), which occurred during the Late Wisconsinan (about 30,000 years to 10,000 years ago) (Clague, 1994). Ice built up rapidly, especially during the climatic

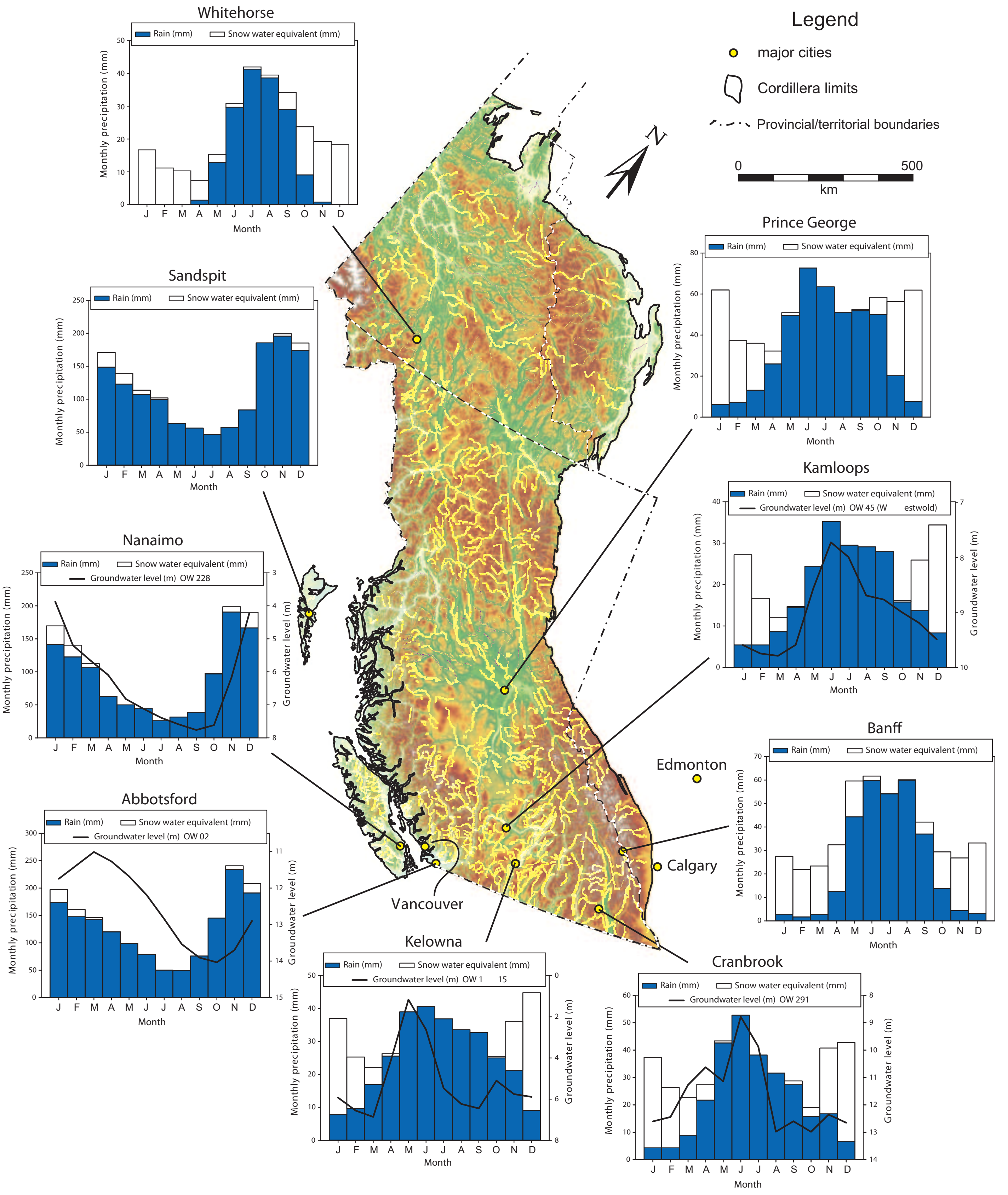

Figure 9.1 Map of the Cordilleran Hydrogeological Region and information on select climate stations and observation wells.

Vashon Stade[2] (18,000–12,000 years ago). In less than 4,000 years glaciers advanced down mountains to coalesce in lowlands and plateaus, creating a vast continental ice sheet that covered the entire Region. At maximum glaciation, the Cordilleran ice sheet covered BC, Yukon, and Southern Alaska and stretched south to Puget Sound in Washington State (Clague, 1994). This sheet developed in the high areas of the Coast Mountains and extended across the entire Pacific coast, achieving a thickness of approximately 2,000 m in the major valleys. Only the highest mountain tops and a few locations near the western margin of the ice sheet were not covered.

Ice sheet melt was much more rapid than ice sheet growth. Between 16,000 years and 12,000 years ago, the ice began to disappear as the climate warmed: melting exceeded ice build-up. Retreat began at the continental shelf, proceeding eastward and northward. Glaciers were active near the end of the Fraser Glaciation, and were restricted to valleys and fjords. Less than 1,000 years after the beginning of deglaciation, present-day Vancouver and Victoria were ice-free. Lowlands were free of ice 12,500–13,000 years ago, and by about 9,500 years ago, glaciers had essentially the same extent as they do today.

The various ice advances removed most

[2] Period of glacial advance.

sediments deposited during previous glaciations. Much of the removed material was "reworked" by the ice and deposited under the ice as till. Generally only sediments from the most recent period of glaciation (the Fraser Glaciation) remain. Older surficial deposits have mostly been obliterated, existing only in isolated locations and as sediments at depth (see the lower orange-coloured aquifer in Figure 9.2a). Knowledge of glacial and inter-glacial surficial deposits prior to the Fraser Glaciation is minimal.

Sands and gravels deposited by meltwaters at the margins of advancing glaciers during the onset of the Fraser Glaciation formed productive aquifers. The advancing glaciers overrode these same sands and gravels, depositing a layer of till on top. Sand and gravel deposits were confined by the till above (see the orange-coloured aquifers confined directly above by the greenish till in Figures 9.2a and 9.3a). The lithology and morphology of these "advance" glaciofluvial sand and gravel deposits are quite varied, and depend on such factors as size of the glaciated area, the steepness and topography of the underlying ground, amount of meltwater, availability of sands and gravels, and distance of sediment transport. One well-studied example of an advance-type glaciofluvial sand and gravel deposit is the Quadra Sand, which occurs along the east coast of Vancouver Island and the BC Coastal Mainland, a principle aquifer in the local area (Clague, 1977). The Quadra Sand was formed by deposition of sand from meltwater streams as a tongue of the Cordilleran ice sheet advanced south along the depression of what is now the Strait of Georgia (the upper orange-coloured aquifer in Figure 9.2a). Similar glaciofluvial sand and gravel deposits formed at the onset of the Fraser Glaciation are evident from well records where sand and gravel occur directly beneath till. Glaciers also dammed drainage courses in many major valleys of the Region's interior, causing glacial lakes to form behind them (the South Thompson River valley, Okanagan Lake, Nicola Lake). Vast amounts of fine-textured silt and clay sediments were transported from tributary streams into these glacial lakes and deposited in the lake's stillwater (*glaciolacustrine*) environment. These silt and clay deposits covered the till beneath the lake and provided a thick confining layer (in addition to the till) above advanced sand and gravel deposits in these interior valleys (see the brown-coloured silt and clay layer in Figures 9.3a). Examples of these silt and clay deposits can be seen beside the South Thompson River east of Kamloops along Highway 1, or beside Lake Okanagan near Penticton.

Unconsolidated aquifers associated with glaciofluvial coarse sands and gravels deposited at the end of the Fraser Glaciation, as glaciers were melting, are typically some of the most productive aquifers in the Region. Meltwaters formed streams capable of moving vast quantities of gravel and sand, depositing them along present-day river valley bottoms (see the yellow-coloured aquifer in Figure 9.3a). Many of these deposits are evident along river valley bottoms as terraces, and are hydraulically connected to the river (e.g., at Grand Forks). Sands and gravels were also deposited onto outwash plains (e.g., at Abbotsford) or deltas (and often rose above present local sea or lake levels as a result of land rising after the ice melted). Since these sands and gravels were deposited at the end of glaciation, many of them have not been covered over by other less permeable deposits and, therefore, are unconfined (see the yellow-coloured aquifer on the left in Figure 9.2a). The Abbotsford-Sumas Aquifer is an example of an unconfined glaciofluvial sand and gravel outwash deposit formed at the end of the Fraser Glaciation (see Box 9-2). Sands and gravels were also deposited onto existing ice during glacial time. As the underlying glacier melted away, the sand and gravel deposits later collapsed to form kames (e.g., aquifers at O'Keefe Valley and Grandview Flats near Armstrong, BC).

Other important unconsolidated aquifers in the Cordillera include more recent fluvial sand and gravel examples, formed during the last 10,000 years (see the yellow-coloured aquifer in the centre of Figure 9.2a). These sands and gravels are deposited by rivers and streams and comprise floodplains (along the Fraser River, the Cowichan River in southern Vancouver Island, the Bow River near Banff, or along smaller streams), deltas (sand and gravel deposited at the mouth of Adams River, famous for its sockeye salmon run, at Shuswap Lake), or alluvial fans (the Vedder River fan at the town of Chilliwack). Although fluvial deposits tend to be unconfined, they can be locally confined in those areas where moving water has slowed and silt or clay has been deposited. Because these sands and gravels are deposited by present-day rivers and streams, they are usually hydraulically connected to the adjacent river or stream.

Sand and gravel deposits are also found along steep mountainous

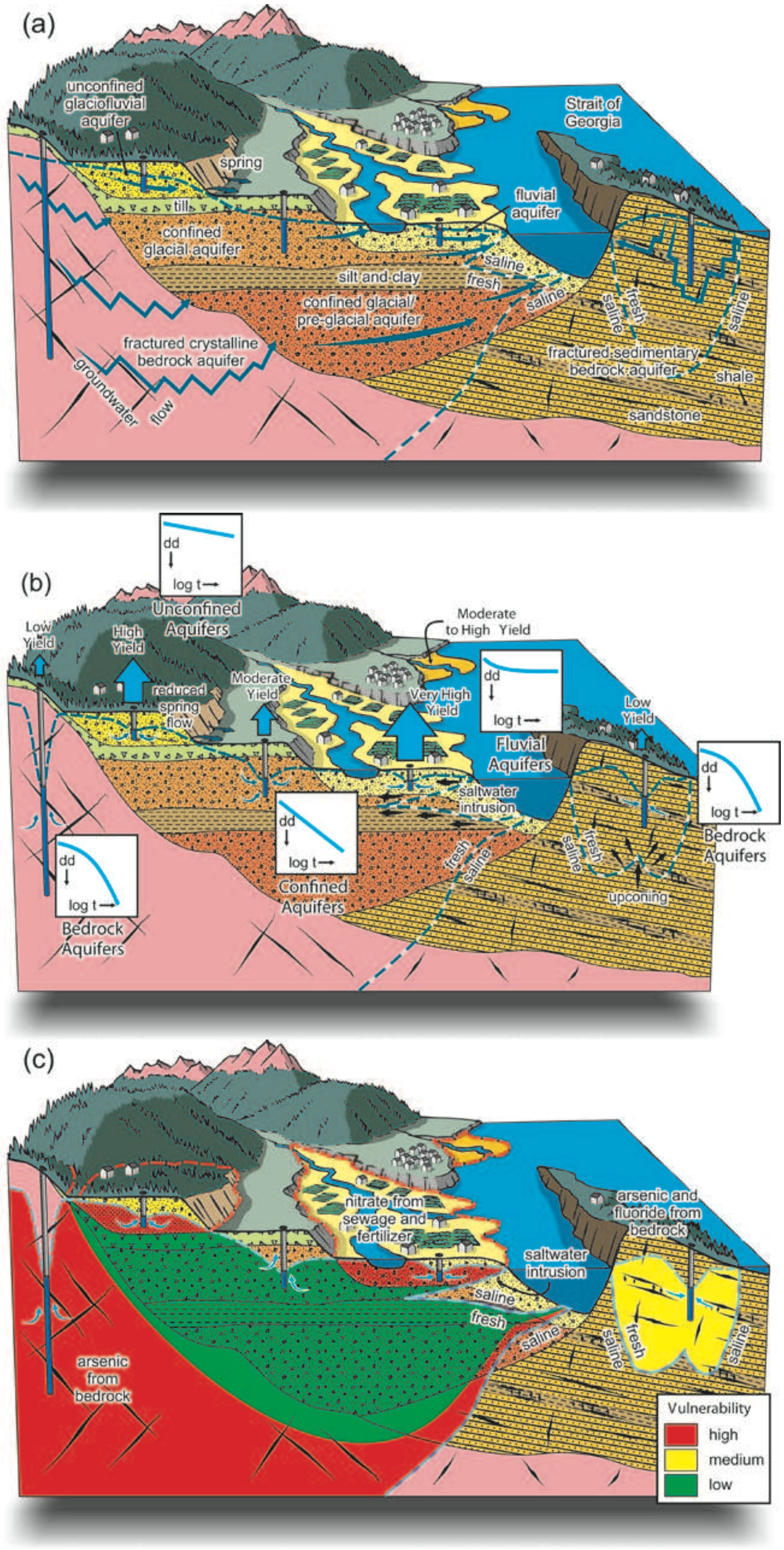

Figure 9.2 Schematic diagram of aquifers in a coastal setting, with respect to **(a)** general geologic, **(b)** hydraulic, and **(c)** vulnerability characteristics. In **Figure 9.2(b)**, the graphs represent how the groundwater level in the well is expected to draw down (dd) over time during pumping, for wells drilled into some of the different types of aquifers.

slopes. These colluvial deposits are primarily formed, not solely from water deposition but rather by gravity. Although colluvial deposits are coarse-textured, they tend to be less well-sorted than fluvial or glaciofluvial deposits and, with their typically limited extent and thickness, are of more limited potential as aquifers.

9.3.2 Bedrock geology

The bedrock geology of the Cordillera is extremely varied and complex due to the Region's geologic, tectonic, and volcanic history. Holland (1976) generalized the Cordillera's bedrock geology into six main types (see Figure 9.4):

1. Intrusive igneous rocks
2. Flat-lying lava, and some sedimentary rocks
3. Flat or gently-dipping sedimentary rocks
4. Folded sedimentary rocks
5. Folded and faulted volcanic and sedimentary rocks
6. Foliated metamorphic rocks

The Western system is comprised mostly of intrusive igneous rocks (the light pink rock in Figure 9.4). This is the main rock type forming the Coast Mountains. Vancouver Island, however, is comprised mostly of folded and faulted volcanic and sedimentary rocks (grey-green and yellow, respectively in Figure 9.4). The southern east coast of Vancouver Island and the Georgia Basin, including the Gulf Islands, are comprised of gently-dipping sedimentary rocks, the Nanaimo Group (Mustard, 1994), overlying older basement rocks.

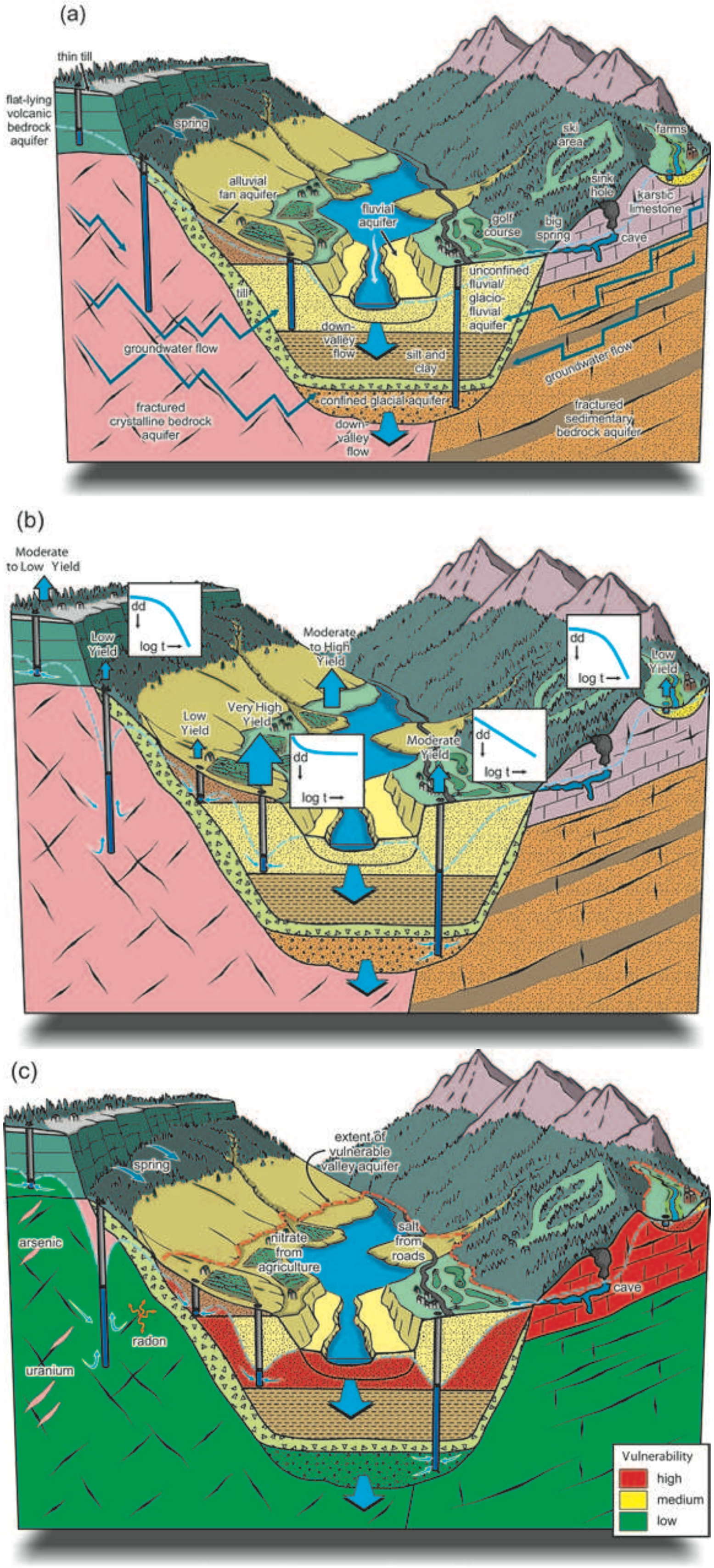

Figure 9.3 Schematic diagram of aquifers in an interior setting, with respect to **(a)** general geologic, **(b)** hydraulic, and **(c)** vulnerability characteristics. In Figure **9.3(b)**, the graphs represent how the groundwater level in the well is expected to draw down (dd) over time during pumping, for wells drilled into some of the different types of aquifers.

Groundwater from these bedrock aquifers is an important source of water supply on Vancouver Island and in the Gulf Islands.

The Eastern system is mostly comprised of folded sedimentary rocks, which form the spectacular Canadian Rocky Mountains (yellow in Figure 9.4). The Interior system is comprised of all six bedrock types, much of which is folded and faulted volcanic and sedimentary rock. A few notable exceptions are the flat-lying lava in the central interior (grey-green in Figure 9.4), foliated metamorphic rocks (as part of the crystalline rock, the light-pink in Figure 9.4) in the Okanagan and Shuswap areas, and flat or gently-dipping sedimentary rocks in the north (in the Spatsizi Plateau and in the area north of Takla Lake).

Despite the presence of different types of bedrock in the Cordillera, permeability exists mostly as a result of development of interconnected porosity, after bedrock formation. This secondary porosity developed either as fractures or faults from tectonic forces or, in limestone, dissolution cavities. Here fractures and faults developed in igneous intrusive, foliated metamorphic, and folded and faulted volcanic and sedimentary rocks, giving these types of rocks sufficient *secondary permeability* to form aquifers (see Figure 9.2a). This permeability, therefore, is generally *anisotropic* (permeability dependent on direction of groundwater flow) because the fractures or faults are discrete and have specific orientations in the bedrock. Porosity and storativity of fractured or faulted bedrock are also very low (a porosity of less than a few percent). We know fractures and faults can store and transmit groundwater because, since the 1970s, drillers, using air rotary drilling rigs, have observed and recorded the fractures and their water yield in their well record when drilling in bedrock.

Limestone sedimentary rock formations may have significant secondary permeability because of large *karst* openings or cavities in rock created as a result of fracture dissolution by water. These cavities can allow huge amounts of groundwater flow through the limestone. Although there are some springs in limestone formations in the Rocky Mountains with flows of up to several tens of litres per second (see Figure 9.3a), the occurrence and extent of karst limestone aquifers in the Cordillera are not well known.

Extensive areas of central British Columbia are underlain by relatively unaltered, flat-lying lava of Tertiary age (e.g., the Fraser and Nechako Plateaus in the central part of the Region). These are mostly basalts and individual flows that can be hundreds of metres thick. This lava serves as an aquifer because groundwater typically occurs in joints, as well as fractured and weathered contact zones between the lava flows (see Figure 9.3a).

9.4 MAJOR AQUIFER TYPES AND THEIR GENERAL CHARACTERISTICS

There are six main aquifer types (four with subcategories) within the Cordilleran Region:

Unconsolidated aquifers

Type 1 Unconfined sand and gravel aquifers of fluvial or glaciofluvial origin occurring along rivers or streams

a. Aquifers occurring along large rivers
b. Aquifers occurring along mid-size rivers or streams
c. Aquifers along small streams

Type 2 Predominantly unconfined deltaic sand and gravel aquifers

Type 3 Predominantly unconfined alluvial fan, colluvial sand and gravel aquifers

Type 4 Sand and gravel aquifers of glacial or

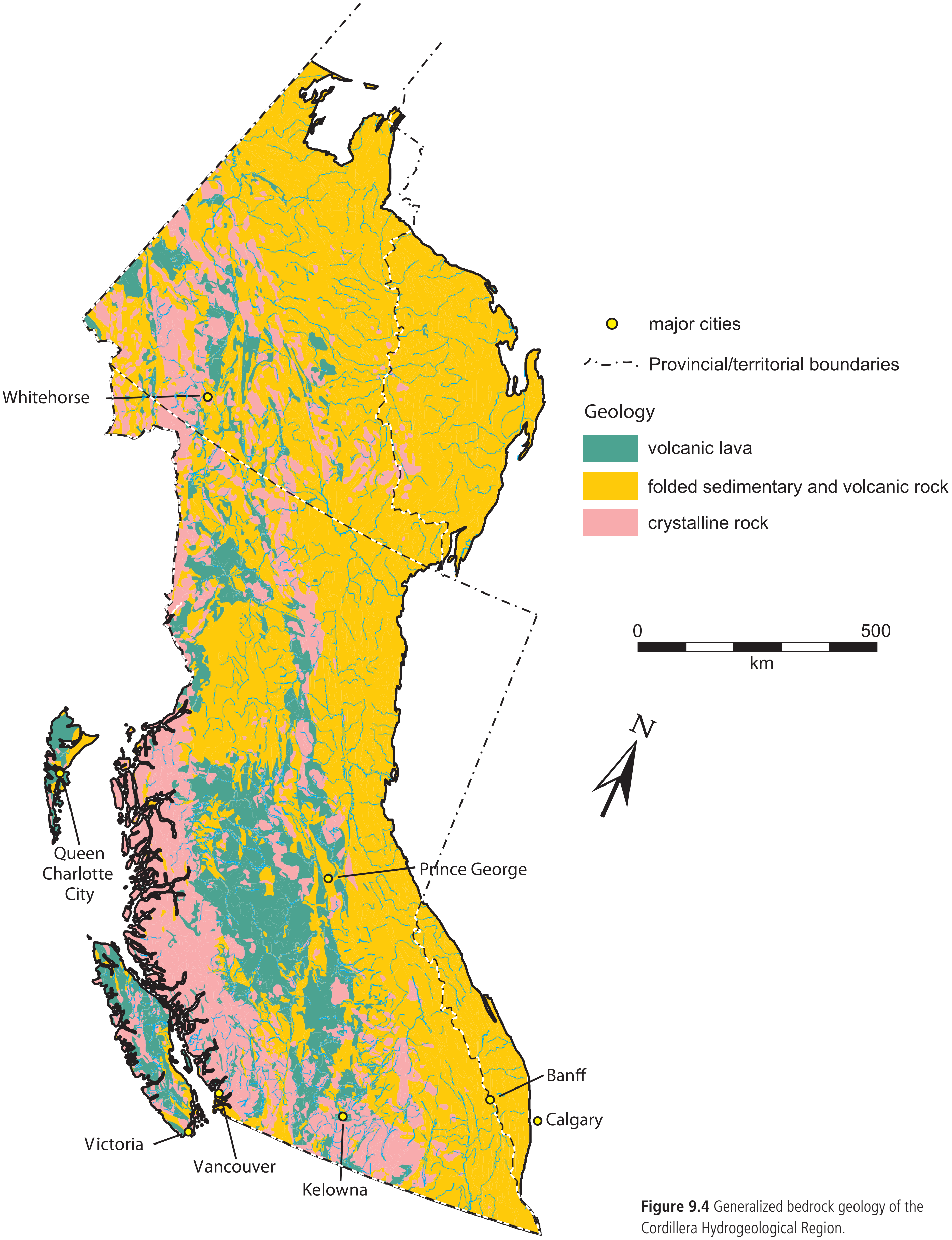

Figure 9.4 Generalized bedrock geology of the Cordillera Hydrogeological Region.

preglacial origin

a. Unconfined sand and gravel aquifers of glaciofluvial origin (These types of aquifers do not generally occur adjacent to present-day rivers.)
b. Confined sand and gravel aquifers of glacial or preglacial origin
c. Confined sand and gravel aquifers associated with glaciomarine environments

Bedrock aquifers

Type 5 Sedimentary bedrock aquifers

a. Fractured sedimentary bedrock aquifers
b. Karstic limestone aquifers

Type 6 Crystalline bedrock aquifers

a. Flat-lying or gently-dipping volcanic flow rock aquifers
b. Crystalline granitic, metamorphic, metasedimentary, meta-volcanic and volcanic rock aquifers

These categories and subcategories of aquifer types are based on geologic and hydrologic, as well as data availability considerations. Many of the aquifer types are illustrated in Figures 9.2a (coastal setting in the Region) and 9.3a (interior setting in the Region). General characteristics for the types of aquifers found in the Region are summarized in Table 9.1.

The main geologic factor in these descriptions is the type of the geologic deposit which comprises an aquifer (e.g., unconsolidated sand and gravel deltaic aquifer at the mouth of a river or a plutonic granitic fractured bedrock aquifer). Geologic deposit is important because it governs an aquifer's hydraulic properties, such as hydraulic conductivity and specific storage.

Another consideration for unconsolidated aquifers is origin and location with respect to surface water bodies, such as rivers, because location may allow a direct hydraulic connection with surface water. Direct hydraulic connection can impact potential well yields because pumping may induce surface water infiltration into these aquifers.

Other possible implications include direct impact on the baseflow of rivers from well pumping or the influence of groundwater quality from the river or lake water. A practical consideration, particularly for unconsolidated buried and gravel aquifers overlain by other unconsolidated deposits, is that it is often difficult to identify their origin based on current limited well record data. It is usually challenging, for example, to determine whether a buried unconsolidated sand and gravel aquifer occurring beneath till or clay is a delta, alluvial fan, or glaciofluvial deposit. Such an aquifer would be lumped into Type 4b as a confined unconsolidated sand and gravel aquifer of glacial or preglacial origin. Similarly, there is no distinction between fluvial or glaciofluvial unconsolidated sand and gravel deposits occurring along river valley bottoms.

9.4.1 Predominantly unconfined aquifers of fluvial or glaciofluvial origin along river or stream valleys (Type 1)

Many river or stream valleys in the Cordillera have shallow, fluvial sands and gravels recently deposited by the river or stream (fluvial origin) as well as sands and gravels deposited at the end of the last glaciation period (glaciofluvial origin). Often these two types of deposits are adjacent and sometimes mixed due to re-working of the sediment. Together they form unconfined aquifers along river or stream valley bottoms.

Aquifers of this type can be further divided into three subcategories. Each has distinctly different characteristics, such as hydraulic connection to the river or stream, yield, and degree of confinement and vulnerability:

a. **Aquifers found along major rivers of higher stream order with potential to be hydraulically influenced by the river**
   These rivers are generally of low gradient and depositional energy which results in deposition of sand and silt (e.g., at the lower reaches of the Fraser River).

b. **Aquifers found along rivers of moderate stream order with the potential to be hydraulically influenced by the river** (see the yellow-coloured aquifer underlying the river in Figure 9.2a)
   These rivers have higher gradients compared to large rivers. Here the depositional energy is high enough to cause deposition of sand and gravel (e.g., the fluvial sand and gravel deposit along the Cowichan River on the east coast of Vancouver Island at Duncan, and the fluvial and terraced glaciofluvial sand and gravel deposits along Kettle River in the southern interior community of Grand Forks).

c. **Aquifers found along lower order (< 3–4) streams in narrow valleys with relatively undeveloped floodplains, where aquifer thickness and lateral extent are more limited** (e.g., fluvial or glaciofluvial deposits along a mountain stream—see the yellow-coloured aquifer on the right in Figure 9.3a).

9.4.1.1 Occurrence, identification and size characteristics

One hundred and twenty-eight (or 14.4%) of the 888 aquifers identified and classified in the Region) are unconsolidated aquifers of fluvial or glaciofluvial origin occurring along river or stream valleys. 3.8% of these are Type 1a, 8.2% are Type 1b, and 2.4% are Type 1c. Table 9.1 suggests, as might be expected, that the areal extent of these aquifers decreases from those located adjacent to large rivers to those next to small-order streams.

Aquifers occurring adjacent to large or moderate-sized rivers (Types 1a and 1b) can generally be identified from a 1:50,000 scale topographic map or from aerial photographs. These aquifers are located along the river floodplain— i.e., the generally flat valley bottom between the river and its surrounding uplands (see Figures 9.2a and 9.3a). Aquifers occurring adjacent to large rivers (the Fraser, Columbia, or Skeena) are predominantly fluvial in origin, formed by deposition of river sediments. Aquifers occurring adjacent to moderate-sized rivers (the Cowichan on Vancouver Island, the Kettle River, or the Okanagan River) can either be fluvial or fluvial/glaciofluvial in origin. The aquifer at Grand Forks, for example, occurs adjacent to the Kettle River and is comprised of both fluvial sediments deposited recently by the river and, more predominantly, glaciofluvial terraced sands and gravels deposited by the river at the end of the last glaciation. Aquifers occurring along smaller streams (Type 1c) may not be as easy to identify from 1:50,000 scale topographic maps or even aerial photographs because some may only be several tens of metres to a few hundred metres wide, and the surrounding floodplain not extensively developed.

Unconsolidated aquifers of fluvial or glaciofluvial origin occurring along river or stream valleys are generally shallow; the average median well depths are 22 m (Type 1a), 22 m (Type 1b), and 19 m (Type 1c) for the three aquifer subtypes (Table 9.1). The depth to water table is also usually shallow, with average median depths of 5 m (Type 1a), 8 m (Type 1b), and 9 m (Type 1c), respectively.

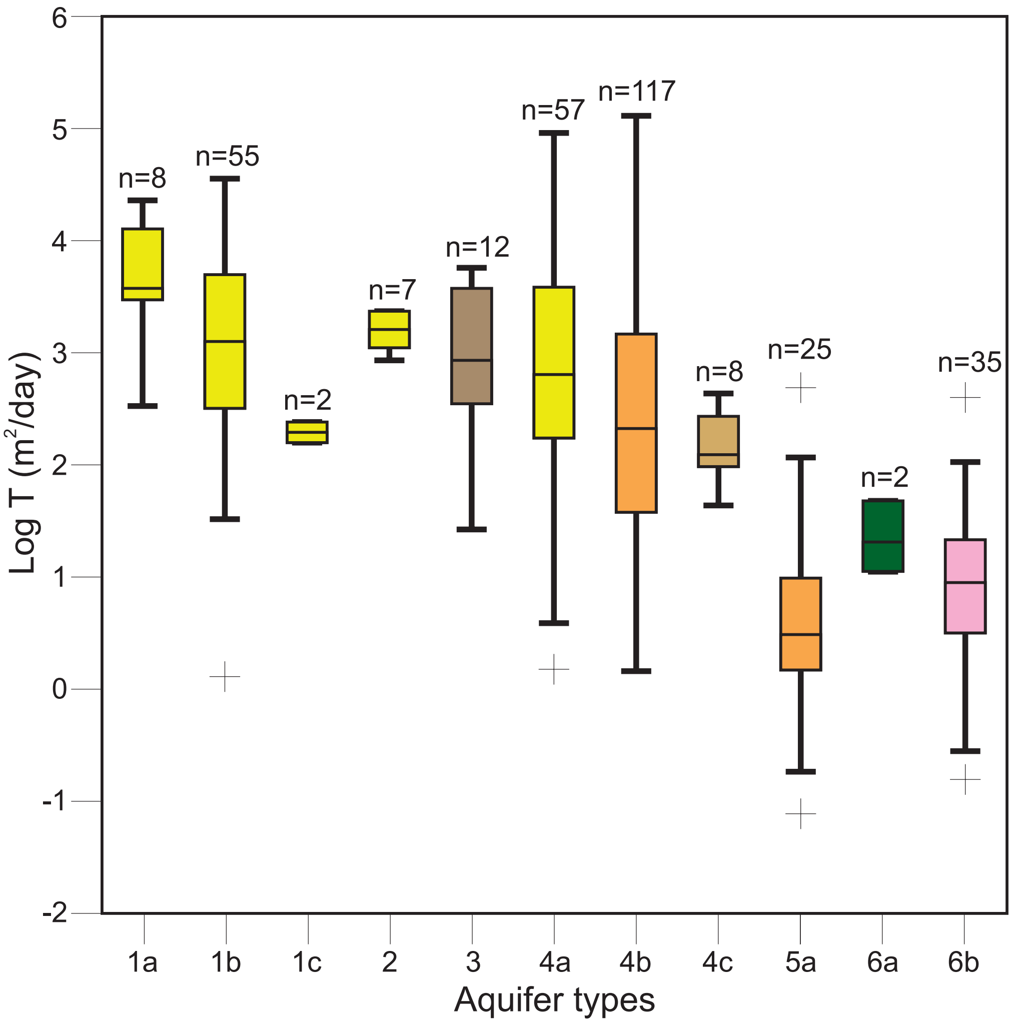

Figure 9.5: Graph depicting maximum, minimum, and geometric mean log transmissivity reported for each aquifer type where data are available.

9.4.1.2 Productivity characteristics and importance as a water supply

Aquifers adjacent to large or moderate-sized rivers (i.e., Types 1a and 1b) can be some of the most productive aquifers in the Cordillera because they comprise sands, or sands and gravels, which are highly permeable (reported transmissivities can range up to over 22,000 m^2/d for aquifers adjacent to major rivers and over 36,000 m^2/d for aquifers along moderate-sized rivers, with geometric mean transmissivities of 4,500 to 1,300 m^2/d, respectively (Table 9.1 and Figure 9.5).

Reported well yields for these aquifers range up to 92 L/s (Type 1a) or 215 L/s (Type 1b), with average median reported yields of 3.5 L/s (Type 1a) and 5.7 L/s (Type 1b), respectively. Another factor which augments an aquifer's productivity is the direct hydraulic connection between the aquifer and its adjacent river. Pumping lowers the hydraulic head in the aquifer and, in turn, can induce infiltration of river water thereby stabilizing pumping drawdown (Figures 9.2b and 9.3b). In such cases, there is also the potential for any significant pumping to negatively impact streamflows in moderate-sized rivers, particularly during summer and fall low flow season.

Aquifer adjacent to moderate-sized rivers, provide drinking water to many communities. Some notable examples include the fluvial aquifer along the lower reaches of the Nechako River (aquifer classification # 92), which provides the water for the City of Prince George (population 77,000); the fluvial aquifer along the lower reaches of the Cowichan River (aquifer classification # 186), which supplies the City of Duncan (population 5,000) on the southern east coast of Vancouver Island; the glaciofluvial aquifers along the Okanagan River in the southern Okanagan Basin (aquifer classification # 254 and 255—Toews, 2007; Wei, 1985; also see Box 6-3 in Chapter 6), which supply the Town of Oliver and surrounding agricultural area; and the fluvial aquifer along the Similkameen River (aquifer classification # 259),

which supplies small towns and farms of the area.

Most aquifers adjacent to large rivers are located along the Fraser River, and with the exception of the aquifer at Quesnel which supplies that town (aquifer classification # 117), most are not heavily used. Other developed aquifers of this type occur near Windermere, along the Columbia River in the East Kootenay, and at Terrace, along the Skeena River, in northwest coastal BC.

Aquifers adjacent to small creeks and streams, due to their small size (and possibly of lesser thickness), are less important sources of community water supply. Consequently, they are less well studied. These aquifers, however, remain an important local water supply for residents, small communities, and farms. Reported well yields range up to 101 L/s and the average median reported yield is 4 L/s. Transmissivity values are available for only 2 aquifers—240 m^2/d (aquifer classification # 482) and 160 m^2/d (aquifer classification # 713). One of the most important aquifers of this type is along the Bonaparte River, which supplies the Village of Cache Creek (aquifer classification # 134; west of Kamloops, with a population of just over 1,100). Although there is generally little data for these types of aquifers, it is possible that some of them may be in direct hydraulic connection with the adjacent creek or stream.

9.4.1.3 Aquifer vulnerability and water quality characteristics

The generally shallow depth of unconsolidated aquifers of fluvial or glaciofluvial origin located beside rivers or streams means that these types of aquifers are usually unconfined or partially confined. Most of them (95%) have been classified as highly (71%) or moderately (24%) vulnerable. The degree of partial confinement seems to be greatest for those aquifers adjacent to small creeks and streams (Type 1c aquifers). Some of these may result from interlayering with less permeable deposits occurring along valley bottom slides.

Local nitrate concerns have been reported in three unconfined sand and gravel aquifers adjacent to moderate-sized rivers: Merritt (aquifer classification # 74); Grand Forks (aquifer classification # 158; Maxwell et al., 2002; Wei et al., 1993); and near Oliver (aquifer classification # 254; Hodge, 1992). Fluoride is known to occur near Cranbrook in the East Kootenay (aquifer classification # 538) and arsenic levels approaching drinking water guideline limits has been detected in the Chilliwack-Rosedale area (aquifer classification # 6; Graham, 2006).

Aquifers adjacent to large rivers appear to have higher proportions of reported concerns related to elevated iron and manganese. One hypothesis suggests that groundwater flow in these aquifers may be relatively slower (due to lower gradient, finer, less permeable sand, and existence of confining layers and lenses at depth) which can result in the possibility of less oxygenated environments and greater dissolution of iron and manganese into the groundwater.

9.4.1.4 Profile: Aquifer at Grand Forks

The unconsolidated aquifer at Grand Forks (aquifer classification # 158), a prime example of a Type 1b aquifer, is located along the Canada-US boundary adjacent to the moderate-sized Kettle River. This aquifer consists of terraced glaciofluvial sands and gravels, and serves as the water supply for the City of Grand Forks and surrounding irrigation districts (population ~8,000). Hydrogeological mapping and modelling work by Allen (2001; 2000), Allen et al. (2004a; 2004b), Scibek and Allen (2006b; 2006c), and Scibek et al. (2007) indicates that groundwater flow is in close hydraulic connection to the Kettle River (see Box 4-1 in Chapter 4 for a discussion of direct and indirect recharge of the Grand Forks Aquifer). Regional groundwater flow is from west to east, in the general direction of the Kettle River flow. The Kettle River appears to be an important source of recharge at the aquifer's upgradient (west) end, although groundwater discharges back out into the Kettle River at the aquifer's downgradient (east) end where the aquifer's thickness pinches out.

There are 24 public water supply wells supplying water to the city, the surrounding irrigation districts, and mobile home parks (Wei, 1999). Reported well yields range up to 189 L/s and transmissivity ranges up to 11,000 m^2/d. Most of the high-yielding wells are located in the western half of aquifer, where the thickness is greatest (up to 80–100 m thick; Wei et al., 2004). Under pumping conditions, significant water infiltration from the Kettle River into the aquifer is expected under regular pumping conditions. Numerical modelling (Allen, 2001; 2000) indicates significant water increase from the Kettle River in the water budget under pumping conditions. Capture zones from all the large-capacity pumping wells (some located more than a kilometre away from the river) extend to the Kettle River. Actual pumping test data from these wells reveal stabilization of the water level in the well during pumping, an indication that the Kettle River is connected to the aquifer and is an important source of infiltration recharge during pumping.

The Grand Forks aquifer illustrates the generally high vulnerability of these aquifer types. Mapping of aquifer vulnerability using DRASTIC (Aller et al., 1986) reveals that most of the Grand Forks aquifer is highly vulnerable, with DRASTIC scores of 140 or greater. The eastern part of the aquifer, where depth to water is the shallowest (within 10 m from the ground surface), has the highest vulnerability (DRASTIC score of generally 180 or greater). Elevated nitrate levels exist locally within the aquifer as a result of nutrient leaching from human activities. (Maxwell et al., 2002; Wei et al., 1993).

9.4.2 Predominantly unconfined deltaic sand and gravel aquifers (Type 2)

9.4.2.1 Occurrence, identification and size characteristics

Twenty-three of the 888 aquifers (or 2.6%) identified and classified in the Region are developed sand and gravel deltaic aquifers (Type 2). This type excludes older deltaic aquifers buried at depth under till/ silt, or clay deposits for the reasons stated in section 9.4 (buried deltaic aquifers are categorized as Type 4b). Type 2 aquifers also exclude larger river deltaic environments (e.g., the lower hydraulic energy environment found in the Lower Fraser River where aquifers are categorized as Type 1a) and those aquifers found in delta kame deposits (Type 4a).

Deltaic aquifers, as the name implies, are commonly found in deltas where a stream or smaller river flows into a standing body of water. Of the 23 deltaic aquifers in the inventory, the ocean is the standing body of water for 13. Deltas can be readily identified from 1:50,000 scale topographic maps by their distinguished deltaic or fan shape (see Figure 9.2a). A delta in profile is much less steep than an alluvial fan, and the material, well-sorted by weight and volume, often results in definite graded layers sloping to standing water. Seasonal variations in stream discharge can result in further stratification of the deposits, as a stream's higher and lower hydraulic energy affects where different materials are deposited.

Type 2 deltaic aquifers are predominantly shallow and unconfined, comprised of sand and gravel and usually local in extent, ranging in area from <1 km^2 to 19 km^2, averaging 5 km^2 (Table 9.1). Well depth and depth to water in a deltaic aquifer are generally less than in alluvial fan aquifers. Wells drilled into deltaic aquifers range in depth from 2 m to 68 m deep, with an average median depth of 12 m. The water table depth in deltaic aquifers is generally shallow (average median depth to water of 3 m) but ranges from <1 m to 43 m.

9.4.2.2 Productivity characteristics and importance as a water supply

Hydrogeologists have determined that it is generally more feasible to develop wells from deltaic aquifers to supply a greater volume of water than that required for domestic use. Well yields for deltaic aquifers have been reported to be as high as 44 L/s: the Lost Shoe Creek aquifer serving the town of Ucluelet, on the west coast of Vancouver Island, near Pacific Rim National Park, has an average median well yield of 6.1 L/s. Reported transmissivity values (7 values from 5 aquifers) range from a minimum of 960 m^2/d to a maximum of 2,400 m^2/d, with a geometric mean of 1,500 m^2/d (see Table 9.1 and Figure 9.5).

In addition to meeting private domestic needs, these aquifers typically supply water to small communities (e.g., aquifer classification #

159—Ucluelet, #189—Mesachie Lake, and #419—Fanny Bay), water utilities, farming, commercial and industrial operations (aquifer classification #67—North Vancouver) including fish hatcheries (aquifer classification # 297, 412, 414, and 419).

In those locations where direct hydraulic connection exists with surface water, significant pumping from wells can induce surface water infiltration into the aquifer in the direction of the pumping wells. This connection may allow higher capacity wells to be developed because pumping drawdown usually reaches equilibrium within hours or days. When, however, the direct hydraulic connection exists with the ocean, there is always the concern that over-pumping could result in saltwater intrusion.

Although deltaic aquifers are fairly productive (most of the deltaic aquifers in the inventory are classified as highly or moderately productive), one aquifer in the inventory was reported to have a water quantity concern. The Trout Creek aquifer, underlying the delta on Okanagan Lake (aquifer classification # 297), is comprised of a higher than average percentage of lower-permeability silts and clays as compared to most developed deltaic aquifers within the Cordillera. A lower energy hydraulic regime and source materials of lower permeability may explain the many wells reported as dry holes, or those wells within this aquifer which report lower than average yields.

9.4.2.3 Aquifer vulnerability and water quality characteristics

The unconfined or partially confined nature of deltaic aquifers is due to a number of factors including aquifier composition, genesis and shallow depths. Most developed deltaic aquifers in the BC Cordillera have been classified as highly (71%) or moderately (29%) vulnerable.

Although half of the developed deltaic aquifers within the Cordillera have overlying commercial or industrial activity, only isolated reports of water quality concerns have been identified. Four of the aquifers support salmonoid fish hatcheries. Three of these hatcheries (sourcing groundwater from aquifers #412, 414, and 419) are located on the east coast of Vancouver Island and operate to enhance Pacific salmon stocks. The other hatchery (sourcing groundwater from aquifer #297) in Summerland (Okanagan Valley) is one of several provincial trout hatcheries operated to support the provincial trout stocking program for recreational fisheries. Many of the Cordillera's deltaic aquifers are located in rural areas and have minimal land use activities over them.

As a general rule, the natural flow rate of fresh water moving to the sea in coastal deltaic aquifers is sufficient to mitigate any negative effects from existing pumping wells (e.g., saltwater intrusion). One well however, constructed in the Sechelt area (aquifer classification # 556), was reported to have "very brackish" water at depth, although we do not know whether this brackish water is due to over-pumping or occurs naturally.

9.4.3 Alluvial, colluvial sand and gravel aquifers (Type 3)

9.4.3.1 Occurrence, identification and size characteristics

Fifty-six of the 888 aquifers identified and classified in the Region (6.3%) are developed alluvial fan aquifers. To date there have been no colluvial aquifers identified and classified within the Region. Older alluvial fan aquifers buried beneath till, silt or clay are categorized under sand and gravel aquifers of glacial or preglacial origin aquifer (Type 4b).

Alluvial fan aquifers typically occur at or near

the base of mountain slopes, either alongside valley bottoms, or, if formed during the last period of glaciation, raised above the valley floor (see the alluvial aquifer in Figure 9.3a). Alluvial fans are formed by sediment deposition from tributary streams as they enter the main valley. Sediments of alluvial fans tend to be coarse, somewhat sorted (e.g., sands and gravels) and permeable, particularly at the head or apex of the fan; sediments tend to be finer and less permeable at the fan's distal end. Alluvial fans can be readily identified from a 1:50,000 scale topographic maps by their distinguished fan shape (see Figure 9.3a). Alluvial fan aquifers are usually local in extent, ranging in area from <1 km^2 to 54 km^2, with an average area of 5 km^2 (Table 9.1).

Wells drilled into alluvial fan aquifers range in depth from 1 m to 141 m deep, with an average median depth of 24 m. The water table depth in alluvial fan aquifers is usually shallow, with an average median depth to water of 9 m, although it can range from <1 m to 99 m.

9.4.3.2 Productivity characteristics and importance as a water supply

Developing wells drilled into alluvial fan aquifers to supply domestic quantities of water has usually proved feasible. Reported well yields can range up to a maximum of 189 L/s (Vedder River Fan aquifer at the City of Chilliwack, 85 km east of Vancouver), with an average median well yield of 4 L/s. Reported transmissivity values (14 values from 8 aquifers) range from a minimum of 25 m^2/d to a maximum of 5,600 m^2/d, with a geometric mean of 710 m^2/d (see Table 9.1 and Figure 9.5).

Because many alluvial fan aquifers are usually small and shallow, they are typically used to supply water to farming and/or commercial operations, and smaller communities. One of the most important alluvial fan aquifers in the Region, from a water supply perspective, however, is the Vedder River Fan Aquifer, which is the water supply source for the City of Chilliwack (population 73,000). This aquifer is 25 km^2 in area and can yield up to 200 L/s to municipal wells. One of the reasons for the Vedder River Fan Aquifer's productivity is its location, adjacent to the Vedder River. It is either in direct hydraulic connection with the river or receives infiltration recharge from the river immediately upstream (one of the City of Chilliwack's municipal well fields is located near the river, at the head of the fan). When direct hydraulic connection exists in alluvial fan aquifers, significant pumping from wells in proximity to surface water can induce infiltration of surface water into the aquifer toward the pumping wells. This connection may allow higher-capacity wells to be developed as pumping drawdown usually reaches equilibrium within hours or days. A number of alluvial fans (aquifer classification # 387, 388, 393, and 394) are sources of water supply for the Resort Municipality of Whistler.

9.4.3.3 Aquifer vulnerability and water quality characteristics

Alluvial fan aquifers are usually characterized as unconfined, or partially confined, as a result of their location at the land surface, and their generally shallow depth. Most developed alluvial fan aquifers in the BC Cordillera (86% of the alluvial fan aquifers) have been classified as highly (54%) or moderately (32%) vulnerable. The Vedder River Fan Aquifer's vulnerability was mapped by Golder Associates (1997) using the GOD vulnerability mapping methodology (Foster, 1987), as part of the work in developing a well protection plan for the City of Chilliwack. This mapping indicated that the Vedder River Fan Aquifer is of "high" to "extreme" vulnerability throughout.

To date, there are only isolated reports of water quality concerns for developed alluvial fan aquifers, a likely reflection of the current lack of intensive land use activities over these generally small, largely rural unconfined water sources.

9.4.4 Sand and gravel aquifers of glacial or preglacial origin (Type 4)

This category contains known surface glaciofluvial sand and gravel aquifers, other sand and gravel aquifers identified in well records as occurring underneath till or glaciolacustrine deposits, and glaciomarine sand, sand and gravel aquifers. These aquifers were deposited by glacial meltwater streams either directly in front of, or in contact with glacier ice. These types of aquifer occur throughout the Region, varying widely in size and represent two-thirds of all unconsolidated aquifers within inventory. The category is subdivided further into three subcategories:

(a) Unconfined glaciofluvial outwash or ice contact sand and gravel aquifers, generally formed near or at the end of the last period of glaciation (see the yellow-coloured aquifer on the left in Figure 9.2a). The Abbotsford-Sumas Aquifer, 65 km east of Vancouver (see Box 9-2 in this chapter) is perhaps the most well-known and studied aquifer of this type in the Cordilleran Region.

(b) Confined sand and gravel aquifers underneath till, in between till layers, or underlying glaciolacustrine deposits (see the orange-coloured aquifers in Figures 9.2a and 9.3a). The

Quadra Sand, which occurs in the Georgia Depression on the east coast of Vancouver Island and along the southern mainland coast, is an excellent example of a confined glaciofluvial sand and gravel aquifer. It is comprised of advanced glaciofluvial sand and gravel deposited as the glacier ice advanced south along the Georgia Depression. Other aquifers occur between till layers, indicating they were deposited during glaciation. Still others may be fluvial, alluvial or colluvial deposits from a time prior to glaciation (and therefore lie underneath till or glaciolacustrine deposits). Unless a confined sand and gravel aquifer has been well studied, it is often hard to determine its geologic origin and morphology based on limited data. Therefore, any water-bearing sand and gravel aquifer occurring underneath till, in between till layers or under glaciolacustrine deposits has been included in this subcategory.

(c) Sand and gravel aquifers occurring underneath known sand, silt and clay deposited under a marine environment near the coast. The few known aquifers of this category occur in the marine sediments at depth in the Fraser Lowland near the mouth of the Fraser River, southeast of Vancouver where marine sediments are interbedded with estuarine and fluvial deposits consisting of fine sand, silt and clayey silts (Halstead, 1986; 1978). The presence of marine shells and remains of other organisms in these aquifers usually confirms their marine origin.

9.4.4.1 Occurrence, identification and size characteristics

Unconsolidated aquifers of glaciofluvial or preglacial origin comprise 413 of the 888 aquifers identified and classified in the Region (46.5%; 7.9% Type 4a, 37.6% Type 4b, and 1.0% Type 4c). Their general hydrogeological characteristics are summarized in Table 9.1. The extent of unconfined Type 4a aquifers can be readily identified from available surficial geology and soils mapping. Known Type 4a aquifers range from <1 to 90 km^2 with an average area of 8 km^2 (Table 9.1) and well depths ranging from 3 to 112 m with an average median depth of 24 m. Mapping the extent of confined Type 4b and 4c aquifers requires greater subsurface information from well records, and examination of geologic exposures in stream valleys or escarpments. Confined sand and gravel aquifers can vary considerably in size and may be relatively large as elongate deposits buried in major river valleys or along coastal areas. Mapped areas for Type 4b and 4c aquifers range from <1 to 332 km^2 and 2 to 194 km^2, respectively with average areas of 13 and 32 km^2, respectively. Well depths for Type 4b aquifers range from 4 to 378 m (average median depth of 39 m) and from 6 to 130 m (average median depth of 61 m) for Type 4c aquifers. The average median depth to water levels in Type 4a aquifers is 10.7 m. Water levels can be within a few metres of land surface or relatively deep (several 10's of metres) depending upon topographic conditions, aquifer thickness and subsurface flow conditions. The average median depths to water levels in confined Type 4b and 4c aquifers are 18 m and 14 m, respectively.

9.4.4.2 Productivity characteristics and importance as a water supply

Glaciofluvial aquifers are an important source of water. They occur throughout the Region and can be found near surface and within economical depths for drilling. The larger and more productive aquifers are able to supply all sectors including industrial, municipal, agricultural and domestic. Reported median well yields for unconfined Type 4a aquifers range up to 126 L/s with an average median of 3 L/s. Highest individual well yields for Type 4a aquifers of 126 L/s are reported for the Abbotsford-Sumas Aquifer and at Mackenzie in northern British Columbia. Reported median well yields for confined Type 4b aquifers range from 4 to 265 L/s with an average median of 2.3 L/s. Maximum well yield of 265 L/s was reported for a well completed in an exceptional confined aquifer under flowing artesian conditions at Fort St. James situated at the mouth of Stewart Lake in northern British Columbia. Reported median well yields for confined Type 4c aquifers range up to 31.5 L/s with an average median of 0.6 L/s. The maximum well yield reported for a Type 4c aquifer in the Hazelmere Valley, 40 km southeast of Vancouver, is 31.5 L/s.

Transmissivity values for Types 4a and 4b aquifers show a wide range from 1.6 to 89,000 m^2/d and 1.5 to 120,000 m^2/d respectively. The geometric mean transmissivity for Type 4a aquifers is 690 m^2/d, for Type 4b aquifers 250 m^2/d, and for Type 4c aquifers is 150 m^2/d (see Table 9.1 and Figure 9.5).

9.4.4.3 Aquifer vulnerability and water quality characteristics

The unconfined or partially confined nature of glaciofluvial Type 4a aquifers makes them especially vulnerable to contamination from land use activities when water tables are relatively shallow (Chesnaux and Allen, 2007; Chesnaux et al., 2007; Wassenaar, 1995; Wassenaar et al., 2006). As a result most aquifers (79%) have been classified as highly vulnerable while 21% aremoderately vulnerable. Local and regional water quality concerns, including nitrates and bacteria, are reported for 8 (11%) of the Type 4a aquifers. Major aquifers affected occur at Abbotsford and Osoyoos (in the Okanagan Basin).

Most confined Type 4b aquifers (74%) are classified as low vulnerability with 25% as moderately vulnerable. There was only one aquifer (out of the 333 Type 4b aquifers) with reported local water quality concerns related to nitrate (aquifer #356 in the north Okanagan). The majority (89%) of Type 4c aquifers are classified as low vulnerability: 11% are regarded as moderately vulnerable, with a report of only one aquifer (aquifer #32 in the Lower Mainland) experiencing local chloride concerns.

9.4.5 Sedimentary bedrock aquifers (Type 5)

9.4.5.1 Occurrence, identification and size characteristics

There are 101 (11.4% of 888 mapped aquifers) developed sedimentary bedrock aquifers identified and classified in the Region (see the brown-coloured aquifers in Figures 9.2a and 9.3a). These are divided into two subcategories (a) fractured sedimentary rocks (95 aquifers) and (b) (potential) karstic limestone (6 aquifers).

The Cordillera Region's complex tectonic history has given rise to a diversity of geological settings in which sedimentary rocks are found in association with old sedimentary basins, as volcanic sediments, or as pockets/slivers of exotic terrains that were accreted onto the North American landmass. The Rocky Mountains are comprised primarily of sedimentary rock, ranging from Proterozoic clastics and carbonates deposited in ancient continental basins, to Cambrian and/or Jurassic shelf and slope carbonate and shale deposited on and near the ancient North American continental margin, to Late Jurassic, and to early Cenozoic marine and/or non-marine clastics eroded from the uplifting Omenica and Foreland Belts (Monger and Price, 2002). These rocks were folded and thrust eastward over the ancient continental margin to form the Rocky Mountains.

Various rock assemblages within the Omenica, Intermontane and Coast Belts are usually metamorphosed, but also include sedimentary rocks formed in island arc and marginal basin settings, or deposited during uplift (Monger and Price, 2002).

Sedimentary rocks within the Insular Belt range in age from the latest Proterozoic to mid-Cretaceous, formed mainly in mostly island arc settings, to mid-Cretaceous and younger clastics eroded from the Coast Belt, to late Jurassic to Holocene clastic-rich accretionary complexes (Monger and Price, 2002).

Fractured sedimentary bedrock aquifers classified within the region range significantly in size from <1 km^2 to 700 km^2, with an average size of 24 km^2 (Table 9.1). Wells drilled into these aquifers range in depth up to a maximum of 331 m, with an average median depth of 56 m. The water table depth is moderate (average median depth to water of 10 m) but can range from 0 m to 155 m. The most likely reason for such large differences is fracturing variations encountered during drilling. One single fracture situated at relatively shallow depth can provide adequate supply for domestic purposes. However, when productive fractures are not encountered at shallow depth, it is necessary to drill deeper. It is not uncommon in fractured sedimentary rock to have two immediately adjacent wells that are vastly different in depth. Fractures at depth often exhibit artesian pressures, leading to shallower water level depths and, sometimes, even flowing artesian conditions. Likewise, springs are typically found in association with fractures that extend from depth up to surface. This can lead to thermal springs (e.g., Banff, Radium, etc.; see Allen et al., 2006; Grasby et al., 2000; 2002; van Everdingen, 1972), when the temperature at depth is high and the transport to surface rapid.

Karst limestone aquifers are often productive aquifers with hard water chemistry. Karst limestone aquifers are capable of moving large quantities of water over great distances in relatively short periods of time. Karst environments can be identified by features such as cave entrances, sinkholes, sinking streams, and karst springs. Occurrence of karstic limestone aquifers in the Cordillera has not been well studied. Carbonate rocks (approximately 80% of which exists as limestone, 20% as dolomite) of variable composition make up approximately 10% of the Cordillera landscape. Most of these soluble rocks are found as extensive belts along the Rocky Mountains, the Purcell Mountains, the southern end of the Interior Plateau, east of Takla Lake in the Cassiar Mountains, on Vancouver and the Queen Charlotte Islands, in addition to other smaller occurrences scattered throughout the Region. The existence of karst springs in the Kananaskis region of the Rockies and limestone caves at Horne Lake Caves Provincial on Vancouver Island suggest karst limestone aquifers may exist in those areas.

The occurrence of potential karstic limestone aquifers has been inferred by overlaying sedimentary bedrock aquifer polygons with a karst potential map (available through the BC Ministry of Forests; Stokes, 1994). Potential karst polygons were initially screened so as to include only those polygons where the likelihood of karst-forming bedrock occurrence was greater than 50% (highest rating), and the estimated intensity of karst development potential was moderate to high. Whenever an 80% overlap between bedrock aquifer polygons and potential karst polygons was found, the aquifers were categorized as potential karstic limestone aquifers.

Based on this approach, six potential karstic limestone aquifers (Type 5b), ranging in size from 2 km^2 to 19 km^2, with an average size of 8 km^2 (Table 9.1) have been identified (see the example column in Table 9.1), although the well logs for these aquifers do not report the existence of solution channels (larger void spaces). The aquifer size likely reflects the area of well development and not the full extent of karstic limestone formation. Wells drilled into these aquifers range in depth up to a maximum of 183 m, with an average median depth of 75 m. The water table depth is moderate (average median depth to water of 16 m) but ranges from <1 m to 96 m.

9.4.5.2 Productivity characteristics and importance as a water supply

Sedimentary bedrock aquifers found within the region typically have limited *primary porosity*, mostly because the rocks are quite old and may have undergone some minor chemical and physical alteration (i.e., low-grade metamorphism). Consequently, aquifer productivity hinges on the degree to which they are fractured or, in the case of karstic limestone, the degree to which dissolution has created solution channels (*secondary porosity*).

Deformation following deposition or emplacement of sedimentary rocks invariably leads to fracturing at a range of scales, from micro-scale cracks to regional-scale faults and fracture zones. Fractures are heterogeneously distributed, depending on the tectonic history of an area. When these fractures are open, they provide pathways for groundwater flow and enhance the aquifer's local permeability. Several factors modify the degree of fracture openness: 1) the amount of precipitate infill, 2) the degree to which mineral dissolution has enhanced fracture size, and 3) the direction of the current stress regime.

Mineral precipitation (e.g., calcite) usually occurs in fractures as a result of changes in the chemical conditions encountered during fluid flow. Such precipitates can essentially seal off fractures and render them impermeable. Similarly, minerals previously precipitated within fractures may dissolve, leading to enhanced permeability. Such dissolution within carbonate rocks, such as limestone, may be so extreme as to lead to open dissolution channels, cavities, and caves, typical of karstic terrain. Current stress regime also plays a major role in determining if fractures are open or closed. Fractures oriented perpendicular to regional compressive stresses will tend to be closed, whereas those oriented perpendicular to regional tensional stresses will be open. Thus, in addition to identifying the direction and intensity of fracturing within an aquifer, it is also important to consider other factors which may serve to modify its permeability.

Sedimentary bedrock aquifers are generally a solid source for the development to supply domestic water even though they have significant ranges in productivity. Reported well yields in fractured sedimentary bedrock aquifers range up to a maximum of 12.6 L/s (Ford Creek area southeast of the City of Chilliwack), with an average median yield of 0.3 L/s. Reported transmissivity values (25 values from 11 aquifers) range from a minimum of 0.1 m^2/d to a maximum of 480 m^2/d, with a geometric mean of 3.7 m^2/d (see Table 9.1 and Figure 9.5). Thus, aquifer productivity is generally quite good but typically lower than that of unconsolidated aquifers.

Well productivity is generally enhanced when the well intersects a fracture zone. On the Gulf Islands, higher-yielding wells have been associated both with mapped lineaments corresponding to fracture zones and near contacts between formations (Mackie, 2002; Allen et al., 2002). Pumping tests conducted in fractured rock aquifers often display linear type flow behaviour, where drawdown effects propagate along the length of a fracture, as opposed to radially away from the well (Allen et al., 2003). This type of flow behaviour occurs because the fracture zone is more permeable than its surrounding rock matrix. In such situations, it is not uncommon for transmissivity values to be higher, on average, although there is also a greater likelihood of interference between wells situated along the same fracture.

Productivity of karstic limestone aquifers can also be expected to be quite high, although no data is currently available to confirm this. Well yields in the six potential karstic limestone aquifers of the region range from 0.01 L/s to 1.26 L/s, with an average median yield of 0.3 L/s— similar to other fractured bedrock types. To date, we have no available estimates of transmissivity for these potential karstic limestone aquifers.

Another well within a karst aquifer of the Dead Man Flats, Bow River valley, Alberta, had a reported yield of 0.3 L/s. Although this well is situated near a karst spring flowing at 11.7 L/s (Toop and de la Cruz, 2002), it failed to tap the spring's source. Reported flows of 30 L/s and 40 L/s from other karst springs (Railside and Watridge springs[3] respectively) in the Kananaskis area, Alberta, suggest that future productive karst aquifers to be identified and developed.

9.4.5.3 Aquifer vulnerability and water quality characteristics

Fractured sedimentary bedrock aquifers have been mapped as unconfined, partially confined, and confined aquifers. The majority are mapped as partially confined, due to the absence of a continuous low-permeability cover layer and a hydraulic response that suggests mostly confined conditions (i.e., these aquifers display a Theis type response for at least part of a pumping test). Consequently, most (44%) are of moderate vulnerability, with roughly equal distribution between high vulnerability (26%) and low vulnerability (29%). Isolated, local and regional reports of water quality concerns have been identified: the most commonly reported local is saltwater (13 cases). Regionally, saltwater is a problem in four aquifers. Other water quality concerns include sulphur, fluoride, and manganese and iron (Allen and Matsuo, 2001; Allen and Pelude, 2001; Kohut et al., 1986). Most of these concerns have been identified in the Gulf Islands, where water quality is affected by proximity to the coast (saltwater intrusion) (Allen and Suchy, 2001b; Dakin et al., 1983) and geological processes such as submergence (Liteanu, 2003), which have given rise to unique water chemistry (Allen and Suchy, 2001b; Allen, 2004; Earle and Krogh, 2006). The vulnerability of the Gulf Islands aquifers (Journeay et al., 2003) was linked to aquifer architecture (Mackie, 2002), and mapped by Denny et al. (2007) to take into account regional structure. Ffracture zones and faults play an important role in determining aquifer vulnerability due to saltwater intrusion and to surface contamination (see Box 6-2 in Chapter 6).

Of the six potential karstic limestone aquifers within the Region, two have been identified as

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[3] For more information on Watridge spring, please see Hike # 71 in Gillean Daffern's *Kananaskis Country Trail Guide, Volume 1* (1996).

confined and four have unknown confining conditions. None have low vulnerability, 50% are of moderate vulnerability and 50% are of high vulnerability. There is a greater likelihood that karstic limestone aquifers will have moderate to high vulnerability due to the potential for solution cavities (created by infiltrating water from surface) which can extend to the surface thus creating potential pathways for surface contaminants to enter the aquifer. Rapid transit times and limited natural cleansing and filtering mechanisms associated with solution channels can readily allow transport of any contaminants or sediments very quickly from one area to another. There are no reports of quality or quantity issues in any of the six potential karst limestone aquifers found in the BC portion of the Cordillera.

9.4.5.4 Profile: Fractured sedimentary aquifers of the Gulf Islands

The most extensively studied Type 5a sedimentary bedrock aquifers in the Cordillera are those located on the Gulf Islands, in the Strait of Georgia on the southwest coast of British Columbia. These islands range in area from approximately 20 to 60 km^2, with elevations up to 400 m above sea level. Their topography is primarily characterized by northwest-southeast trending ridges and valleys. Rocks comprising the islands belong to the *Late Cretaceous* Nanaimo Group (~91–66 Ma) and consist of alternating sequences of interbedded sandstone-dominant and mudstone (or siltstone)-dominant formations (Mustard, 1994). Contacts between the formations are typically transitional and are usually characterized by the presence of interbeds. While massive sandstone units are common, massive mudstone units are not; mudstone is typically interbedded with sandstone. The primary porosity of the Nanaimo Group is low and is considered to be of minor importance in the storage and flow of groundwater (Dakin et al., 1983; England, 1990). As a result, permeability is thought to be derived primarily from fractures (*secondary porosity*).

Four major tectonic features exist in the sedimentary rocks of the Nanaimo Group: these provide the secondary porosity necessary for groundwater movement. From oldest to youngest, these features include 1) northwest trending and northeast dipping thrust faults associated with compression by a southwest vergent thrust system (England and Calon, 1991; Mustard, 1994; Journeay and Morrison, 1999); 2) northwest trending buckle folds associated with northeast vergent thrust faults resulting from southeast directed extension (Journeay and Morrison, 1999); 3) shallow dipping features representing bedding plane partings, which are believed to have formed during uplift and/or isostatic rebound after deglaciation (Mackie, 2002); and 4) northeast trending fault and fracture zones as well as bedding perpendicular jointing, present at local scales (Mustard, 1994; Mackie, 2002).

Mackie (2002) used fracture measurements from rock exposures on the Gulf Islands to arrive at a conceptual model that could describe the range of potential permeability within the different sedimentary units. He defined hydrostructural domains on the basis of fracture intensity measured in the less fractured sandstone (LFSS), the interbedded mudstone and sandstone (IBMS-SS), and in association with faults and fracture zones (FZ).

Surrette and Allen (2008) used the fracture data to estimate potential permeability for each. Based on the results of fracture flow modelling, Surrette and Allen (2008) demonstrated that the two highly fractured domains (IBMS-SS and FZ) have an average permeability, on the order of 10^{-13} m^2 (hydraulic conductivity of 10^{-6} m/s), due to enhanced fracture-network connectivity. In contrast, the LFSS domain has an average permeability of 10^{-14} m^2 (hydraulic conductivity of 10^{-7} m/s). Surrette and Allen also observed anisotropy within the permeability, with maximum permeability generally aligned in a northwest-southeast direction, consistent with regional tension perpendicular to this direction.

The possibility of increased infiltration rates within FZ domains, coupled with a high-storage potential relative to other domains suggests that fault zones with similar characteristics are likely zones of recharge. As a result, these recharge zones have an increased capacity to store and transmit infiltrated water throughout the interconnected fracture-network. Surrette et al. (2008) showed that in a regional sense, there is a weak, but consistent, pattern of increasing permeability in both modelled and observed data toward the southeast along the chain of islands, from Galiano Island in the northwest to Saturna Island in the southeast. Values also tended to increase in proximity to the hinge of a large-scale antiformal fault propagation fold structure running parallel to the islands and superimposed high-angle brittle fault structures. This work has shown that fracturing is heterogeneous within the sedimentary layers and depends on the nature of the bedding (i.e., finer bedding gives rise to higher fracture intensity). Consequently, the finer grained interbedded mudstones and sandstones have a higher potential permeability. Furthermore, regional scale structure and current stress regime imparts heterogeneity and anisotropy to fracturing and, thus, contributes to permeability.

9.4.6 Crystalline bedrock aquifers (Type 6)

This category covers crystalline bedrock of various ages ranging from the younger and extensive basaltic lava flows of the *Tertiary* age to older igneous and metamorphic "basement" type rocks (see Figures 9.2a and 9.3a). Crystalline bedrock aquifers are subdivided into two subcategories: flat-lying to gently-dipping volcanic flow aquifers (Type 6a) and fractured crystalline rocks (Type 6b). Groundwater flow in crystalline rocks is through fractures. Flow in flat-lying to gently-dipping volcanic rocks can also be through broken, scoriaceous and weathered contact zones between lava flows. Interflow zones in some areas may also contain granular deposits such as sand and gravel.

9.4.6.1 Occurrence, identification and size characteristics

Sixteen (16) of the 888 aquifers (2%) identified and classified in the Region are developed Type 6a—flat-lying to gently-dipping volcanic flow aquifers. Extensive areas of central British Columbia are underlain by relatively unaltered, flat-lying lava of the Tertiary age (e.g., the Fraser and Nechako Plateaus in the central part of the Region). A smaller developed basalt flow aquifer occurs in the Grant Hill region (aquifer classification # 19) of the Lower Mainland in British Columbia. These lava flow areas often have obvious geological boundaries which define the aquifer's areal extent locally. The developed extent varies from <1 to 6,546 km^2, with an average area of 484 km^2 (Table 9.1).

The largest single continuous aquifer in the Cordillera is the flat-lying or gently-dipping volcanic flow rock aquifer in the 100 Mile House area of the Fraser Plateau region (aquifer classification #124). When this aquifer is completely mapped, its area is expected to cover more than 7,000 km^2.

Wells drilled here range in depth up to 242 m deep, with an average median depth of 62 m. Water table depth is relatively shallow (average median depth of 19 m) but ranges from <1 m to 130 m.

One hundred and fifty four of the 888 aquifers (17.3%) identified and classified in the Region are developed Type 6b crystalline aquifers. This subcategory includes igneous intrusive or metamorphic rocks (such as the coast granitic pluton north of Vancouver). Because the meta-sedimentary, older volcanic and meta-volcanic rocks are most similar in hydrogeological properties to granitic and metamorphic rocks, they have been included in this subcategory. Groundwater flow in fractured crystalline rocks is mostly along joints, fractures, and faults. Typically there is negligible internal primary porosity so storage is limited.

These Type 6b aquifers occur over a broad portion of the Region. They do not have obvious geological boundaries to define their extent locally. Groundwater production is typically from fractures and joints. Fracture nature and density is controlled by both regional and local stress fields in addition to ancient tectonic features, making it difficult to develop predictive aquifer models. There are also significant heterogeneities between wells within a defined aquifer area, as variability in the nature and orientation of individual fracture relative to a well influences production rates and degree of interference between wells. The developed extent of these aquifers varies from <1 to 538 km^2, with an average area of 31 km^2 (Table 9.1). Wells drilled into Type 6b crystalline aquifers can be up to 268 m deep, with an average median depth of 71 m. The water table depth is relatively shallow (average median depth of 15 m) but ranges from <1 m to 213 m.

9.4.6.2 Productivity characteristics and importance as a water supply

Groundwater production in flat-lying to gently-dipping volcanic rocks is primarily through joints and fractures, although it also occurs in broken, weathered zones between flows. High yielding groundwater zones within the lavas are the "brecciated or erosional zones," which are like interconnecting "fingers". Yield of a given well will depend on whether or not these brecciated/erosional zones are present. Regional fractures or fault zones are also significant as major groundwater supply sources (Brown, 1969).

Permeability of these aquifers sometimes exists as *primary porosity* due to the vesicular nature of the rock, and the interconnected porosity, after bedrock formation. This *secondary porosity* developed as a result of fractures, joints or faults formed by tectonic forces. Permeability also exists, largely, as within interflow zones which occur between lava flows. This porosity may result from weathering, fracturing from extreme heat in contact zones, or, in some cases, deposition and subsequent burial of unconsolidated sediments by lava flows.

The interflow zones within these aquifers vary in nature, with some zones exhibiting only centimetres of weathering, while others a significant thickness of trapped alluvial sands and gravels when an old stream channel has been covered by a basaltic flow (Livingston, 1967). Variabilities in fracturing, thickness, and extent of unconsolidated material found in the interflow zones result in significant heterogeneities between wells within any defined aquifer area. Variability in the nature and orientation of individual fracture, or interflow zone relative to a well influences production rates and the degree of interference between wells.

Well yields for flat-lying lava aquifers vary widely, with a range from <1 to 15 L/s reported. The average median well yield is, however, relatively low at 0.3 L/s. Reported transmissivity values (3 values from 1 aquifer) range from a minimum of 11 m^2/d to a maximum of 47 m^2/d, with a geometric mean of 23 m^2/d. Water quantity concerns with flat-lying to gently-dipping volcanic rock aquifers are uncommon. The Tertiary basalt flow rocks of central British Columbia probably represent the largest reserve of good-quality ground water in the province (Livingston, 1967). Only a few reports of poor water supplies exist for any of the wells completed in these lavas. High hardness values (286 mg/L) were reported in one of the community wells for 100 Mile House (Foweraker, 1981).

The dominant use of Type 6a aquifers in the Cordillera is for drinking water (domestic and municipal) and for minor farming purposes. These aquifers are typically considered moderate to low in vulnerability and also have moderate to low demand.

Well yields for Type 6b crystalline aquifers vary widely. Ranges from <1 to 126 L/s have been reported, although the average median well yield is relatively low at 0.4 L/s. Well yield is dependent on the well encountering water-bearing fractures within the drill hole. Kenny (2004) examined whether the proximity to mapped lineaments, well depth, and well location could influence well yield of crystalline aquifers in the Victoria area.

Voeckler and Allen (2012) used outcrop measurements of fractures, lineament data from orthophotos, and Landsat imagery to model fracture distributions within crystalline rocks in the Okanagan Basin. Their results estimated hydraulic conductivities in the range of 10^{-8} to 10^{-7} m/s.

Reported transmissivity values (35 values from 19 aquifers) range from a minimum of 0.2 m^2/d to a maximum of 400 m^2/d, with a geometric mean of 9.2 m^2/d (see Table 9.1 and Figure 9.5). Transmissivity of crystalline aquifers is also expected to be anisotropic. For example, Kohut et al. (1983) reported on the highly directional drawdown observed during the pumping test of an irrigation well in a granitic aquifer (aquifer classification # 608) north of Victoria.

The dominant use of the Cordillera's type 6b crystalline aquifers is for drinking water. These aquifers are typically considered moderate to low in vulnerability, with a moderate to low demand. Roughly two-thirds of these aquifers are classified as low productivity. Water quality concerns with developed crystalline aquifers are uncommon. There have been, however, isolated issues over non-health related problems relating to high sulphur and iron content, as well as seawater intrusions in coastal areas. Twelve aquifers (8%) report concerns with high arsenic content (typically from aquifers in fractured granite, likely related to naturally occurring arsenic bearing minerals). No issues regarding radioactive elements as noted in other granite hosted aquifer systems have been reported.

9.4.6.3 Aquifer vulnerability and water quality characteristics

The majority of Type 6a flat-lying volcanic rock aquifers (69%) are classified as low vulnerability; 25% are classified as moderately vulnerable and 6% as highly vulnerable.

The majority of Type 6b crystalline aquifers (56%) are classified as moderately vulnerable and 13% as highly vulnerable. Vulnerability of crystalline bedrock aquifers depends on the nature, extent and thickness of the unconsolidated sediments overlying the bedrock aquifer. Where exposed at surface, crystalline bedrock aquifers can be directly

TABLE 9.1 SUMMARY OF HYDROGEOLOGICAL CHARACTERISTICS OF THE MAJOR AQUIFER SYSTEM TYPES IN THE CORDILLERAN HYDROGEOLOGICAL REGION (BASED ON BC'S INVENTORY OF CLASSIFIED AQUIFERS)

AQUIFER TYPE	NO. OF AQUIFERS (% OF TOTAL INVENTORY)	RANGE; AVERAGE SIZE (KM^2)	AVERAGE RANGE; AVERAGE MEDIAN WELL DEPTHS (M)	AVERAGE RANGE; AVERAGE MEDIAN WELL YIELDS (L/S)	RANGE; GEOMETRIC MEAN TRANSMISSIVITY (M^2/D)	HYDRAULIC CONNECTIONS WITH SURFACE WATER	EXAMPLES OF AQUIFER TYPES
1. Unconfined aquifers of fluvial or glaciofluvial origin along river valley bottoms							
a. Aquifers along higher-order rivers	34 (3.8%)	<1–142; 27	12–82; 22	1.8–17; 3.5	350–22,000; 4,500	Common	Agassiz, Chilliwack-Rosedale
b. Aquifers along moderate-order rivers	73 (8.2%)	<1–120; 15	11–53; 22	1.5–41; 5.7	1.0–36,000; 1,300	Common	Grand Forks, Duncan, Chemainus, Nechako, Merritt
c. Aquifers along lower-order streams	21 (2.4%)	<1–23; 7	9–43; 19	1.4–22; 4.0	160–240; 200 (based on 2 values)	Unknown	Cache Creek, Little Fort
2. Unconfined deltaic aquifers	23 (2.6%)	<1–19; 5	5–27; 12	1.5–15; 6.1	960–2,400; 1,500	Common	Scotch Creek near Chase
3. Unconfined alluvial, colluvial fan aquifers	56 (6.3%)	<1–54; 5	13–47; 24	1.6–23; 4.0	25–5,600; 710	Common in aquifers adjacent to surface water	Vedder River Fan at Chilliwack
4. Aquifers of glacial or preglacial origin							
a. Unconfined glaciofluvial aquifers	70 (7.9%)	<1–90; 8	12–59; 24	1.3–22; 3.0	1.6–89,000; 690	Common in aquifers adjacent to surface water	Abbotsford, Langley, Hopington
b. Confined glacial or preglacial aquifers	334 (37.6%)	<1–332; 13	20–83; 39	0.8–12; 2.3	1.5–120,000; 250		Quadra Sand aquifers in the Georgia Basin, Okanagan and Coldstream valleys
c. Confined glaciomarine aquifers	9 (1.0%)	2–194; 32	23–176; 61	0.1–14; 0.6	45–410; 150	Limited	Nicomekl-Serpentine in Surrey and Langley
5. Sedimentary bedrock aquifers							
a. Fractured sedimentary bedrock aquifers	95 (10.7%)	<1–700; 24	22–139; 56	0.1–2.5; 0.3	0.1–480; 3.7	Limited	Nanaimo Group aquifers in the Gulf Islands and east coast of Vancouver Island
b. Karstic limestone aquifers	6 (0.7%)	2–19; 8	35–125; 75	0.1–1; 0.3	N/A	Unknown, but possible	Limestone aquifers in the Canadian Rockies, Sorrento, Fort St. James
6. Crystalline bedrock aquifers							
a. Flat-lying volcanic flow rock aquifers	16 (2%)	<1–6,546; 484	21–129; 62	0.1–3.2; 0.3	11–47; 23 (based on 3 values)	Limited	Aquifer classification # 124 around 70 Mile House, British Columbia
b.Crystalline granitic, metamorphic, meta-sedimentary, meta-volcanic and volcanic rock aquifers	154 (17.3%)	<1–538; 31	28–152; 71	0.1–4.8; 0.4	0.2–400; 9.2	Limited	Saanich granodiorite, granitic aquifers along Sunshine Coast, metabasalt aquifer at Metchosin near Victoria

impacted by surface land use activities. Since these aquifers are dominated by fracture permeability and fracture induced porosity, travel times for contaminants can be quick, and opportunities for attenuation low.

9.5 GROUNDWATER USE IN THE REGION

Groundwater is an important water supply source within the Region. Throughout the Cordillera, there are some unique motivations for using groundwater as a supply:

1. Surface water resources in some areas are fully allocated (for example, in some watersheds in the southern interior of BC).
2. Communities develop groundwater supplies to avoid the cost of treating surface water.
3. Groundwater quality and quantity are generally excellent (see Section 9.7).

It is estimated that 1 million people[4] in the Cordillera Region rely on groundwater for drinking water. This supply ranges from municipal systems to private residential wells. Communities such as Abbotsford (population 129,000), Township of Langley (population 100,000), and Chilliwack (population 73,000) in the Lower Mainland, Parksville-Qualicum Beach (population 21,000) on Vancouver Island, Prince George (population 77,000) and Quesnel (population 11,000) in Central BC, and Banff (population 6,700) and Jasper (population 4,600) in the Canadian Rockies are examples of communities relying on groundwater as their water source. Spatially, groundwater use has historically been focused in valley bottoms and plateaus throughout the main settlement corridors (see locations of reported wells in Figure 9.6).

Throughout this Region, groundwater has historically been used largely (by volume) for industrial processing (mineral, pulp, and paper), agriculture, and aquaculture (Wei and Allen, 2004; Hess, 1986; Foweraker et al., 1985), and is, therefore, vitally important in sustaining the region's economy. Overall figures in BC indicate that approximately 55% of the water volume pumped annually is for industrial use, 20% for agricultural and 25% for municipal and rural uses (Hess, 1986). The high industrial use of groundwater is unique to BC and to the Cordillera. Groundwater is also increasingly used as a viable source of low-temperature geothermal energy.

9.6 WATER STORED IN DEVELOPED AQUIFERS WITHIN THE REGION

The amount of groundwater potentially stored in developed aquifers within the Cordilleran Hydrogeological Region is estimated to be 7.9–19.6 km^3. This volume[5] represents capacities from developed aquifers identified and classified in the BC Cordillera only covering approximately 20,000 km^2 (<2%) of the entire 1.4 million km^2 of the Cordilleran Hydrogeological Region (Table 9.2). The volume of groundwater stored in undeveloped aquifers (e.g., in remote, undeveloped areas) and in developed aquifers in the Region where aquifers have not been mapped and classified has not been included in the volumes in Table 9.2. The amount of groundwater stored in developed aquifers within the Region was calculated from the following general equation (Rivera, 2007):

$$V = S \times A \times h_o \qquad (9.1)$$

where:

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[4] This number is estimated from: Nowlan (2005).

[5] By volume stored, we mean the volume of groundwater that is stored and can potentially be released from an aquifer when the groundwater level is lowered.

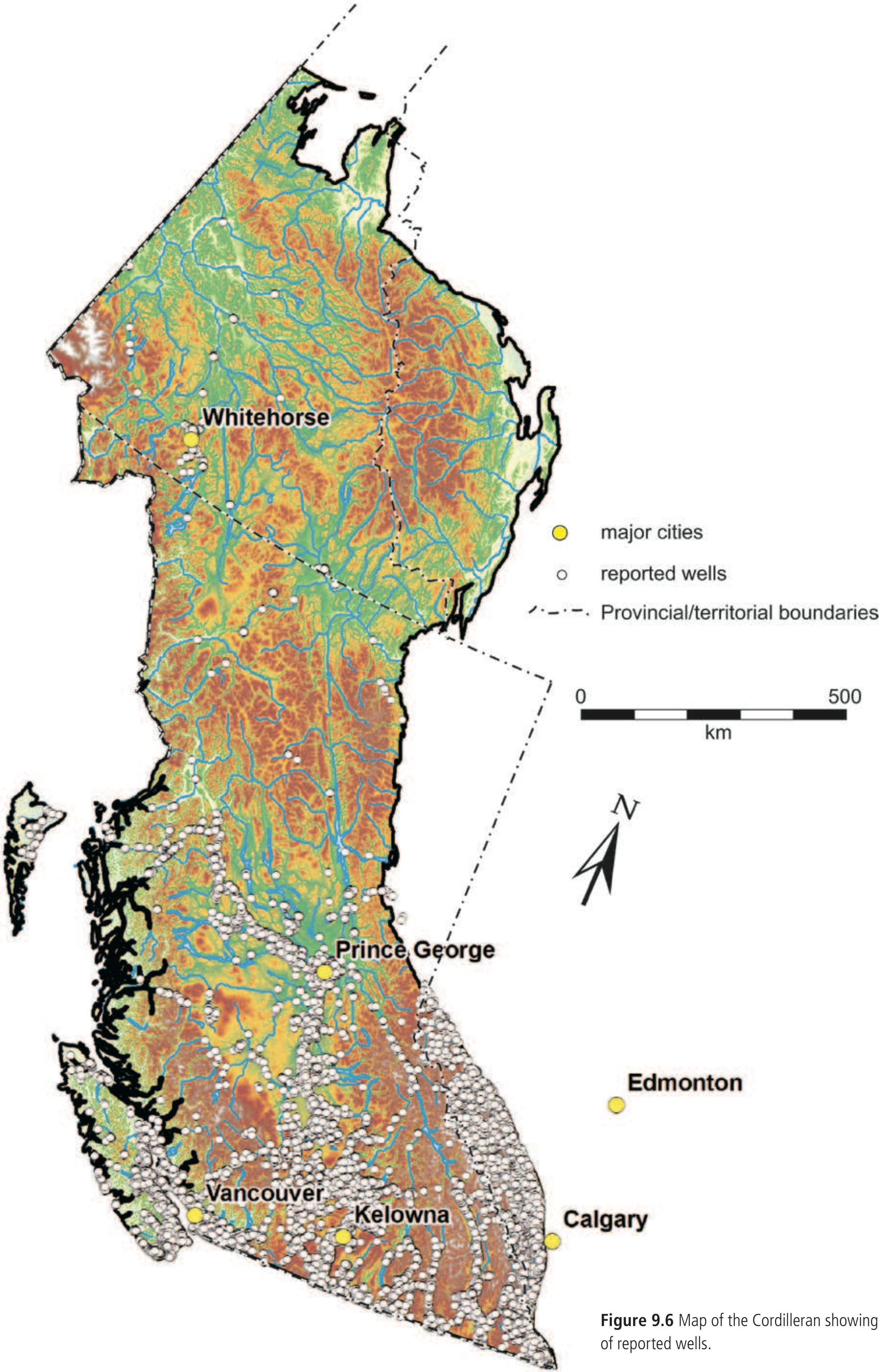

Figure 9.6 Map of the Cordilleran showing location of reported wells.

TABLE 9.2 TOTAL SURFACE AREA AND ESTIMATED TOTAL VOLUME OF GROUNDWATER STORED IN DEVELOPED AND CLASSIFIED AQUIFERS (BY AQUIFER TYPE)

AQUIFER TYPE	TOTAL SURFACE AREA OF DEVELOPED AND CLASSIFIED AQUIFERS (KM^2)	ESTIMATED TOTAL VOLUME IN DEVELOPED AND CLASSIFIED AQUIFERS (KM^3)
1a	932	2.67–6.24
1b	1,110	2.76–6.46
1c	168	0.27–0.64
2	116	0.14–0.32
3	292	0.67–1.56
4a	566	1.08–2.52
4b	3,997	0.01–0.05
4c	291	0.001–0.01
5a	2,007	0.05–0.14
5b	51	0.002–0.02
6a	6,779	0.09–0.26
6b	4,426	0.14–1.33
Total	**20,735**	**7.88–19.55**

V is the volume of water stored in an aquifer;
S is the aquifer storativity, or if an aquifer is unconfined, the specific yield;
A is the mapped areal extent of the aquifer; and
h_o is the groundwater level above the bottom of the aquifer.

In estimating the volume of groundwater in each type of aquifer, representative values and range of values of storativity or specific yield were assumed for each aquifer type: the difference between the average depth to water and average well depth was used to represent the average groundwater level above the bottom of the aquifer. Since the average well depth is shallower than the bottom of the aquifer, the use of the difference between depth to water and well depth is conservative. The total volume of groundwater stored in each type of aquifer is presented in Table 9.2. Table 9.2 shows that, generally, unconfined, unconsolidated aquifers can store and release more groundwater than confined, unconsolidated aquifers and fractured bedrock aquifers. The relatively small average volume of groundwater in confined, unconsolidated aquifers (Types 4b and 4c) reflects the low value of aquifer storativity used in the calculation compared to the larger specific yield value used for unconfined, unconsolidated aquifers. In total, fluvial sand and gravel aquifers (Types 1a and 1b), alluvial fan aquifers (Type 3) and glaciofluvial aquifers (Type 4a)—all generally unconfined aquifers—comprise over 80 to over 95% of the total groundwater stored in developed aquifers and reflect their importance as developed water supply aquifers in the Region. The total volume of groundwater in the Region is undoubtedly much greater.

9.7 WATER QUALITY

The Cordilleran Hydrogeological Region is blessed with many aquifers with the potential to yield large quantities of water to serve domestic, industrial, and agricultural requirements.

TABLE 9.3 SUMMARY OF RESULTS FROM THE WATER QUALITY CHECK PROGRAM—PHYSICAL PARAMETERS

PARAMETER	NUMBER OF SAMPLES	RANGE	MEDIAN	PERCENT OF SAMPLES EXCEEDING DRINKING WATER QUALITY GUIDELINES
TDS	5,013	<10 to >9,800 mg/L	185 mg/L	12% (>500 mg/L)
Hardness	11,550	<10 to >7,700 mg/L	77 mg/L	3.5% (>500 mg/L)[6]
Total Alkalinity	11,600	<10 to 7,734 mg/L	110 mg/L	10% (>300 mg/L)[7]
pH	11,606	<5 to >10	7.6	9.7% (pH<6.5); 6.2% (pH>8.5)

The natural chemical quality within these aquifers is excellent, for the most part. Between 1977 and 1993, the province of British Columbia provided over 11,000 subsidized laboratory analyses through the BC Water Quality Check Program (WQCP) to residents in the BC Cordillera relying on well water. Laboratory analyses were performed on a limited range of water quality parameters concerning health issues, or as general indication of water quality. Although this data set has an inherent spatial bias (e.g., more data may be from the west coast volcanic belts as opposed to the eastern Cordillera carbonate areas; more data from the south than the north), the analysis nevertheless contains the widest geographic coverage of the Region from where groundwater is used, over an extended period of time. The overview of groundwater quality provided in this section is primarily based on data set from the BC Water Quality Check Program (1977–1993), as well as on documented water quality concerns identified through aquifer classification mapping and other available groundwater quality studies. Groundwater quality data for the Cordillera outside of BC and for public water supply wells was not readily accessible and these areas have not been included in the summary for the Region.

9.7.1 General groundwater quality in the Region

According to the data, total dissolved solids (TDS) in the Cordillera range from as low as <10 mg/L to over 9,800 mg/L, with a median of 185 mg/L (see Table 9.3 and Figure 9.7a), reflecting the generally low total mineralization of groundwater in the Region. 90% of the samples had TDS of <650 mg/L. The highest reported TDS was found in coastal bedrock aquifers and may reflect wells drilled into brackish groundwater close to the ocean.

Water hardness (expressed as $CaCO_3$) ranged from <10 mg/L to over 7,700 mg/L (see Table 9.3 and Figure 9.7b). Water hardness in most groundwater is occurring naturally from weathering of limestone, sedimentary rock, and calcium bearing minerals. Over 50% of the samples had hardness of <80 mg/L, indicating water in the Region is generally soft. Over 90% of the samples had hardness of <340 mg/L, while 3.5% had hardness concentrations over 500 mg/L, while (the limit above which water is considered unacceptable). Soft water tended to be found in areas with mainly igneous rock formations, whilehardness in areas with mainly sedimentary rock tended to be greater. Water is also generally softer along the coast than in the interior

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[6] No numerical guideline; 80 to 100 mg/L as $CaCO_3$ is acceptable; over 200 mg/L as $CaCO_3$ is poor but can be tolerated; over 500 mg/L as $CaCO_3$ is normally unacceptable.
[7] No guideline.

of the Region.

Total alkalinity, expressed as $CaCO_3$, ranged from <10 mg/L (generally low pH waters) to >7,700 mg/L, with a median value of 110 mg/L (see Table 9.3 and Figure 9.7c). 90% of the samples had total alkalinity values of <325 mg/L.

The pH values ranged from <5 to >10 (see Table 9.3 and Figure 9.7d). 84.1% of the samples had pH values of between 6.5 and 8.5 (the pH range within the Guidelines for Canadian Drinking Water Quality, known as GCDWQ, for pH), 9.7% of the groundwater samples had pH values < 6.5, and 6.2% of the samples had pH value > 8.5. pH values of lower than 6.5 were all found along the coastal areas of the Region; pH values of greater than 8.5 were found in the Lower Mainland, Gulf Islands (likely wells intersecting seawater as a fraction) and Vancouver Island, as well as in the interior of the Region.

9.7.2 Common water quality concerns in the Region

Of the 888 aquifers classified and mapped in the Cordillera Region, 4% (38 aquifers) have documented health-risk related quality concerns (including nitrate, arsenic, fluoride, boron), and 4% (39) have "salty water". These issues are isolated, local, or regional in extent. Table 9.4 (adapted from Cui and Wei, 2000) lists the groundwater quality parameters of concern, range of values and median from the analytical results, and percentages of samples exceeding Canadian Drinking Water Guidelines. Generally, only a small portion of groundwater samples had certain water quality parameters above Canadian Drinking Water Guidelines.

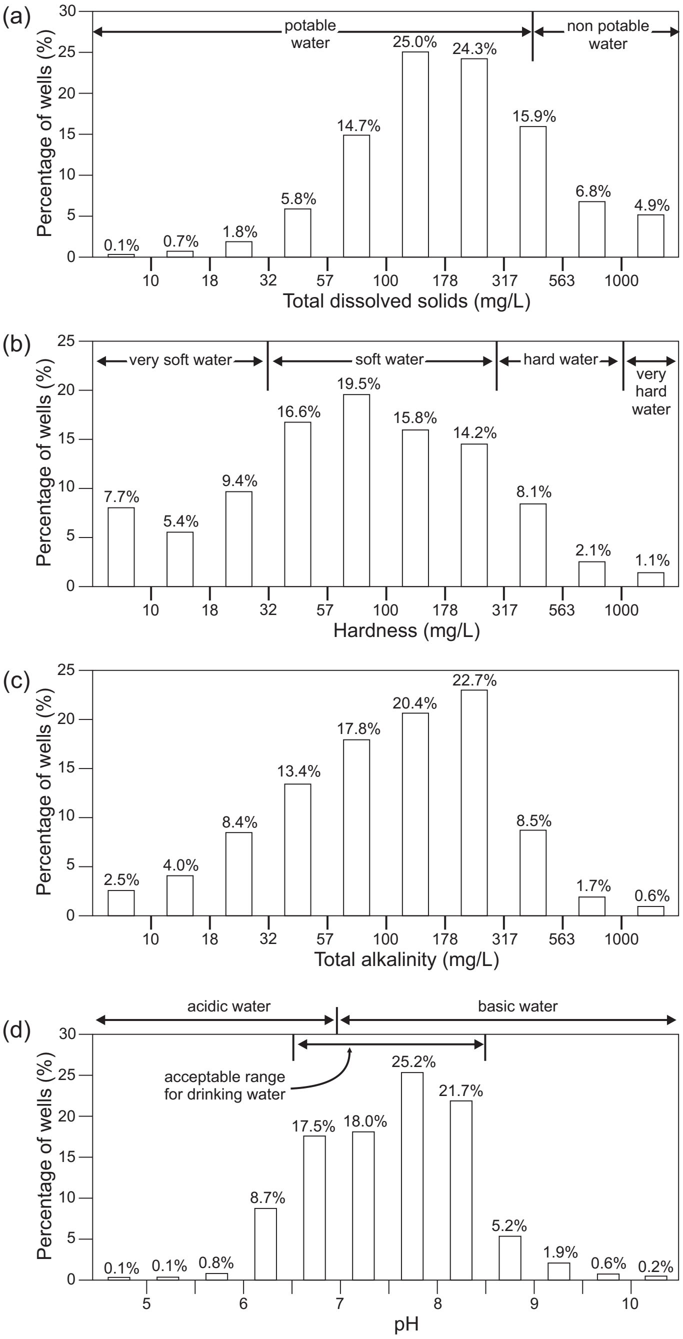

Figure 9.7 These graphs depict, from top to bottom, (a) total dissolved solids (TDS), (b) hardness, (c) total alkalinity, and (d) pH in wells in the Cordilleran Hydrogeological Region, sampled as part of the BC Water Quality Check Program between 1977 and 1993. Please note that the horizontal axis for the TDS, hardness, and alkalinity graphs shows the distribution of values on a logarithmic scale.

Although several water quality concerns (both naturally occurring and as a result of human activity) exist in the Region (e.g., fecal coliform bacteria and *E. coli*, metals, volatile organics), there are a few that have occurrence with potential aquifer-wide impact: nitrate, arsenic, fluoride and boron, and salty water (sodium, chloride).

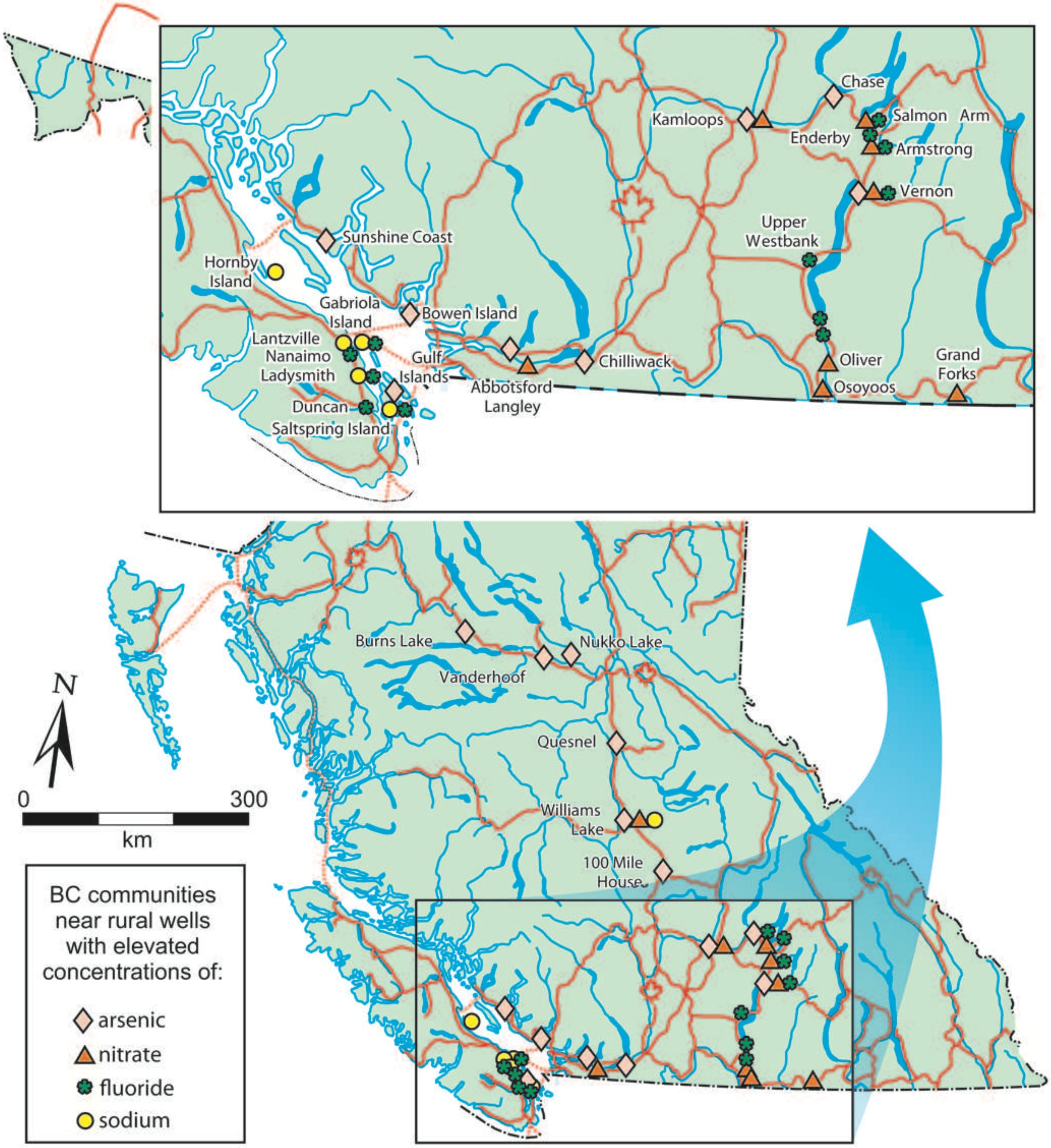

Figure 9.8 Areas of known elevated arsenic, sodium, fluoride and nitrate-nitrogen in wells within the Cordilleran Hydrogeological Region (based on data from the BC Water Quality Check Program).

9.7.2.1 Nitrate

Nitrate (NO_3) is the most significant non-point source contaminant in the Cordillera Region. Nitrate ranges from non-detectable to over 100 mg/L NO_3-N (Table 9.4). The median NO_3-N value is 0.05 mg/L. Less than 2% of the samples tested contained nitrate-nitrogen (NO_3-N) higher than the Canadian Drinking Water Guideline; 7%

of the samples had NO_3-N values of above 3 mg/L, the concentration above which groundwater quality is interpreted to be affected by human activities. Elevated nitrate is known to occur in some aquifers within the Lower Fraser Valley (e.g., Carmichael et al., 1995; Hii et al., 1999; 2005; Liebscher et al., 1992; McArthur and Allen, 2005), near Langley and Abbotsford, for example, plus the Southern Okanagan interior of the Region (Hodge, 1992; 1985a; 1985b), and Grand Forks (Maxwell et al., 2002; Wei et al., 1993). Nitrates also occur in other areas, but in isolated cases (see Figure 9.8). Most exceedances occur in areas of intensive agricultural activity, or at locations where septic tanks are the main method of sewage disposal.

Localized to widespread nitrate typically occurs in unconfined, unconsolidated aquifers—Types 1b (3 aquifers) and Type 4a (8 aquifers); these are the most vulnerable aquifers in the Cordillera. These unconfined aquifers also occur along valley bottoms and in plains, where agricultural activities exist. Localized nitrate may also be found in confined, unconsolidated aquifers—Type 4b (1 aquifer), although windows in the confining layer may allow nitrate to be transported downward into the aquifer. To date, no bedrock aquifers show any significant nitrate contamination.

Nitrate is usually introduced into groundwater through diffuse and/or widespread sources (non-point sources) to pinpoint. They include leaching of chemical fertilizers or animal manure. Point sources of nitrate include septic and sewage discharges. Recent studies have used nitrogen isotopes to distinguish between different sources of nitrate-nitrogen in groundwater (to differentiate between chemical fertilizer versus manure fertilizer, for example, Wassenaar, 1995; Wassenaar et al., 2006; Wei, 1992); human waste and septic sources, however, produce nitrate that is indistinguishable from animal waste (Kendall, 1998). In addition to nitrate, pesticides at trace levels have been detected in Cordillera well water, although only in isolated instances (e.g., Lower Mainland – Carmichael et al., 1995; Liebscher et al., 1992).

9.7.2.2 Arsenic

A total of 112 samples from the 2226 Water Quality Check Program sample results (5%) had arsenic present at concentrations above the historic laboratory method detection level of 0.4 mg/L. Current analytical methods have much lower detection limits, and, as a result, these results provide an incomplete picture of arsenic occurrence within the Region. The GCDWQ is 0.010 mg/L.

The most common source of naturally occurring elevated arsenic levels in groundwater is the weathering of arsenic bearing minerals and ores. Arsenic is found primarily in areas with arc, back-arc, and oceanic volcanic rocks or meta-volcanic rocks (i.e., crystalline bedrock aquifer types). There are, however, recent reported occurrences in sedimentary rock (on Saturna Island and Saltspring Island in the Gulf Islands) and in unconsolidated aquifers (the aquifer underneath the San Juan River on southern Vancouver Island, and the aquifer at Chilliwack-Rosedale (Graham, 2006), in the Lower Mainland. Localized high arsenic concentrations have been found in well water from several areas within the Region (Figure 9.8); these are almost always associated with arsenic-containing bedrock formations. Arsenic concentrations above the drinking water guideline have been found in some rural wells near the communities of 100 Mile House, the Sunshine Coast, Powell River and the Howe Sound (Mattu and Schreier, 2000; Carmichael, 1995), the Okanagan Valley (e.g., Vernon), and other parts of the interior of the Region (e.g., Burns Lake, Chase, Kamloops, Quesnel, Vanderhoof, and Williams Lake). Elevated arsenic has been found in isolated wells on Saltspring Island, the Lower Mainland (Zubel, 2002), and near Nukko Lake (Figure 9.8). Arsenic levels above the drinking water guideline may be identified in other areas of the Region as more water quality results become available.

9.7.2.3 Fluoride and boron

Some 3% of the samples tested contained fluoride concentrations above the drinking water limit of 1.5 mg/L while 0.7% had boron above the drinking water limit of 0.5 mg/L (Table 9.4). Fluoride is found in some sedimentary, volcanic, and crystalline bedrock aquifers. High concentrations of fluoride in groundwater were observed in rural wells near the communities of Armstrong, Duncan, Enderby, Gabriola Island, Ladysmith, Nanaimo, Okanagan Falls, Penticton, Salmon Arm, Saltspring Island, and Vernon (BC Environment and Environment Canada, 1994; see Figure 9.8). On the east coast of Vancouver Island and the adjacent Gulf Islands, Earle and Krogh (2006) observed a strong correlation between fluoride and pH, also with boron. Their study contained 30 samples with pH greater than 8.5, 17 had fluoride levels greater than 1.5 mg/L.As a result, Earle and Krogh proposed that these elevated concentrations were the result of base-exchange softening, as discussed by Allen and Suchy (2001b). Fluoride in groundwater in the Cordillera can also result from runoff and infiltration of chemical fertilizers in agricultural areas.

9.7.2.4 Salty water (sodium and chloride)

The most common natural sources of elevated sodium levels in groundwater are the erosion of salt deposits and sodium bearing rock minerals; the naturally occurring brackish water of some aquifers, and salt water at depth in coastal areas. Ambient concentration of sodium in groundwater within the Region typically ranges from a few mg/L to over 100 mg/L. Samples with high sodium concentrations (>200 mg/L), generally associated with “salty water”, were found either along coastal areas, where seawaters were the possible sources, or in areas where road salts might be the contributors (Figure 9.8). High values of chloride are often found in conjunction with high sodium; however, concentrations of sodium can be increased due to base-exchange or water-softening processes (Allen and Suchy, 2001b).

Naturally occurring brackish or saline groundwater has been found in deep marine sediments (Type 4c) in the Lower Mainland (Halstead, 1978), locally in some sedimentary bedrock aquifers (e.g., Nanaimo Group—Type 5a) or in crystalline bedrock aquifers (Type 6b) on the Gulf Islands and Vancouver Island (Kohut et al., 1986; Allen and Suchy, 2001a), and those aquifers associated with thermal springs (Grasby and Lepitzki 2002, Grasby et al., 2000; Allen et al., 2006). Saline groundwater is typically characterized by high levels of sodium and chloride, although elevated sulphate may also be present. Unconsolidated aquifers underneath the San Juan River and Cowichan River (Kohut, 1981) also have documented concern about salty water in the estuary.

Sodium and chloride contamination, due to saltwater intrusion, is a threat to groundwater supplies located within coastal areas. In some instances, saltwater intrusion has already occurred, most notably in the Gulf Islands (Allen and Suchy, 2001a), where a number of wells (e.g., Gabriola

TABLE 9.4 SUMMARY RESULTS FROM THE WATER QUALITY CHECK PROGRAM —PARAMETERS OF HEALTH CONCERNS

PARAMETER	NUMBER OF SAMPLES	RANGE*	MEDIAN	PERCENT OF SAMPLES EXCEEDING DRINKING WATER QUALITY GUIDELINES
Nitrate-nitrogen	11,660	ND to >100 mg/L	0.05 mg/L	1.6% (>10 mg/L)
Arsenic	2,226			5% (>0.04 mg/L Detection Limit)[8]
Fluoride	8,349	ND to >100 mg/L	0.1 mg/L	3.2% (>1.5 mg/L)
Boron	10,343	ND to >75 mg/L	0.01 mg/L	0.69% (>5 mg/L)
Sodium	2,209	<1 to 3,000 mg/L	9.3 mg/L	Sodium - 5.1% (>200 mg/L)
Total Coliform	11,321	<1 to 24,000 CFU	ND CFU	15.3% (>10 CFU)

* ND= Not Detected

Island, Hornby Island, Saturna Island, Mayne Island, Saltspring Island) have Na concentrations up to thousands of mg/L depending upon the location and depth of the well (Allen and Suchy, 2001a; Allen and Matsuo, 2001; Kohut et al., 1986; Dakin et al., 1983).

Typically, saltwater intrusion occurrences are restricted to narrow islands and peninsulas where land for groundwater recharge is limited. However, closely-spaced residential lots serviced by individual private wells along the coast are also at risk of groundwater quality degradation. Elevated concentrations of sulphate have also been observed in certain areas of the Gulf Islands (Allen and Suchy, 2001a; Allen and Matsuo, 2001). An increase in the groundwater content of sodium or chloride above ambient or natural levels in non-coastal areas may indicate pollution from point or non-point sources, such as from the application of road salt or from nearby landfills.

9.7.2.5 Bacteria

The presence of coliform bacteria in well water either reflects naturally occurring sources, anthropogenic sources, such as septic tank effluent, or inadequate disinfection. Occurrence of coliform bacteria in the Cordillera Region appears to be generally local in extent. Of the 12,000 samples analyzed for total coliform bacteria (Water Quality Check Program), 15% had concentrations greater than the drinking water guideline of 10 CFU (colony forming unit) per 100 mL water, 80% of the samples taken had between 1 and 10 CFU/100 mL and 5% of samples had less than or equal to 1 CFU/100 mL. There was no geographic occurrence pattern for total coliform organisms above the guideline. Twelve sites sampled in the Abbotsford-Sumas aquifer during 2004 showed the presence of fecal coliform, and 111 sites were found to have elevated total coliforms (as high as 1,500 CFU per 100 mL) (Hii et al., 2005). The distribution of bacteria contamination, however, appeared to be localized to a few specific wells and not reflective of overall aquifer water quality.

9.7.2.6 Other parameters

Iron, manganese, and hydrogen sulphide gas are problematic in some parts of the Cordillera

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[8] Historically, samples from the WQCP were analyzed using a method with a detection limit that is higher than the current Guideline for Canadian Drinking Water Quality for arsenic (current guideline is 0.010 mg/L). Therefore, historic values likely range from Not Detected (ND) to hundreds of parts per billion (mg/L).

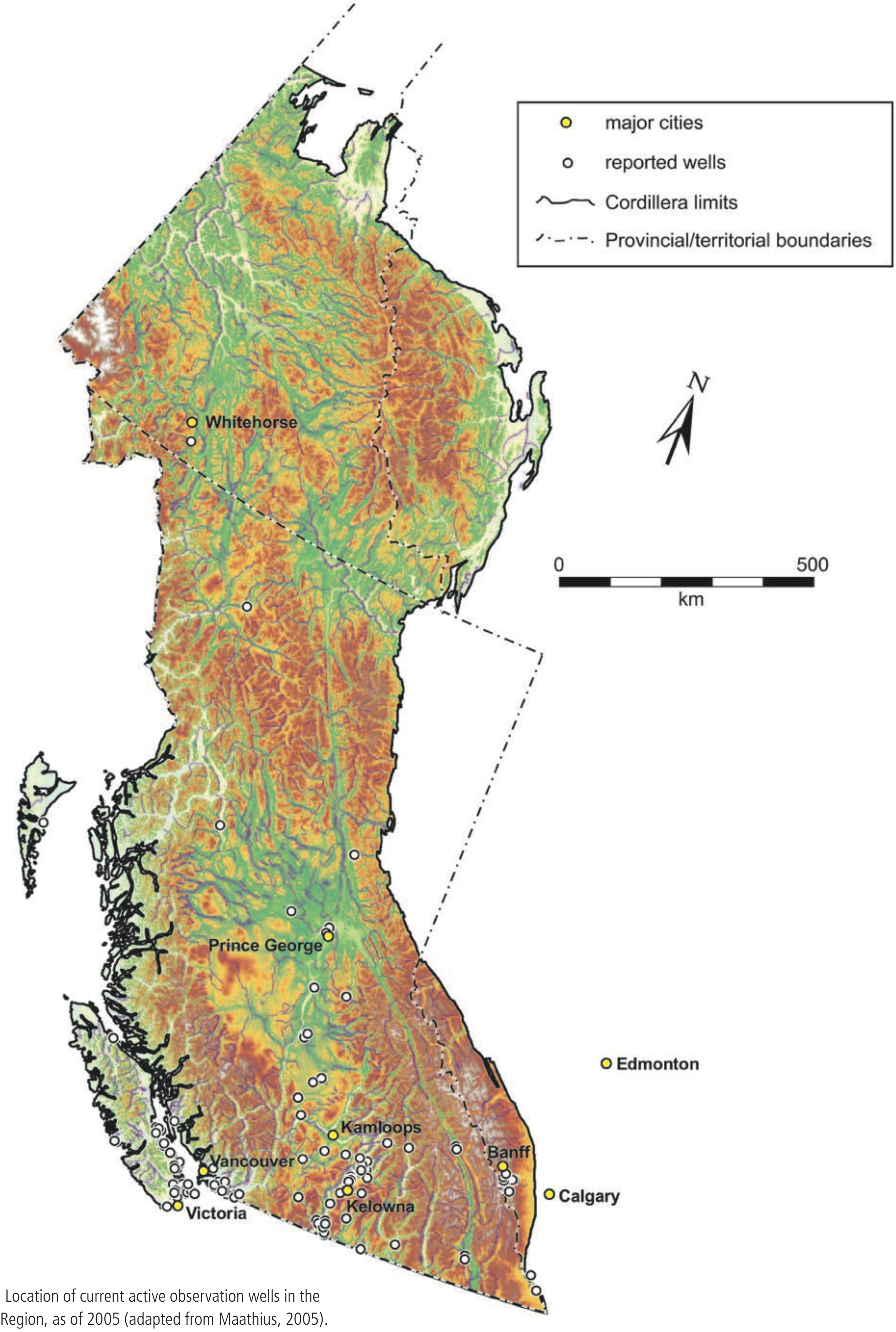

Figure 9.9 Location of current active observation wells in the Cordilleran Region, as of 2005 (adapted from Maathius, 2005).

Region. The most common groundwater sources of iron and manganese occur naturally, from weathering of iron and manganese bearing minerals and rocks. Industrial effluent, acid mine drainage, sewage and landfill leachate may also contribute. The concentration of iron and manganese in well water can fluctuate seasonally and will vary with the well depth and location, and the geology of the area. Iron and manganese are found naturally in groundwater containing little or no oxygen, typically in deeper wells (but not always), in areas where groundwater flow is slow, and in those areas where groundwater flows through soils rich in organic matter. Locally, concentrations of iron and manganese can range up to several mg/L. In one residential area south of Revelstoke, historical observations suggest iron and manganese in well water fluctuate with the level of the nearby Columbia River (as fluctuation of the river may affect the groundwater rate of flow to the river and, therefore, the amount of oxygen in the groundwater; Wei, 1983). Concentrations of Mn exceeding the MAC (maximum allowable concentration) have been found in roughly one third of the wells sampled on the Gulf Islands (Allen and Pelude, 2001).

Groundwater containing dissolved hydrogen sulphide (H_2S) gas imparts a characteristic "rotten egg" odour and taste. Although not normally analyzed during a routine chemical analysis, hydrogen sulphide gas is often detected by smell during sampling. It has been noted on some of the Gulf Islands (e.g., Saturna and Hornby Island), and likely is present in other parts of the Region.

Phosphorous, a principal constituent of concern in septic tank effluent has been detected in groundwater entering lakes in the Okanagan Valley (BC Environment and Environment Canada, 1994).

When the BC Ministry of Health tested household basements for radon gas (BC Ministry of Health, 2007), a number of communities, mostly within BC's interior of BC, had levels above 200 Bq/m^3. Although no groundwater sampling for radon gas has been done in these areas, it is possible that concentrations could be similarly high.

9.8 GROUNDWATER MONITORING IN THE CORDILLERAN HYDROGEOLOGICAL REGION

Four different senior levels of government within the Cordillera—Yukon and Northwest Territories, the province of Alberta and the province of British Columbia—have groundwater level and ambient quality monitoring responsibilities for the Region. We will address, in this section, the distribution of observation wells within the Region, both spatially and by aquifer types. Much of the information presented here is derived from *Groundwater Observation Well Networks in Canada* compiled by Maathius (2005).

In 2005, there were 162 observation wells existing in the Cordillera (153 of these wells were operated by the province of British Columbia, 8 by the province of Alberta, and 1, in Whitehorse, by the Yukon Territory) to monitor groundwater conditions in the Miles Canyon Basalt aquifer. Most of these wells are located in developed areas, largely in the southern half of the Region, where groundwater development has historically been most intensive (Figure 9.9). Figure 9.10 charts the proportion of active observation wells by aquifer types. Most of the active observation wells monitor groundwater levels in Type 1b, 4a, 4b, 5a, and 6b aquifers. Distribution of the Observation Well Network in BC was recently reviewed (Kohut, 2007).

Groundwater levels for BC's observation wells reported online (http://www.env.gov.bc.ca/wsd/

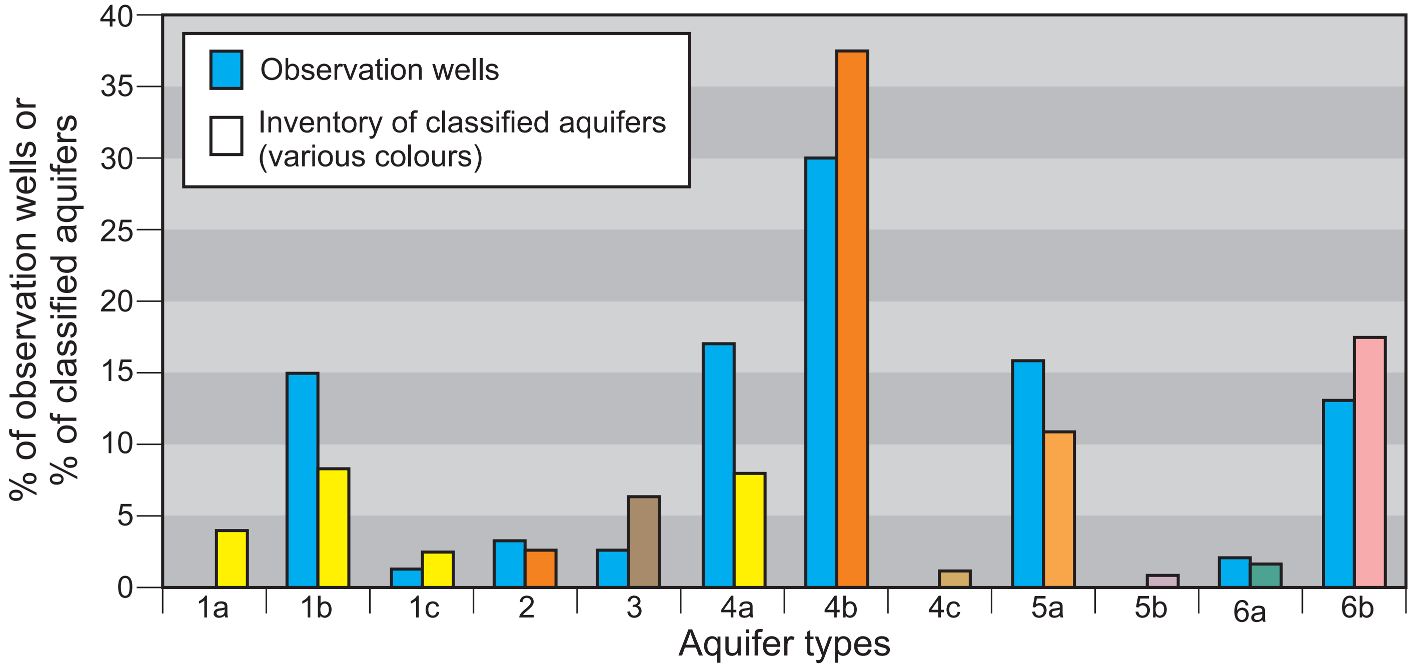

Figure 9.10 Percentage of current observation wells compared to percentage of classified aquifers by aquifer types.

data_searches/obswell/map/obsWells.html, and groundwater level data for all observation wells in BC can be downloaded from the web: http://www.env.gov.bc.ca/wsd/data_searches/obswell/map/obsWells.html.

Moore et al. (2007) undertook a review of the historic climate, hydrometric and groundwater level data throughout BC, to examine groundwater trends. Decreasing groundwater levels during late summer in naturalized settings coincided with decreasing streamflow in many parts of the province (Allen et al., 2008). The 2007 Environmental Trends Report http://www.env.gov.bc.ca/soe/indicators/water/ for BC revealed the fact that groundwater levels in BC are declining over time in a number of observation wells within the Cordillera. Between 2000 and 2005, some 35% of observation wells monitoring groundwater levels affected by human activities (e.g., local pumping industry, agriculture or drinking water) showed declining water levels.

The 2000 to 2005 reporting period also revealed a notable increase in observation wells showing declining groundwater levels due to human activities compared to previous reporting periods (1995–2000, 1990–1995, and 1985–1990). It is not yet known if this increase can be attributed to additional observation wells being installed in heavily developed aquifers, or to a general increase in human activities over these aquifers, or both.

The provinces of BC and Alberta also monitor ambient groundwater quality. Most observation wells in BC are sampled regularly either every year to every few years in this regard. BC also operates an Ambient Groundwater Quality Monitoring Network comprised of private residential, municipal, and monitoring wells in areas where non-point sources of contamination occur, or in IA—heavily developed, highly vulnerable aquifers. To date, this network covers the Lower Mainland (Abbotsford, Langley, Hopington, Belcarra), Whistler, Southern Interior (Merritt, Oliver, Osoyoos, Cache Creek, Armstrong, Grand Forks, Scotch Creek), Vancouver Island and Gulf Islands (Hornby Island, Gabriola, Chemainus, Cowichan River). Data for Ambient Groundwater

Quality Network is available online (http://www.env.gov.bc.ca/emswr/).

9.9 CONCLUSIONS

The Cordilleran Hydrogeological Region occupies four jurisdictions—British Columbia, Alberta, Yukon and Northwest Territories, and is one of the most diverse and unique in Canada with respect to relief, climate, and hydrogeology. Our discussion of aquifers within the Region has been based largely on the inventory of developed aquifers mapped and classified since 1994 by the province of British Columbia, as well as more comprehensive study reports of select aquifers. Records indicate six major types of aquifers (with subtypes) within the Region, each with its own unique hydrogeological characteristics:

Unconsolidated aquifers

Type 1. Unconfined sand and gravel aquifers of fluvial or glaciofluvial origin occurring along rivers or streams
- a. Aquifers occurring along large rivers
- b. Aquifers occurring along mid-size rivers or stream
- c. Aquifers along small streams

Type 2. Predominantly unconfined deltaic sand and gravel aquifers

Type 3. Predominantly unconfined alluvial fan, colluvial sand and gravel aquifers

Type 4. Sand and gravel aquifers of glacial or preglacial origin
- a. Unconfined sand and gravel aquifers of glaciofluvial origin (These types of aquifers do not generally occur adjacent to present-day rivers.)
- b. Confined sand and gravel aquifers of glacial or preglacial origin
- c. Confined sand and gravel aquifers associated with glaciomarine environments

Bedrock aquifers

Type 5. Sedimentary bedrock aquifers
- a. Fractured sedimentary bedrock aquifers
- b. Karstic limestone aquifers

Type 6. Crystalline bedrock aquifers
- c. Flat-lying or gently-dipping volcanic flow rock aquifers
- d. Crystalline granitic, metamorphic, metasedimentary, meta-volcanic and volcanic rock aquifers

One of the unique characteristics of unconsolidated sand and gravel aquifers within the Region is the small size (ranging from an average size of 5 km^2—Type 2 and 3—to 27 km^2—Type 1a in average size); these are not considered "regional" aquifers but nonetheless constitute some of the most productive and important aquifers in Canada (with reported average median well yields of up to 6.1 L/s and geometric mean transmissivities ranging from 200 to 4,510 m^2/d). Many of the unconsolidated sand and gravel aquifers (Types 1, 2, 3 and 4a) were formed at or after the end of the last period of glaciation these are shallow, predominantly unconfined, comprised of coarse-textured sediments, and therefore, highly vulnerable to contamination from the land surface. Older, deeper unconsolidated sand and gravel aquifers formed during or at the advance stages of the last period of glaciation (Type 4b), or of glaciomarine origin (Type 4c), are generally confined and much less vulnerable.

Bedrock aquifers within the Region generally exhibit fractured flow, and possibly channelized flow (potential karstic limestone aquifers—Type 5b). The largest bedrock aquifer is the volcanic flow aquifer (aquifer classification # 124) situated in Central British Columbia which occupies at least

6,546 km^2 (known mapped area). Bedrock aquifers usually yield lesser quantities of groundwater (average median yields range from 0.3 to 0.4 L/s) and have lower transmissivities (geometric mean transmissivities of 3.7 to 23 m^2/d) than unconsolidated sand and gravel aquifers. The vulnerability of bedrock aquifers within the Region varies depending on the nature, amount, and extent of overlying unconsolidated sediments present.

Groundwater quality of the Region is normally excellent with respect to TDS (median of 185 mg/L), hardness (median of 77 mg/L), total alkalinity (median of 110 mg/L), and pH (average of 7.6), although concerns exists about elevated nitrate, arsenic, fluoride, and salty water in specific aquifers. Elevated nitrate is usually found in predominantly unconfined, unconsolidated sand and gravel aquifers (mostly Types 1b and 4a). Elevated arsenic and fluoride appear to be naturally occurring. Elevated arsenic is found in crystalline and some sedimentary bedrock aquifers (Types 5a and 6b) but also in unconsolidated aquifers (Type 1a). Elevated fluoride is found in sedimentary and crystalline bedrock aquifers (Type 5a and Type 6). Elevated salty water occurs in unconsolidated glaciomarine aquifers (Type 4c) in the Fraser Lowland near Vancouver, as well as sedimentary (Type 5a) and crystalline bedrock (Type 6b) aquifers in coastal areas such as the Gulf Islands and Vancouver Island.

Although much has been learned about aquifers within the Canadian Cordillera over the last 50 years, more studies are required, especially at the local scale. This will result in specific place-based science to support management and/or protection of local groundwater resources within the Region. Given the unique characteristics of many of the Cordillera Region's aquifers, and the increasing demand and pressures on the groundwater resource they provide, we recommend the following:

- Detailed local mapping (at 1:20,000 to 1:50,000 scale) and characterization of specific high-priority aquifers or basins, including a better understanding of the relationship between surface water and groundwater for specific high-priority Type 1, 2 and 4a aquifers
- Expand groundwater level monitoring in developed aquifers, especially in the northern and eastern portion of the Region to monitor groundwater use, resource development, and any effects on groundwater availability
- Regional vulnerability mapping of developed aquifers given the numerous unconfined, unconsolidated aquifers that exist in the Region to influence appropriate local land use planning and practices
- Develop and expand acquisition of groundwater quality data in the Region to gain greater understanding about the occurrence and origin of naturally occurring chemicals and microbiological species of concern in groundwater, such as arsenic and bacteria
- Engage local communities to support use of place-based hydrogeological information in local decision making
- Establish regular dialogue between federal, provincial, and territorial governments to promote exchange of information and coordinate activities, where appropriate

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Financial and in-kind support from the BC Ministry of Environment and Geological Survey of Canada for this work is also greatly appreciated.

BOX 9-1 BRITISH COLUMBIA AQUIFER CLASSIFICATION SYSTEM

The British Columbia aquifer classification system was developed in 1994 (Kreye and Wei, 1994). Its main objective was to interpret and synthesize raw well construction report (well record) data to identify and classify developed aquifers to

- Provide a framework to direct detailed aquifer mapping and assessment
- Provide a method of screening and prioritizing management, protection and remedial efforts on a provincial, regional and local level
- Identify the level of management and protection an aquifer requires
- Build an inventory of developed aquifers in the province
- Increase public knowledge and understanding of the groundwater resource

Data used for classifying aquifers come from various sources (primarily available well records, geologic mapping, and specific groundwater reports). The aquifer classification system contains two main components:

a) Classification component

b) Ranking value component (see Figure 9.11).

The classification and ranking value components are determined for the aquifer as a whole, and not for parts of aquifers.

The **classification component** characterizes an aquifer on the basis of groundwater resource development and level of vulnerability to contamination. The **ranking value component** assigns a number value indicating the aquifer's relative importance.

Classification Component

The classification component categorizes aquifers based on current level of groundwater development (categories I, II, and III for high, moderate and light development, respectively) and vulnerability to contamination (categories A, B, and C for high, moderate, and low vulnerability, respectively). The combination of the three development and three vulnerability categories results in nine aquifer classes, ranging from IA to IIIC as seen in the Figure 9.12.

These nine aquifer classes have an implied priority from IIIC, the lowest priority for management and protection to IA, the highest.

Specific management objectives also set priorities. Should the objective be assurance of a sustainable water supply then heavily developed I aquifers (i.e., IA, IB, IC) should be given attention.

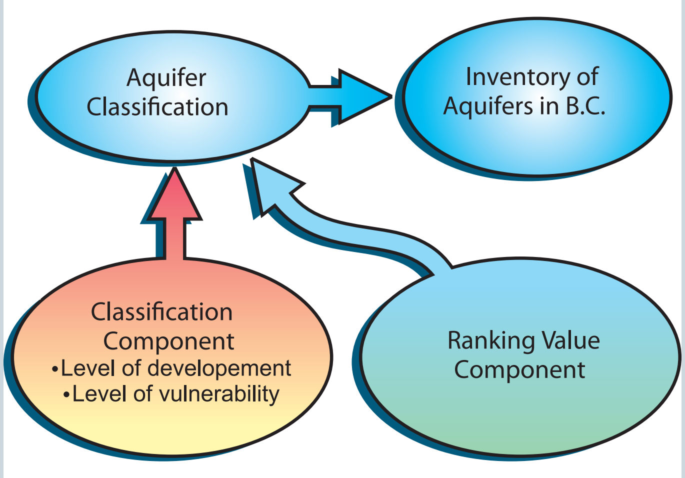
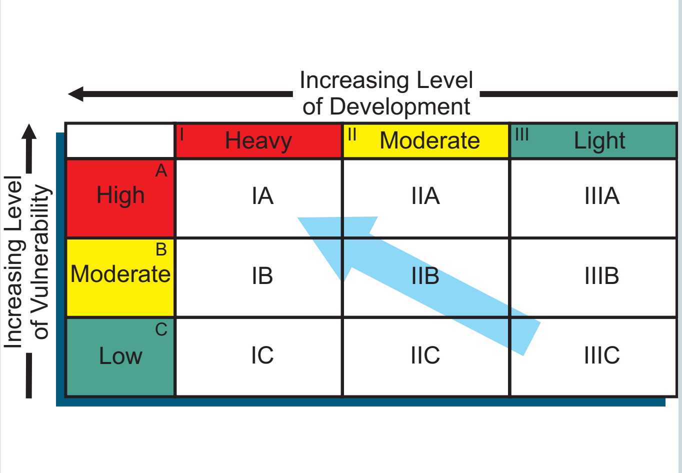


Figure 9.11 The British Columbia Aquifer Classification System.



	I Heavy	II Moderate	III Light
A High	IA	IIA	IIIA
B Moderate	IB	IIB	IIIB
C Low	IC	IIC	IIIC

Figure 9.12 Aquifer classes.

When the objective is protection of groundwater quality, then highly vulnerable A-aquifers (i.e., IA, IIA, IIIA) become primary concerns.

Level of development, a relative and subjective term, compares the amount of groundwater withdrawn from an aquifer (demand) to the aquifer's inferred ability to supply groundwater for use (productivity). Levels of development are usually determined subjectively by assessing well density, water use and aquifer productivity (calculated from reported well yield and specific capacity), and recharge sources.

An aquifer's **level of vulnerability** is a measure of its vulnerability to any contaminant introduced at the land surface. Vulnerability in such a system is considered to be intrinsic to the aquifer, based on hydrogeology: it does not consider existing type of land use or nature of potential contaminants.

Assessment of vulnerability is not an assessment of the risk of contamination. An aquifer's level of vulnerability is qualitative and based on type, thickness and extent of geologic sediments overlying the aquifer, depth to water (or depth to top of confined aquifers), and porosity (when reporting on bedrock aquifers), and type of aquifer material.

Ranking Value Component

The ranking value component assigns a number value indicating the relative importance of an aquifer. Assigned values are derived from seven criteria: 1) aquifer productivity, 2) aquifer vulnerability to surface contamination, 3) aquifer area, 4) demand on the resource, 5) type of groundwater use, and known documented groundwater concerns related to 6) quality, and to 7) quantity.

This point value is determined by summing each criterion, with the lowest ranking value possible being 5 and the highest-ranking value possible being 21. Generally, the aquifer with the highest-ranking value has the greater priority. Table 9.5 shows the ranking values applied for each criterion.

TABLE 9.5 AQUIFER RANKING VALUES

Increasing ranking value →

	1	2	3
Productivity	low	moderate	high
Vulnerability	low	moderate	high
Area	< 5 km^2	5 - 25 km^2	> 25 km^2
Demand	low	moderate	high
Type of use	non-drinking water	drinking water	multiple
Quality concerns	isolated	local	regional
Quantity concerns	isolated	local	regional

All hydrological and water use criteria are of equal weight. Each is assigned a point value ranging from 1 to 3 according to the magnitude of concern or importance. Exceptions are quality and quantity concerns, where the point values range from 0 to 3. A zero value (0) is assigned if no known or documented concerns exist. Once individual values have been assigned, all other values are summed to obtain an overall ranking for the specific aquifer.

Productivity describes yield from wells and springs and the abundance of groundwater in any given aquifer. Indicators of productivity (e.g., reported well yields, specific capacity of wells, and transmissivity of the aquifer) are used to infer potential productivity of that aquifer.

Vulnerability is the potential for an aquifer to be degraded. The higher an aquifer's vulnerability, the greater the potential for degradation, necessitating a higher priority for directing protection and management efforts to that aquifer.

Aquifer size refers to the areal extent (in square kilometres) of the aquifer. Usually, larger aquifers have more regional importance when compared to smaller aquifers. For those aquifers straddling the international border, size is generally reported only for that portion located within Canada.

Demand is assessed subjectively, based on domestic well density, number and type of production wells, and general knowledge of groundwater use (such as for drinking water or irrigation) and land use within the area.

Type of water use of an aquifer reflects the variability and diversity of the resource as a supply. Categories of water use include non-drinking, drinking (municipal or domestic), and multiple (both drinking and other applications such as commercial, industrial, and agricultural).

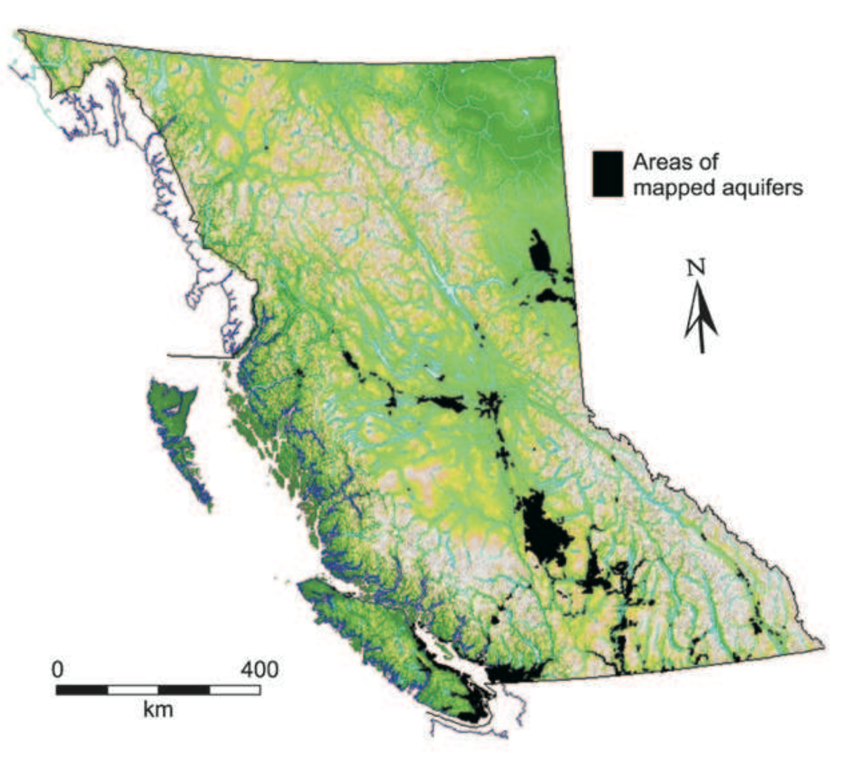


Figure 9.13 Mapped developed aquifers in BC (as of 2007).

Quality concerns are defined by the presence of contaminants in the aquifer that pose a health risk. Contaminates may include nitrate, pesticides, volatile organic compounds, fluoride, arsenic or sea water intrusion. Contaminants may be naturally occurring or introduced by human activities.

Quantity concerns are defined by demand exceeding supply. Evidence of demand exceeding supply includes instances of well interference or aquifer mining, presence of dry wells, and situations in which primary source aquifers are unable to meet demands on a seasonal or cyclical basis.

Ranking values for the aquifers ranged from a high of 21 to a low of 5. Only 5% of all aquifers have a ranking value of 14 or greater. The highest ranking values were associated with unconsolidated aquifers and were attributable to quality/quantity concerns, aquifer size, productivity, and level of demand on those aquifers.

Aquifer classification has now been completed in most areas of BC where groundwater resources have been developed. Once a new aquifer is classified, it is added to the Province's aquifer inventory. As of 2007, 888 developed aquifers have been identified, mapped, and classified within the BC Cordillera (Figure 9.13).

The inventory of aquifers shows:

Unconsolidated aquifers:	70%
Bedrock aquifers:	30%
IA aquifers (highly developed & highly vulnerable):	4%
I aquifers (heavily developed):	8%
A aquifers (highly vulnerable):	27%
B aquifers (moderately vulnerable):	31%

The high percentage of unconsolidated aquifers identified reflects the association between population distribution and river valley locations where aquifers are typically developed in sand and gravel deposits. Bedrock aquifers are generally found on valley sides or in upland and plateau areas where the population is more sparse. Almost 30% of unconsolidated aquifers were reported as highly productive, versus less than 1% of bedrock aquifers.

17% of classified aquifers have documented quantity and/or health-risk related quality concerns. 107 aquifers have reported quality concerns, 63 have reported quality concerns; some aquifers have both. These concerns may be isolated, local, or regional in extent.

Development of the classification system stimulated a demand for aquifer information far greater than expected because the information was accessed by a myriad of other user groups beyond the target group of hydrogeologists, planners and water managers. A guidance document (Berardinucci and Ronneseth, 2002) was produced to promote the appropriate use of the aquifer classification system and to assist users in interpreting and using the aquifer maps. This document can be found at: http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/reports/aquifer_maps.pdf. These aquifer maps, and other hydrological information, are also available on-line on the web at: http://webmaps.gov.bc.ca/imf5/imf.jsp?site=wrbc.

BOX 9-2 ABBOTSFORD-SUMAS AQUIFER

The Abbotsford-Sumas aquifer, located in Lower Fraser Valley in southwest British Columbia and northwest Washington State is approximately 161 km^2 (62 sq. miles) in area, roughly bisected by the Canada-USA border (Figure 9.14). The aquifer spans uplands and three river valleys. The uplands are centred on the City of Abbotsford, and extend westward through Langley, and south to Lynden, WA. The Sumas Valley, which borders the aquifer to the east, is a large sediment-filled deep bedrock valley that receives aquifer discharge. The Nooksack River valley, to the south, receives the largest discharge component from the uplands and the aquifer. To the north is Fraser River floodplain, where a small component of groundwater discharge from the aquifer occurs (Cox and Kahle, 1999).

The aquifer is highly productive and provides water supply for nearly 10,000 people in the USA (towns of Sumas, Lynden, and scattered agricultural establishments) and 100,000 people in Canada, mostly in the city of Abbotsford, but also in the Township of Langley. Almost half the groundwater is pumped to supply fish hatcheries in Abbotsford, BC. Industrial use is becoming important as evidenced by the construction of a power plant near Sumas, WA. Pumping is significant, and is on the order of 1/7 to 1/8 of total annual recharge.

The coastal climate is humid and temperate, with significant rainfall over most of the year. Recharge to the aquifer is primarily from direct precipitation, mostly from October to May. Recharge varies spatially and is estimated to range from 650 to 1000 mm/year, with greater recharge occurring to the north, coinciding with the strong precipitation gradient across the Region (Scibek and Allen, 2006a). Groundwater discharge occurs through spring flow, and seepage to small streams and rivers.

The aquifer is composed of uncompacted sands and gravels of the Sumas Drift, a glacial deposit formed at the end of the last period of glaciation. There is significant heterogeneity of the geologic units, resulting in potentially complex groundwater flowpaths. The thickness of Sumas Drift can be up to 65 m; its thickest dimension is in the northeast where glacial terminal moraine deposits are found. The deepest part of the aquifer system in this Region is located along the Canada-USA border south of the city of Abbotsford, toward Lynden, WA; the most productive areas are near Sumas, WA in southwest end of the Sumas Valley. The transmissivity of the aquifer averages 109 m^2/d, with a specific yield of 0.1.

This particular aquifer is largely unconfined, although part of the aquifer within Sumas Valley is confined. The aquifer under discussion is underlain by a glaciomarine stony clay deposit (Armstrong et al., 1963), which reaches ground surface to its western boundary; this unit is believed to act as a regional aquitard and is referred to as the Fort Langley Formation. There is a regional groundwater divide to the north, centred on the Langley uplands. To the south, the aquifer is bounded by the Nooksak River, and to the east and southeast, the aquifer is bounded by Tertiary bedrock, which

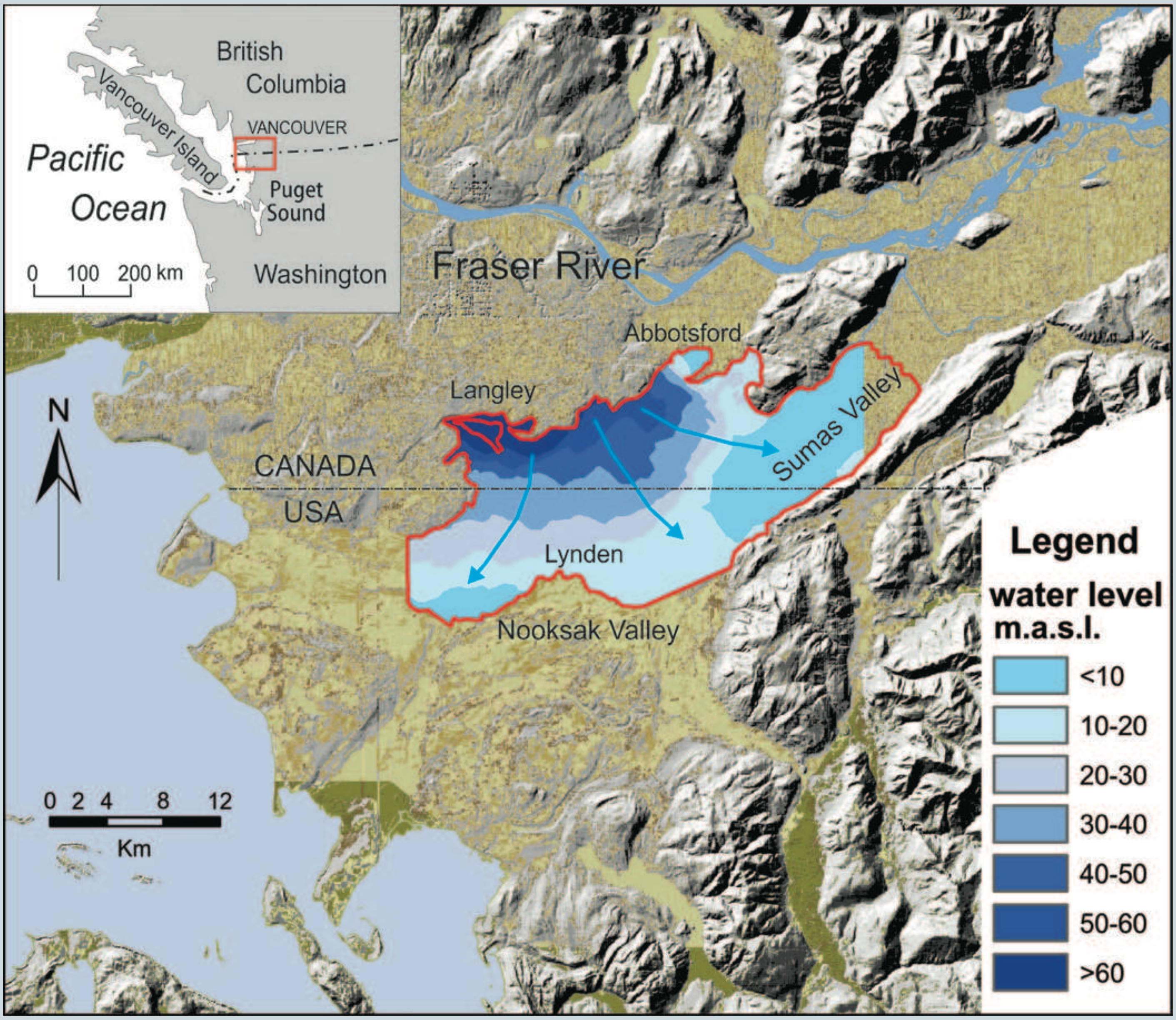


Figure 9.14 Topography of the Lower Fraser Valley, and outline of Abbotsford-Sumas aquifer. Groundwater flows south from areas of high water table (dark blue) to areas of low water table (light blue).

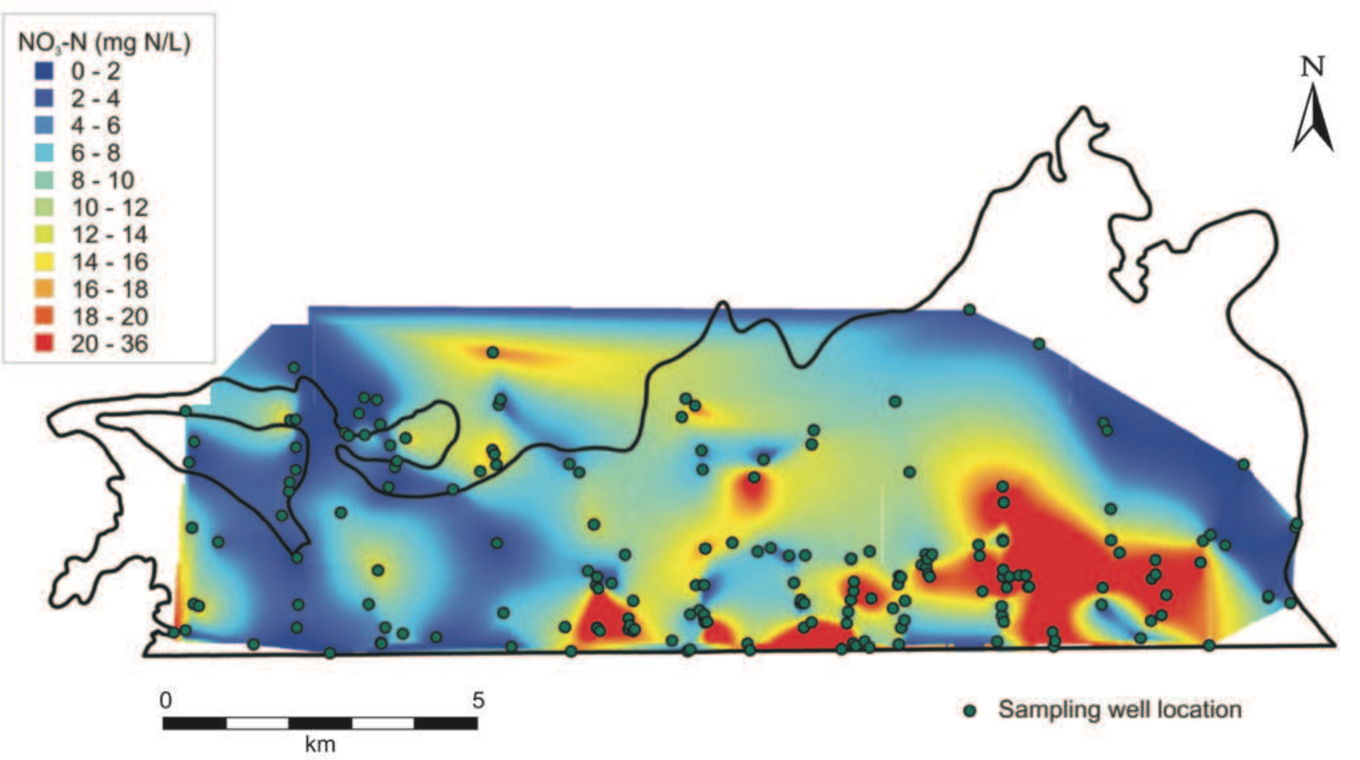


Figure 9.15 Nitrate distribution for the period 2002 to 2004 in the Abbotsford-Sumas Aquifer.

outcrops as mountains on both sides of Sumas Valley (Figure 9.14).

Elevated concentrations of nitrates have been documented in the Abbotsford-Sumas aquifer since the early 1970s (Kohut et al., 1989; Liebscher et al., 1992). The maximum allowable concentration (MAC) guideline as set by Health Canada (2008) for nitrate-nitrogen (NO_3-N) in drinking water is 10 mg/L: approximately 40% of 300 wells sampled in 2005 had concentrations that surpassed this value (Hii et al., 2005). Figure 9.15 shows a map of nitrate concentration from the period 2002–2004 for the Canadian portion of the aquifer.

The main source of nitrate is attributed to agricultural activities: raspberries are the predominant crop above the Canadian portion of the aquifer. Fertilizer application practices associated with raspberry production have been identified as significant contributors to nitrates within the aquifer (Liebscher et al., 1992; Hii et al., 1999; Zebarth et al., 1998; Mitchell et al., 2003). There are also a significant number of poultry farms present in the area, and manure produced from these operations is another potential source of nitrate contamination. Septic system sources are not considered to be a major contaminant source for this particular aquifer.

A study of nitrogen origin and fate within the aquifer (Wassenaar, 1995) indicates that soil nitrate was predominantly derived from nitrification of manure and, to a lesser extent, from ammonium-based fertilizers. Later work by Wassenaar et al. (2006) suggests a shift in nitrogen sources, away from manure sources toward inorganic fertilizer sources, following a recent (since 1992) shift in agricultural practice away from the use of manure fertilizer to synthetic fertilizer (as a response to a challenge to the industry to reduce nitrate loading). Hii et al. (2005) indicated that the farming industry as a whole responded to this challenge, although results of the latest survey (Hii et al., 2005) indicate that the extent of nitrate contamination throughout the aquifer has not changed dramatically.

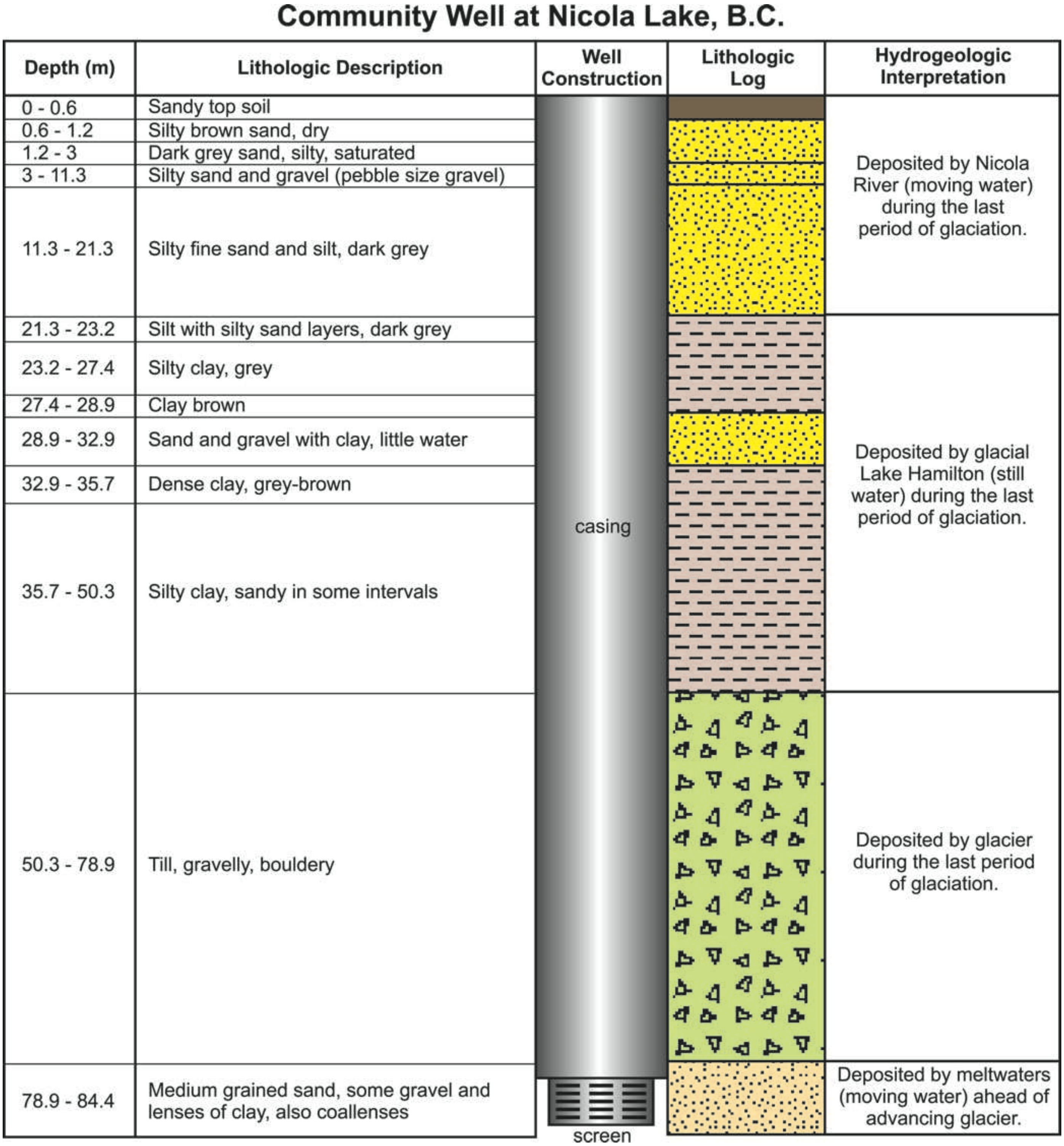
Chesnaux and Allen (2007) and Chesnaux et al. (2007) simulated nitrate leaching through the vadose zone and found that nitrate mobilization to the water table is rapid, on the order of only a couple of months, but that ongoing loading at the surface continues to yield high nitrate concentrations within the aquifer.

Wassenaar et al. (2006) measured the age of groundwater in wells using isotopic $^3H/^3He$ dating techniques to discover groundwater ages upward of 30 years. Wei (1989) similarly determined a chemical response time constant of ~10 years for the aquifer. Both studies suggest that it may take a decade, or more, for an aquifer to show changes in NO_3-N levels in response to nitrate loading changes.

BOX 9-3 INTERPRETING LOCAL SURFICIAL GEOLOGY AND UNDERSTANDING THE LOCAL GROUNDWATER RESOURCES FROM WATER WELL RECORDS

We would like to pay tribute to Canadian well drillers for contributing to the knowledge of groundwater resources throughout this country. Drillers record lithology encountered during drilling, depth of water-bearing units, groundwater level, and estimate of well yield. This information allows hydrogeologists to begin assembling pictures of the aquifers and the hydrogeology of a local area in order to help develop and protect local groundwater resources. This information, when interpreted, is also valuable in understanding how specific aquifers may have been formed.

Surficial geologic history and hydrogeology of a specific area within the Cordillera (or elsewhere in Canada) can often be inferred from the lithology contained in a well record and a knowledge of the area's glacial history. The degree to which scientists can interpret geologic history depends on the depth of the well, the method of drilling, and quality of lithologic description recorded by the driller. Figure 9.16 depicts the lithologic description for a community well (Kala, 1983) at Nicola Lake, northeast of Merritt in the southern Interior System. This description, together with a knowledge of the surficial geology and glacial history of the area (Fulton, 1975), allows the on-site surficial geologic history to be inferred. The well cited here is located in the Nicola River floodplain and the saturated sand, to 21.3 m depth, is interpreted to be deposited by the Nicola River at the end of or after the last period of glaciation. This sand is inferred to have been deposited in a fluvial environment to form an unconfined, unconsolidated aquifer (Type 1b) here. Beneath the sand, from 21.3 m to 50.3 m depth, are mostly clay and silt deposits. These sediments must have collected within a still-water environment, most likely during the last period of glaciation when the area was submerged under Nicola Lake (Glacial Lake Hamilton). The layer of sand and gravel between 28.9 m and 32.9 m depth may reflect an episode where the lake receded and coarser-textured sediments were deposited in a fluvial environment. A layer of till exists between 50.3 m and 78.9 m depth, most likely deposited by the local glacier during the last period of glaciation. Saturated sand and gravel found beneath the till (below 78.9 m) is interpreted to be glaciofluvial sand and gravel deposited by meltwaters ahead of the advancing glacier. This deeper sand and gravel unit is a confined, unconsolidated aquifer (Type 4b) and the source of water for the well (which is completed with a screen intake opposite this unit). Had the well been only 20 m



Community Well at Nicola Lake, B.C.

Depth (m)	Lithologic Description	Well Construction	Lithologic Log	Hydrogeologic Interpretation
0 - 0.6	Sandy top soil	casing		Deposited by Nicola River (moving water) during the last period of glaciation.
0.6 - 1.2	Silty brown sand, dry			
1.2 - 3	Dark grey sand, silty, saturated			
3 - 11.3	Silty sand and gravel (pebble size gravel)			
11.3 - 21.3	Silty fine sand and silt, dark grey			
21.3 - 23.2	Silt with silty sand layers, dark grey			Deposited by glacial Lake Hamilton (still water) during the last period of glaciation.
23.2 - 27.4	Silty clay, grey			
27.4 - 28.9	Clay brown			
28.9 - 32.9	Sand and gravel with clay, little water			
32.9 - 35.7	Dense clay, grey-brown			
35.7 - 50.3	Silty clay, sandy in some intervals			
50.3 - 78.9	Till, gravelly, bouldery			Deposited by glacier during the last period of glaciation.
78.9 - 84.4	Medium grained sand, some gravel and lenses of clay, also coallenses	screen		Deposited by meltwaters (moving water) ahead of advancing glacier.

Figure 9.16 Graphical representation of a well log for a community well at Nicola Lake, illustrating how the local surficial geology and presence of aquifers can be interpreted from the lithologic description.

deep, interpretation of the surficial geologic history would have been much more limited. One can also appreciate that the driller's description is also critical in allowing the surficial geologic history to be correctly and less ambiguously interpreted.

BOX 9-4 AQUIFER RESPONSE TIMES

One important question water resource managers or communities ask themselves is: “How quickly can we expect to detect a change in groundwater level from a drought?” or “If nutrient source controls were implemented, how quickly would we be able to see a change in the nitrate concentration within the aquifer?”

How quickly an aquifer responds to a change in hydraulic stress (e.g., increase or decrease in the amount of water input or increase in well pumping) or chemical stress (e.g., decrease in nitrogen loading) can be estimated by calculating an aquifer’s hydraulic or chemical response time, a concept presented by Gelhar and Wilson (1974).

We do know that hydraulic response time can be calculated, knowing the key aquifer parameters (see equation 9.2 below):

$$\tau_h = S \times L^2 / \beta \times T \qquad (9.2)$$

where:

τ_h is the aquifer’s hydraulic response time;

S is the aquifer’s storativity, or if an aquifer is unconfined, the specific yield;

L is the length of groundwater flowpath in an aquifer;

β is a geometric shape factor of an aquifer (generally varies between 2.5–3.5); and

T is the aquifer transmissivity.

Equation 9.2 shows that the greater the length of the groundwater flow system (or the larger the aquifer size), or the lower the transmissivity of an aquifer, the longer the aquifer’s hydraulic response time would be. Small, highly transmissive aquifers (such as those in the Cordillera) are expected to have relatively quick hydraulic response times and they react quickly to changes in hydraulic inputs or outputs.

Hydraulic response times have been calculated for 33 different aquifers within the Cordillera, including unconsolidated aquifers, usually unconfined (Types 1b and 4a), unconsolidated confined aquifers (Types 4b) and bedrock aquifers (Types 5a and 6b), where data are available. Hydraulic response times for these 33 aquifers range from less than a year to up to 8 years. All of the confined, unconsolidated aquifers (16 aquifers), 7 of the 9 unconfined, unconsolidated aquifers, and 7 of the 8 bedrock aquifers had response time of less than 2 years, suggesting they react very quickly to hydraulic inputs and outputs. The rapid response times for all the aquifers are mostly attributable to their generally localized extent, resulting in the development of limited flow systems.

Figure 9.17 plots hydraulic response times for some unconfined, unconsolidated aquifers. Also plotted are curves that allow hydraulic response times to be estimated graphically for various values of transmissivity, given the length of the groundwater flowpath. Based on equation 9.2 (similar curves can be generated for unconsolidated, confined aquifers and bedrock aquifers using equation 9.2 by substituting the appropriate storativity or specific yield for confined and bedrock aquifers, respectively). Note that in Figure 9.17, all the aquifers have estimated flowpaths of only a few kilometres in length. For unconfined, unconsolidated aquifers, the rapid response times are also explained by the relatively high transmissivity of these aquifer types. Confined, unconsolidated aquifers have even faster response times because the storage ability of confined systems is smaller than the specific yield of unconfined systems. The

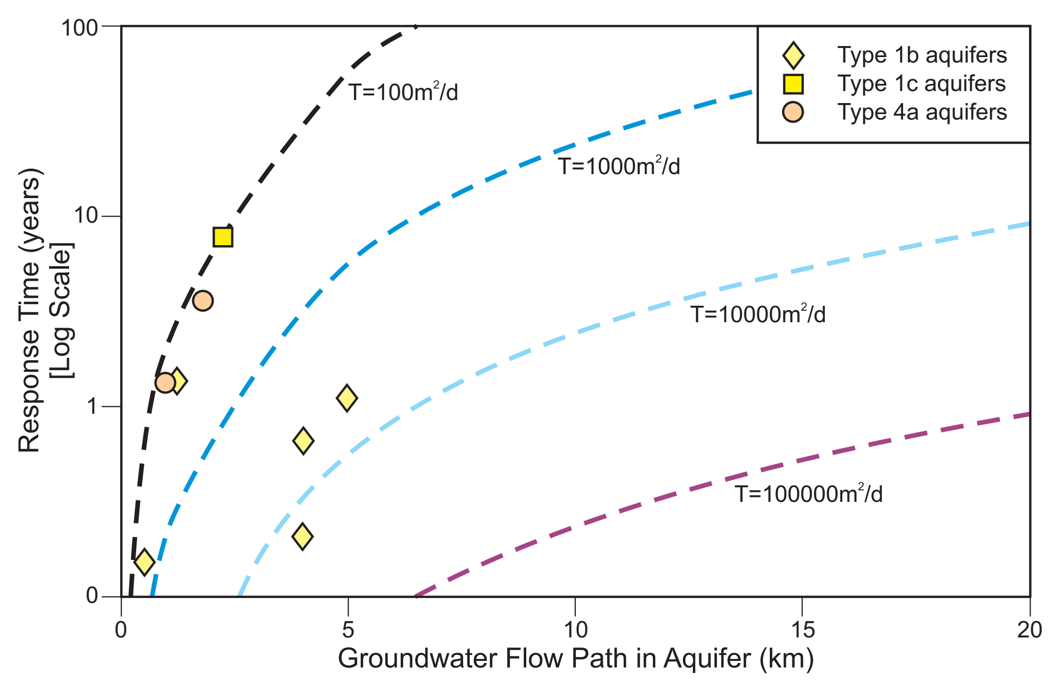


Figure 9.17 Hydraulic response times for specific aquifers and hydraulic response time curves for varying transmissivity values (m²/d) for unconfined, unconsolidated aquifers.

quick response times for bedrock aquifers reflects not only the limited length of their flow systems but also the small specific yield corresponding to the low fractured porosity typical of bedrock aquifers in the Cordillera.

The equation for chemical response time is:

$$\tau_c = n \times h_o / N \qquad (9.3)$$

where:

τ_c is the aquifer's chemical response time;
n is the porosity of the aquifer;
h_o is the groundwater level above the bottom of the aquifer; and
N is the recharge.

Equation 9.3 shows that lower porosity, thinner aquifers, and greater recharge lead to faster aquifer chemical response times. A thin aquifer in a wet, coastal setting with greater recharge would be expected to have relatively quick chemical response times.

Chemical response times were calculated for 12 aquifers. These times ranged from less than a year to over 60 years. For the 4 unconsolidated aquifers in the study, chemical response times ranged from years to decades. Limited aquifer thickness and low recharge for aquifers in arid regions of the Cordillera were identified as the main factors in increasing chemical response times. In fractured bedrock aquifers, the generally quick chemical response times may be explained by the low-fracture porosity typically found in bedrock.

Although response time calculations only provide a crude estimate of how an aquifer, responds to changes in hydraulic, and chemical inputs and outputs, the results do illustrate that hydraulically and chemically, many aquifers within the Cordillera can be expected to react quickly to changes in stresses. This is because of the generally limited size, specific aquifer physical properties (e.g., transmissivity, specific yield and porosity, degree of confinement) and climate (which affects recharge).

BOX 9-5 THERMAL SPRINGS OF THE CORDILLERAN REGION

One interesting groundwater anomaly of the Cordilleran Hydrogeological Region is the fact that over 140 thermal springs occur in the area, the only region in Canada to have such features (including the Cordilleran portion of the Northern Region—Grasby and Hutcheon 2001, Grasby et al., 2000; Allen et al., 2006; Caron et al., 2008; Figure 9.18). These springs, with a few, rare exceptions, occur in the bottoms of the major valley systems.

Although thermal springs are normally associated with regions of high heat flow, this is by no means a prerequisite. Thermal springs can be associated with 1) high heat flow areas, including the volcanic belts of the west coast and high heat flow region of the McKenzie Mountains, 2) crustal scale Eocene normal faults, found across southern BC, and 3) anomalous structural features that locally enhance permeability, like the thermal springs found in the Rocky Mountains. The thermal springs at Banff, for example, occur in one of the lowest heat flow regions of the Cordillera. The anomalous structure at Cascade Mountain, however, enhances permeability along the Sulphur Mountain thrust, allowing deep groundwater circulation (Grasby et al., 2003). Stable isotope data indicates that all of these springs originate as meteoric water. The high temperatures reflect circulation of groundwater to depth, where the water is heated before returning to surface (Figure 9.19).

Temperature of any thermal spring outlet reflects a combination of local geothermal gradient, circulation depth, and flow rate. The variability in heat flow and geothermal gradients within the southern Rocky Mountain Trench affecting thermal springs has been shown by Allen et al. (2006). Lower gradients require greater circulation depths for groundwater to obtain heat. The depth of groundwater circulation is typically restricted by the strength of the rock it is flowing through; increasing stress at depth closes fracture networks, thus inhibiting circulation. Empirical evidence suggests a practical limit for circulation at around 5 km. This observation is consistent with the deepest estimated circulation depths for springs in the Cordillera. Research has shown that when groundwater circulates too fast, advective heat transport will cool the region, while when the circulation is too slow, the groundwater will cool during its ascent to surface (Ferguson et al., 2009; Foster and Smith, 1988).

Unique aquatic ecosystems are a common feature of thermal spring outlets. The northern limit of most plant and animal species is often a function of climatic factors (e.g., how cold a winter can these organisms survive). The discharge of thermal waters in Canada's northern climate creates microclimates which

Figure 9.18 A pool of warm water at the Meager Creek Hot spring, Southwestern British Columbia.

often support rare and unique ecosystems. The warm microclimates of thermal springs allow plant species (e.g. the southern Maiden Hair Fern at the Fairmont Spring) to survive as isolated communities at climates much farther north than their normal distribution. There are also documented cases of unique animal species (e.g., the Banff Springs Snail) evolving to adapt to thermal waters (Grasby and Lepitzki, 2002). Along with hosting rare ecosystems, spring outlets often develop extensive travertine mounds as unique hydrogeological features. These mounds are typically formed by calcium carbonate precipitating from solution in response to degassing of carbon dioxide (CO_2) as the waters equilibrate to atmospheric pressure (Figure 9.20). This degassing can result in the local formation of extensive structures which grow and spread over thousands of years.

The unique and rare occurrence of thermal springs is appreciated by all that find them—it is very difficult to encourage a moose soaking in a hot pool to leave so you can sample the water! People likewise enjoy these features; over 10 thermal spring resorts have been developed across the Cordillera Region. The majority of these thermal springs are situated in remote locations and found in mostly a natural state.

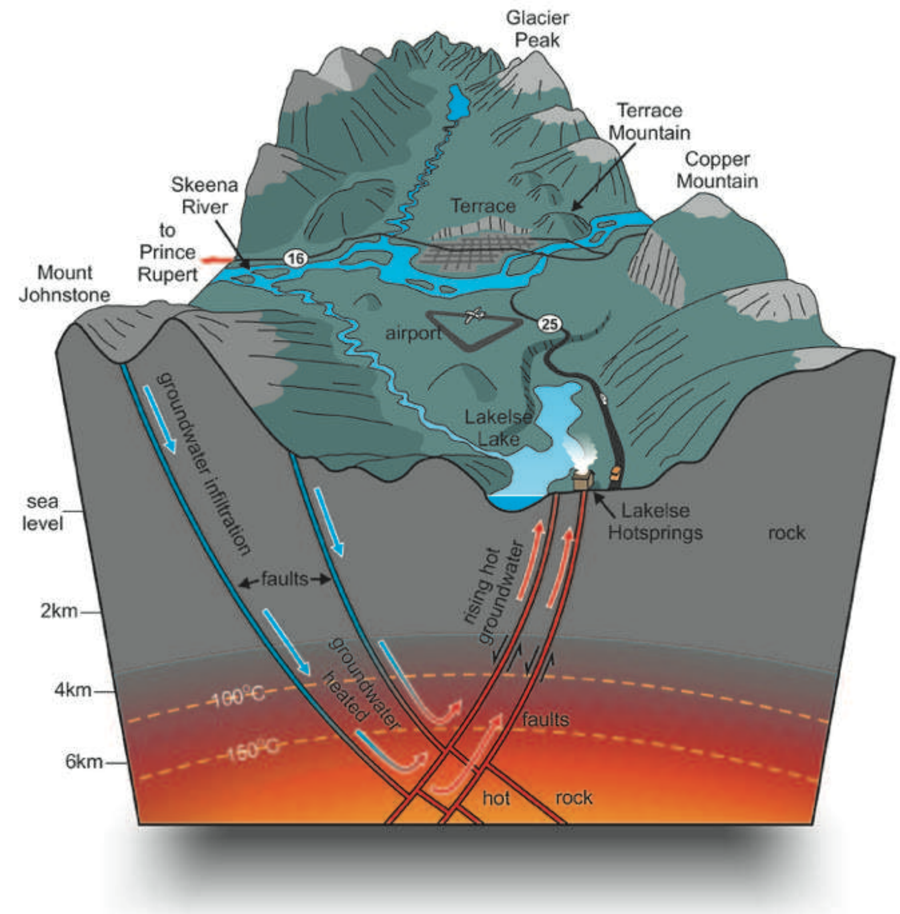
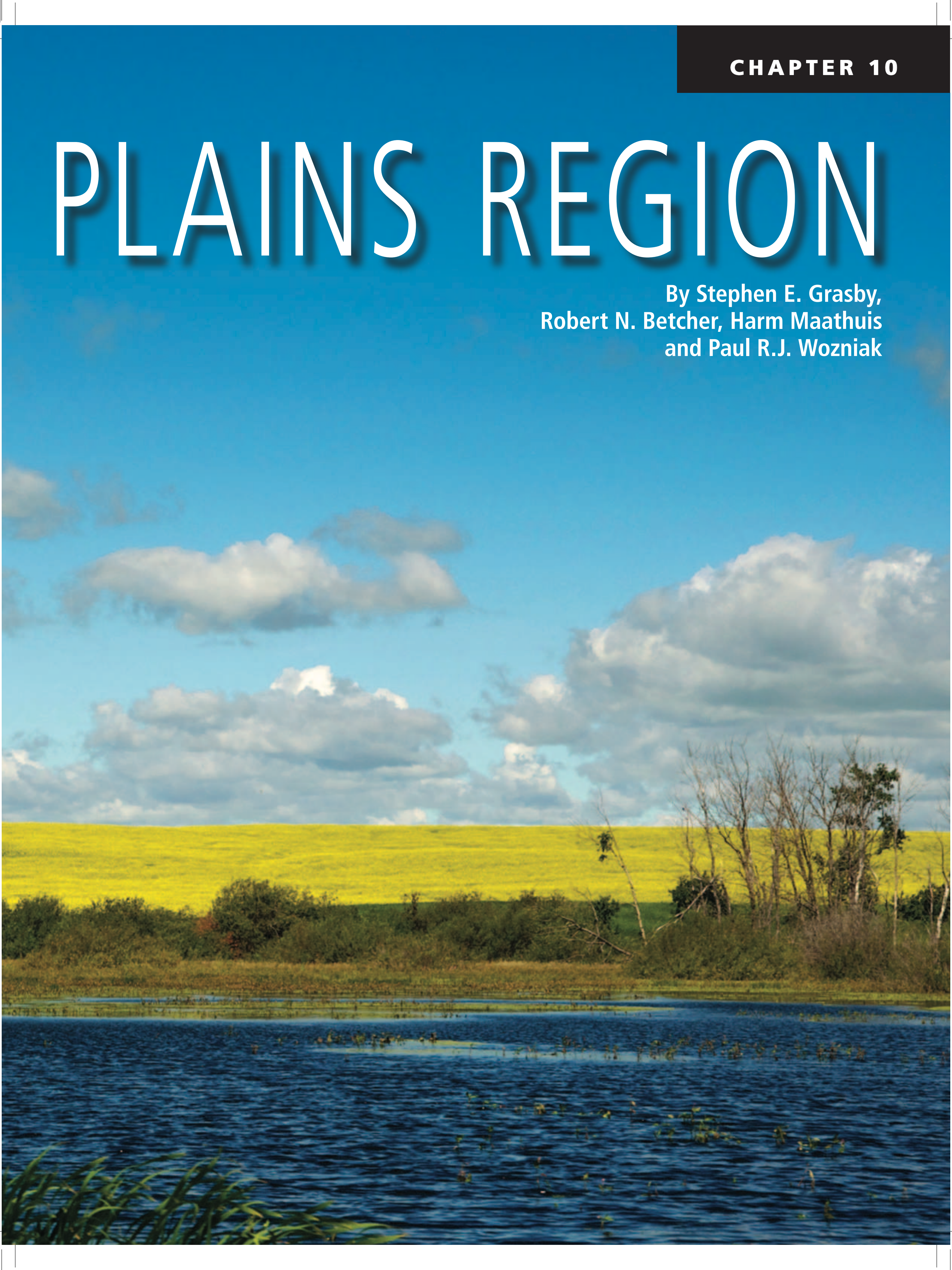


Figure 9.19 Schematic diagram showing the occurrence of the Lakelse Hot Spring in Northwest British Columbia.

Figure 9.20 Travertine mound forming at the Sculpin warm spring, McKenzie Mountains, Northwest Territories.

PLAINS REGION

By Stephen E. Grasby,
Robert N. Betcher, Harm Maathuis
and Paul R.J. Wozniak



10.1 INTRODUCTION

The Plains Region (Figure 10.1), Canada's agricultural heartland, is a major world grain producer. Covering over 1.7 million km^2, the region has a sparse population of 5.2 million, the majority of which is concentrated in a few major cities. Most large urban centres are supplied by surface water, whereas rural populations rely largely on groundwater. Domestic groundwater use varies across the region and is estimated to be 23% in Alberta, 43% in Saskatchewan and 30% in Manitoba (Statistics Canada, 2003).

In the southern portion of the region, surface water is heavily used for major irrigation withdrawals, municipal use, hydroelectric power generation and small-scale industry. In some drainage basins within southern Alberta, sustainable rates of surface water withdrawal are now considered fully allocated and there are no new surface water licences available to meet growing demand associated with rapid population growth. Consequently, the demand for groundwater resources is expected to grow substantially. Given the shortage of supply and rapidly increasing demand, the southern Plains Region will probably have some of the greatest water supply challenges in Canada's near future. While there is growth in water demand in the Athabasca River Basin because of oil extraction from the oil sands of northern Alberta, total use accounts for only a minor component of the discharge to date.

10.2 PLAINS HYDROGEOLOGICAL REGION

The Plains Region is bound on the east and north by the Canadian Shield and on the west by the deformation front of the Rocky Mountain Foothills. While the interior plains extend north to the Arctic Ocean, the Plains Hydrogeological Region, as used here (Sharpe et al., 2008) and consistent with Brown (1967), has a northern boundary defined by the southern limit of continuous permafrost and a southern boundary defined by the international border.

10.2.1 Physiographic description

The entire Plains Region is characterized by low-relief landscapes and generally flat or rolling hills with some steep embankments along incised river valleys. The easternmost part is formed by the Manitoba Lowlands. This low-lying area (elevations under 400 masl) was mostly covered by glacial Lake Agassi during the retreat of the last continental ice sheet (Teller and Leverington, 2004), with lake sediments forming the flattest portion of the region. To the west, the landscape rises along the ~200-metre-high Manitoba Escarpment to the Saskatchewan Plain. The Saskatchewan Plain is characterized by thick deposits of glacial till, hummocky moraines and localized glacial lake sediments forming a rolling but generally flat landscape with elevations from 460 m to 760 masl on average. However, there are some localized areas with more topographic relief. The Cypress Hills between southern Alberta and Saskatchewan form isolated highlands up to a height of 1,460 masl Further west, the plains rise gradually to the Alberta Plain with elevations up to 1,600 masl. The Alberta Plain has more varied relief and defined erosional features than the plains to the east. Northern Alberta is characterized by forested lowlands with a series of disconnected plateaux (rising up to 1,000 masl) dissected by the Peace and Athabasca river valleys.

Vegetation zones in the Plains Region show defined patterns largely related to precipitation and temperature variations across the region. The triangle-shaped short-grass prairie region is centred roughly in the southern portion of the Alberta-Saskatchewan border. As one proceeds west, east and north from there, a transition occurs to long-grass prairie, and then into aspen parkland, with increasing net precipitation and decreasing average temperatures. These three zones form the prairie portion of the Plains Region. As one proceeds northward, one encounters aspen parkland that transitions to the northern Boreal Forest Region on the northern plains (Figure 10.2a).

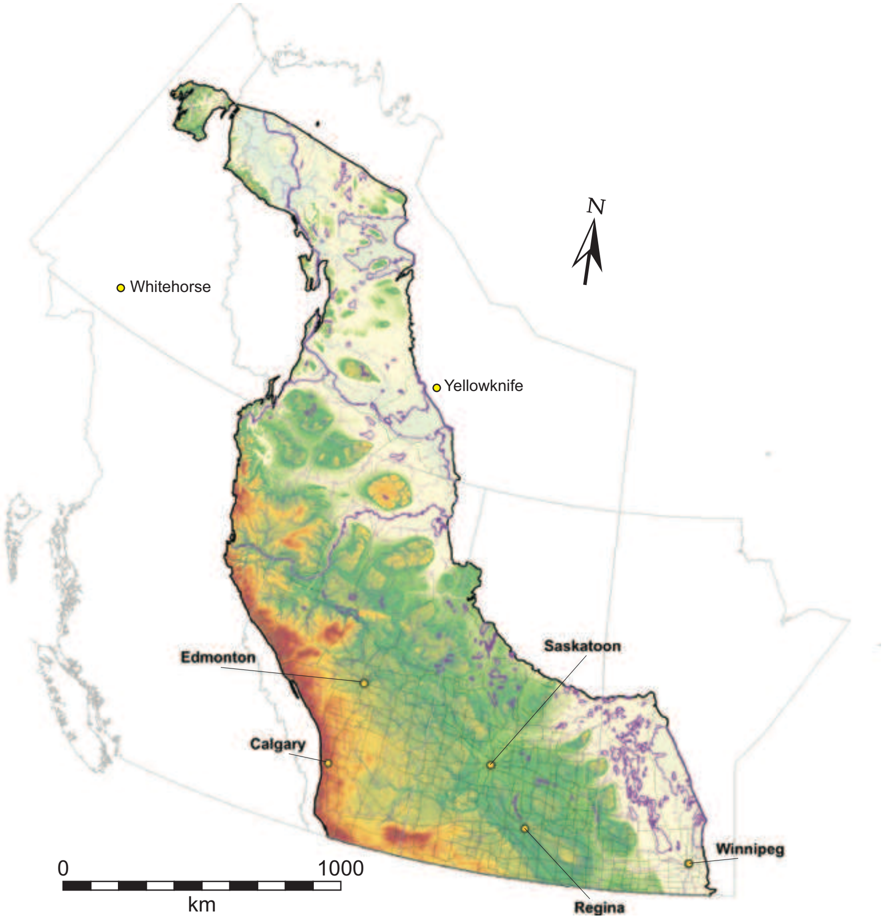


Figure 10.1 Map of Plains Hydrogeological Region, showing major rivers, political boundaries, cities, shaded topography and major road networks.

10.2.2 Demographics

According to the 2006 Census, the population of the Plains Region was about 5.2 million, a 6.5% increase over the five years from the previous census. Most of the population (about 4 million people) live in urban areas, while an additional 102,000 live in outlying urban areas and the remainder in small communities and rural settings. Urban and rural areas have approximately the same average number of inhabitants per private dwelling (2.4). Of the 5.2 million people within the Plains Region, the majority live in southern Alberta (~3 million), while Saskatchewan and Manitoba each have about 1 million people, and 57,000 people live in the plains portion of northeast British Columbia.

10.2.3 Climate

The Plains Region is characterized by long cold winters and warm dry summers. Average temperature varies across the region, with the highest annual mean temperature in the southwest and decreasing northward. Average minimum and maximum temperatures vary across the region by up to 12°C (Figure 10.2). Average annual temperatures have risen by 1.5°C during the approximately 100-year period that records have been kept (Figure 10.3). This trend has been observed in a number of locations within the region (Zhang et al., 2000; Chen et al., 2004, 2006) and has been documented in borehole temperature profiles (Majorowicz et al., 2006; Skinner and Majorowicz, 1999).

Mean annual precipitation is very low across the Plains Region, varying from 285 mm to 600 mm per year, with the lowest values recorded in southeastern Alberta and southwestern Saskatchewan (Figure 10.4). Precipitation in the region is dominated by rainfall (300 mm/year to 400 mm/year)

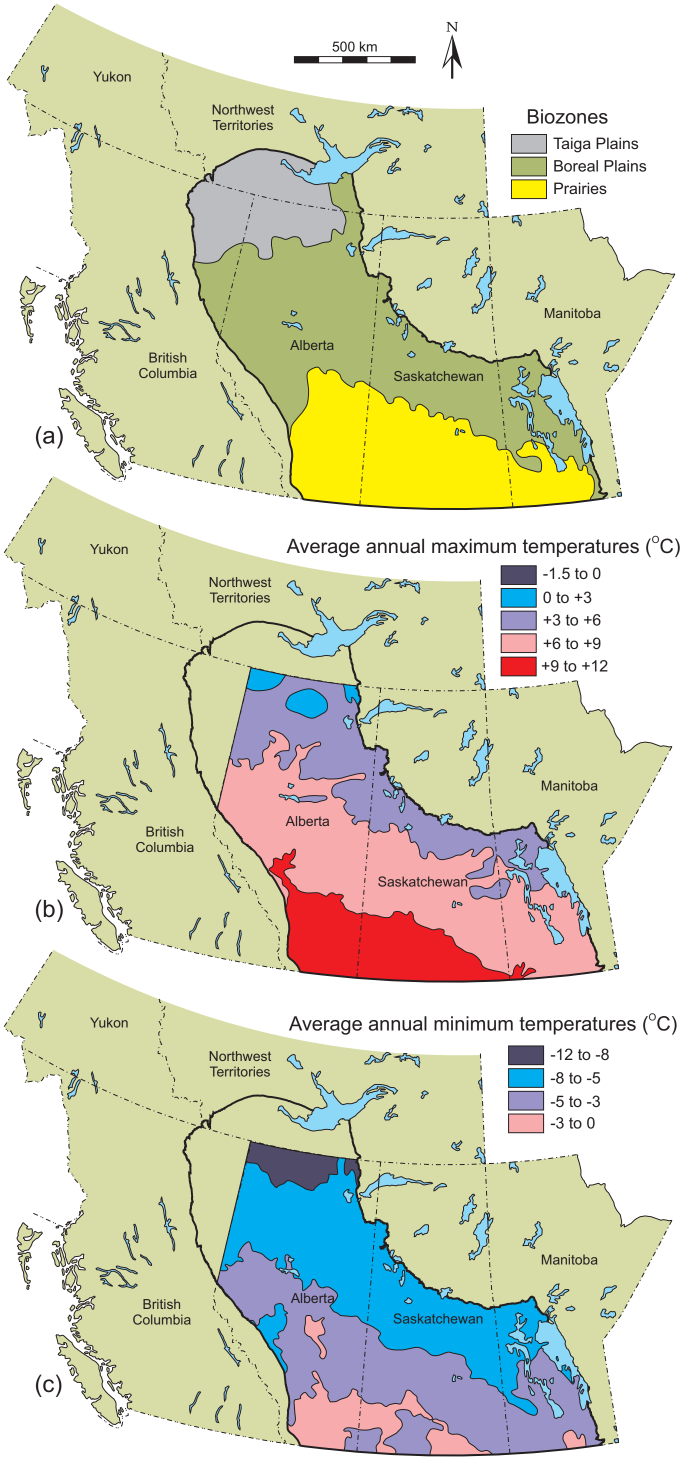


Figure 10.2 (a) Principal biozones of the southern part of the Plains Region as influenced by **(b)** Average annual maximum temperatures (°C) and **(c)** Average annual minimum temperatures (°C), calculated from daily temperatures during the 1961–1990 period (from Nyirfa and Harron, 2002).

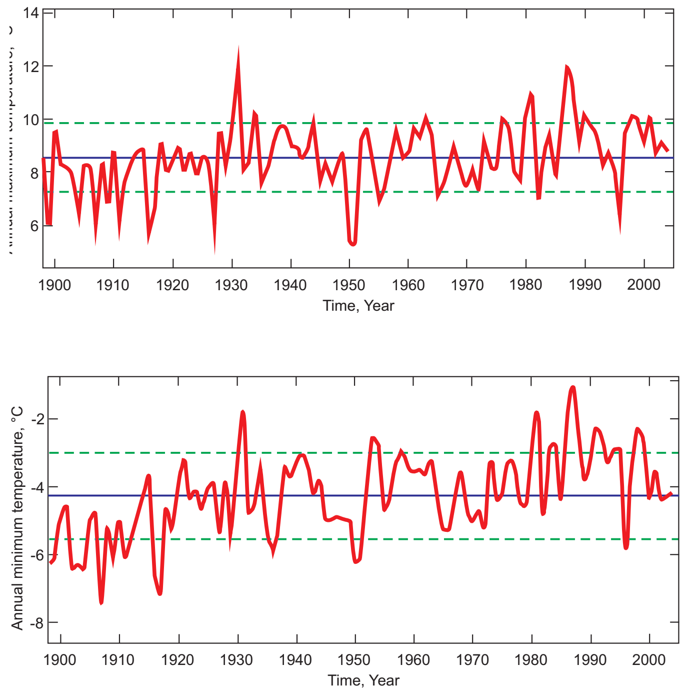


Figure 10.3 Maximum and minimum temperature time series (for Saskatoon). The annual average temperature is shown by a solid red curve with mean (blue) and plus/minus one deviation (green). Note overall the increase of approximately 1.5°C over past 100 years. Data source: Environment Canada (Adjusted Historical Canadian Climate Data).

with smaller amounts of snowfall (100 mm/year to 200 mm/year). Precipitation time series show no definitive trends over the last 100 years (Figure 10.5); however, some studies suggest that an overall increase has occurred in the northern areas (Zhang et al., 2000), while the southern Prairies have seen a decrease (Gan, 1998). Nonetheless, tree ring studies suggest that the 20th century may have been a period of higher-than-normal precipitation in the Plains Region, when comparisons are made on a 1,000-year time scale. Evidence of prolonged periods of sustained multidecadal drought has also been observed (Sauchyn and Beaudoin, 1998; Case and MacDonald, 2003; St. George and Nielsen, 2002). During the warm, dry period of the hypsithermal, before 6000 BC, prairie peatlands were less extensive (Zoltai and Vitt, 1990) and regional groundwater tables were 6 m to 15 m lower than present (Remenda and Birks, 1999). Evidence also suggests that deep groundwater circulation systems were less active (Grasby et al., 2003).

Both temperature and precipitation records indicate that relatively short-term instrumented

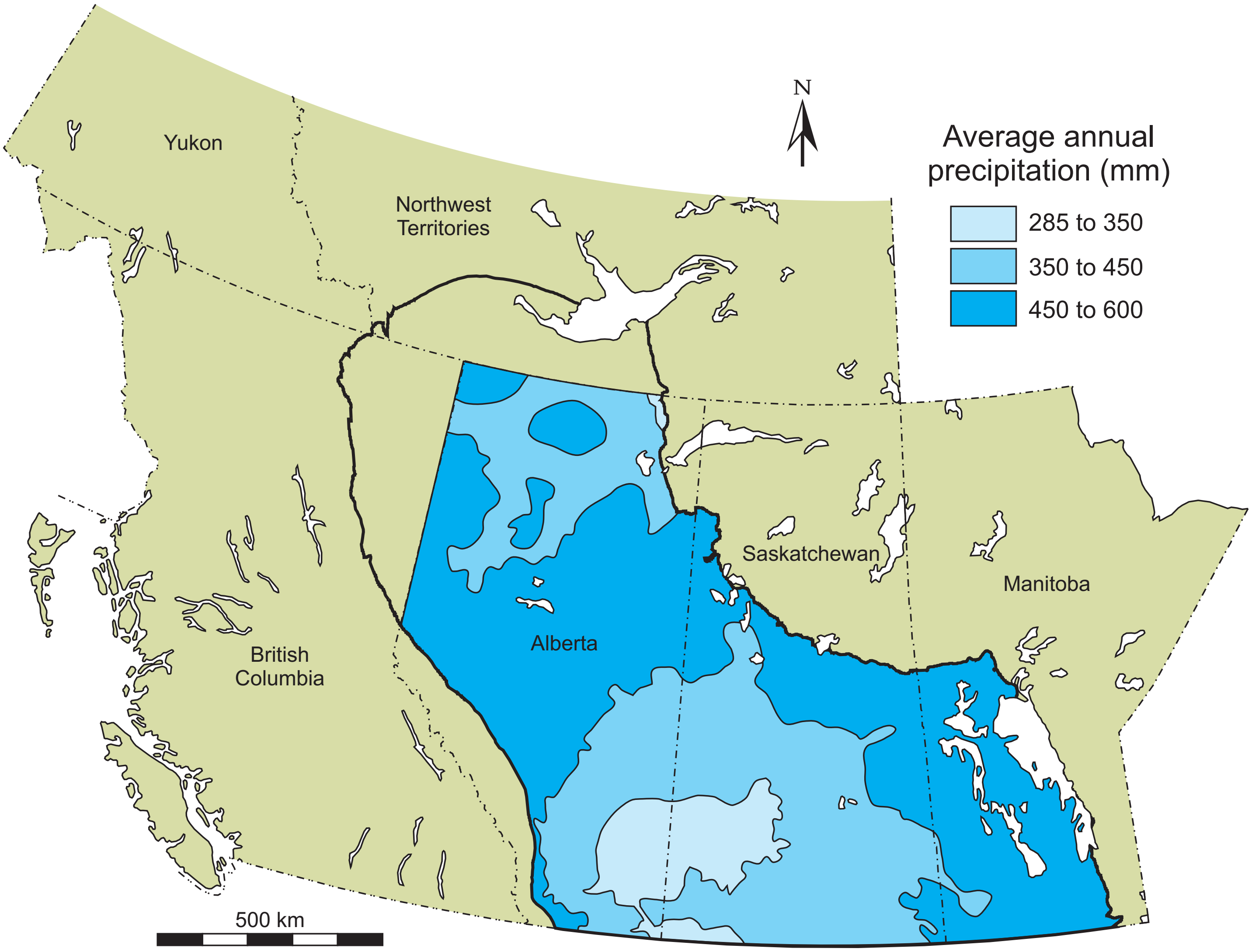


Figure 10.4 Average annual precipitation from 1961 to 1990 (from Nyirfa and Harron, 2002).

records may not be representative of longer-term climate variability (Chen and Grasby, 2009). Studies of long-term trends in groundwater levels in southern Manitoba show a strong correlation with precipitation patterns, as well as temperature, (Chen et al., 2002, 2004), indicating that changes in these parameters may have a significant impact on groundwater availability. Caution therefore needs to be exercised when using these historical climate records to model future groundwater resources.

The evapotranspiration potential within the region is high, ranging from 500 mm/year to 700 mm/year: in many places, it exceeds annual precipitation, creating a net moisture deficit (Figure 10.6). Moisture deficits in most of the southern portion of the region create semiarid conditions that limit surface water and recharge to groundwater systems. The majority of runoff moving through major river systems of the southern plains is generated in the Cordillera Region to the west rather than internally. Much of the southern Plains Region is characterized by closed basin conditions (Last, 1989).

10.2.4 Surface water

The Plains Region is drained by three major river systems—the Nelson, the Churchill and the headwaters of the Mackenzie—in addition to the relatively small headwaters portion

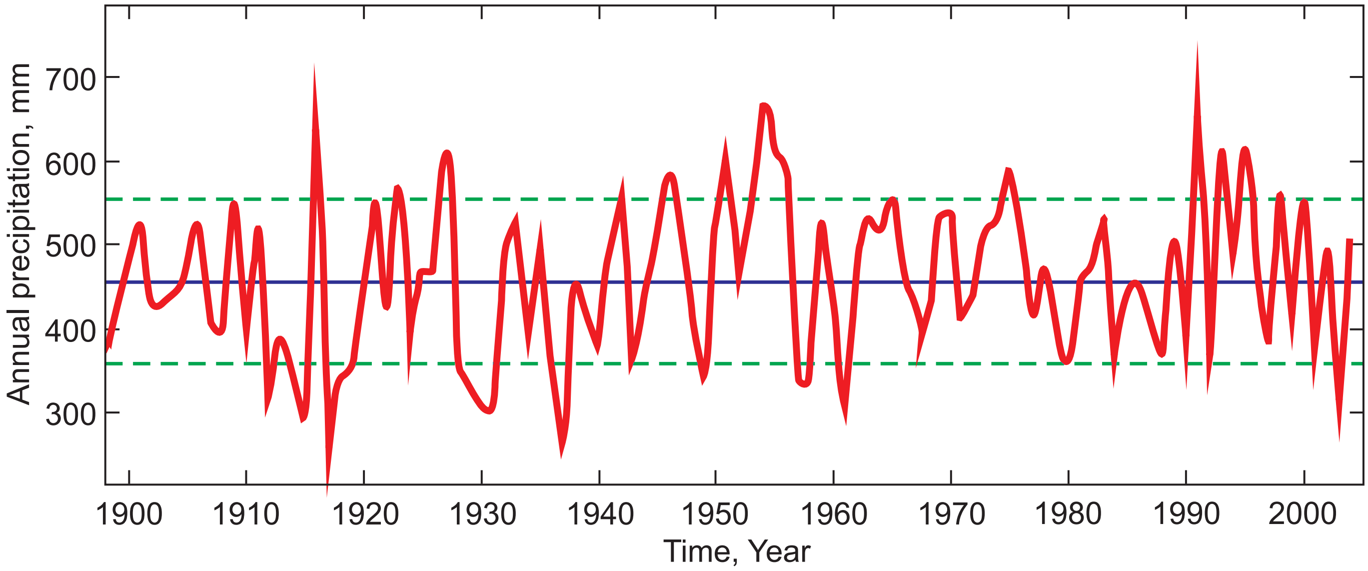


Figure 10.5 Annual precipitation at Regina, shown by the solid red curve with mean (blue solid) and plus/minus one deviation. Note no definitive trend indicated over the last 100 years. Data source: Environment Canada (Adjusted Historical Canadian Climate Data).

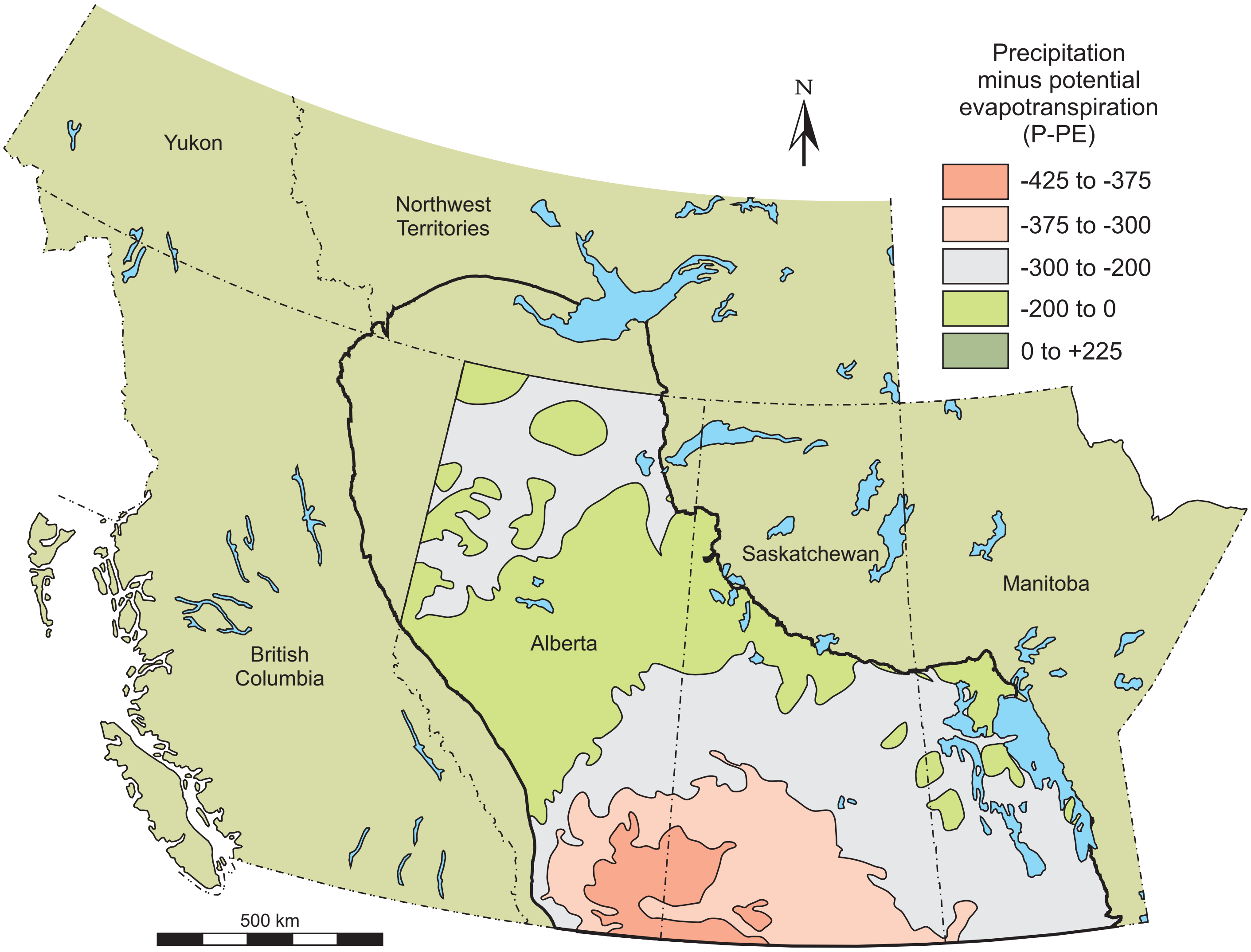


Figure 10.6 Average moisture deficit in different climate regions within the southern part of the Plains Region. The average moisture deficit is calculated from the differences between annual precipitation and potential evapotranspiration in the 1961–1990 period (from Nyirfa and Harron, 2002).

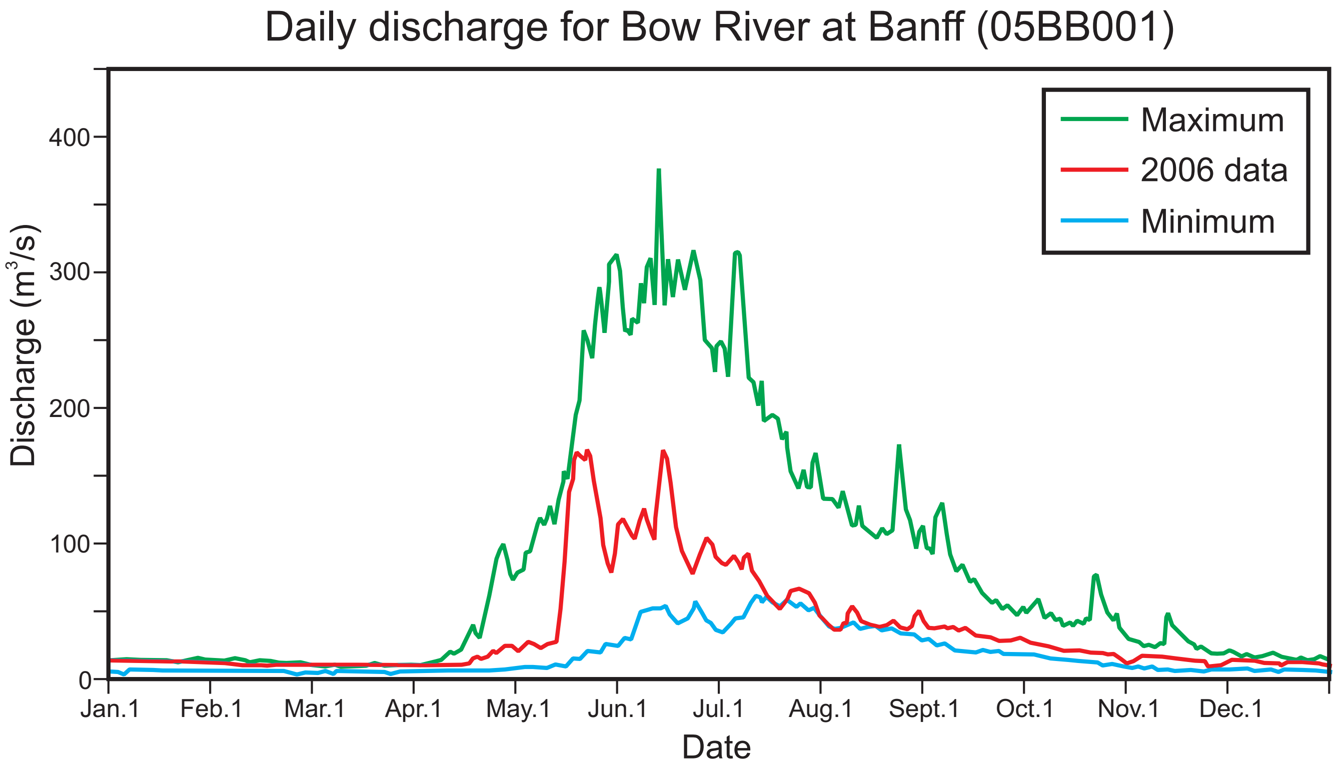


Figure 10.7 Example of annual hydrograph of streamflow for the Bow River at Banff based on 98 years of records (1908–2006).

of the Missouri River, along the southern border of Alberta and Saskatchewan (Figure 10.1), and the Red River of southern Manitoba. The Saskatchewan River is further divided into the North and South Saskatchewan basins, and the South Saskatchewan, in turn, is divided into the Oldman, Bow and Red Deer basins. Most of the region's population, agriculture and industry, are located within the Nelson Basin (including the major sub-basins of the Saskatchewan and Red Rivers). The Nelson River supplies an average of 75 km^3 of water per year, 90% of which originates as runoff from the eastern slopes of the Rocky Mountains (Martz et al., 2007). Hydrographs are characterized by a large spring peak related to snowmelt, which then tapers through the summer to winter baseflow conditions (Figure 10.7).

10.2.5 Geology

The plains are underlain by sedimentary rocks of the Western Canada Sedimentary Basin (WCSB) (Figures 10.8 and 10.9). These range in thickness from zero along the eastern erosional edge to over 4 km in the west. While all of these sediments are filled with groundwater, most of that resource is of naturally high salinity. Only rock in the near surface (typically the upper 400 m) contains water of sufficiently low salinity to be suitable for human use. A detailed description of the 700-million-year geological history of the Basin can be found in Mossop and Shetsen (1994).

The basal sedimentary units of the Basin are Cambrian sandstones and conglomerates, overlain in parts of the area by sandstone and shale of the Middle Ordovician Winnipeg Formation. This was followed by marine carbonate deposition throughout most of the Paleozoic. Extensive marine evaporites were also deposited in the central portion of the Basin, forming the thick potash accumulations found throughout central Saskatchewan and in parts of Alberta and Manitoba. Following the onset of mountain building to the west, the

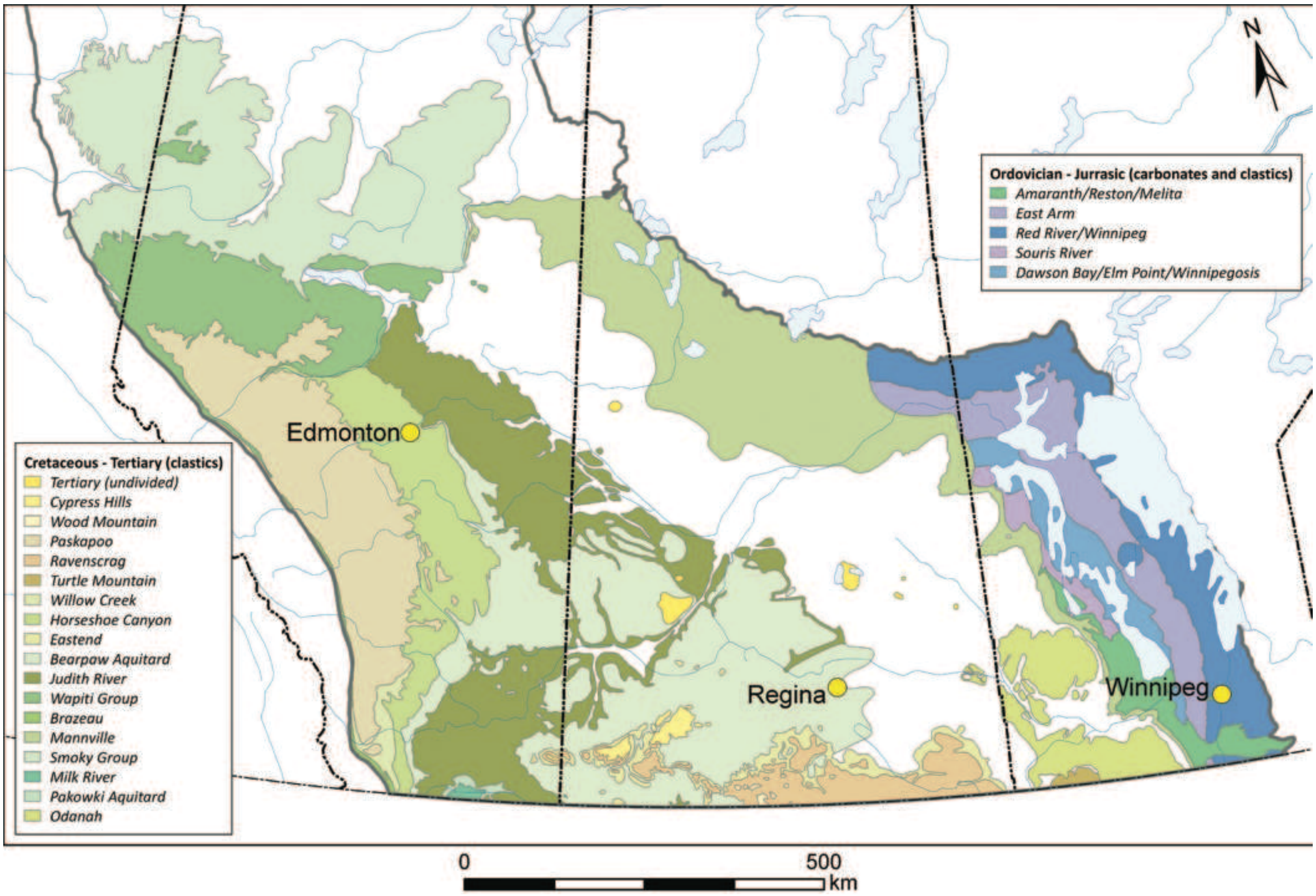


Figure 10.8 Distribution of major bedrock units in the southern part of the Plains Region (based on geology derived from Hamilton et al., 1999; Macdonald and Slimmon, 1999; Massey et al., 2005; Wheeler et al., 1997).

depositional environment changed to largely clastic inland environments throughout the Mesozoic. This sedimentation was initiated by the accumulation of thick marine shale sequences that graded into extensive marine sandstones. During the Cretaceous, deposition transitioned into fluvial systems, including extensive coal deposition in some parts of the region. The youngest bedrock sequences consist of Tertiary fluvial deposits which covered much of the region. With the end of mountain building, these units suffered significant erosion, leaving many isolated erosional remnants of Tertiary sediments across the Prairie Region (e.g., Paskapoo, Ravenscrag, Turtle Mountain Formations). In most areas, the near-surface bedrock is now dominantly shale, along with marine sandstone units and some localized areas of fluvial deposits. In Manitoba and northeastern Alberta, freshwater-bearing carbonate rocks occur near the surface, forming large aquifer systems.

Most of the Plains Region, except for the Cyprus Hills, was glaciated during the Pleistocene, leaving a complex history of till, glaciofluvial and lacustrian complexes, moraine features and other deposits related to glacial retreat, referred to collectively as glacial drift. The regional Quaternary history has been well defined in Saskatchewan (Christiansen and Schmidt, 2005; Barendregt et al., 1998; Christiansen, 1968a, b, 1979, 1992; Schreiner, 1990) and more locally in Alberta (Andriashek and Fenton, 1989) and Manitoba (Klassen, 1979, 1989; Teller and Fenton, 1980).

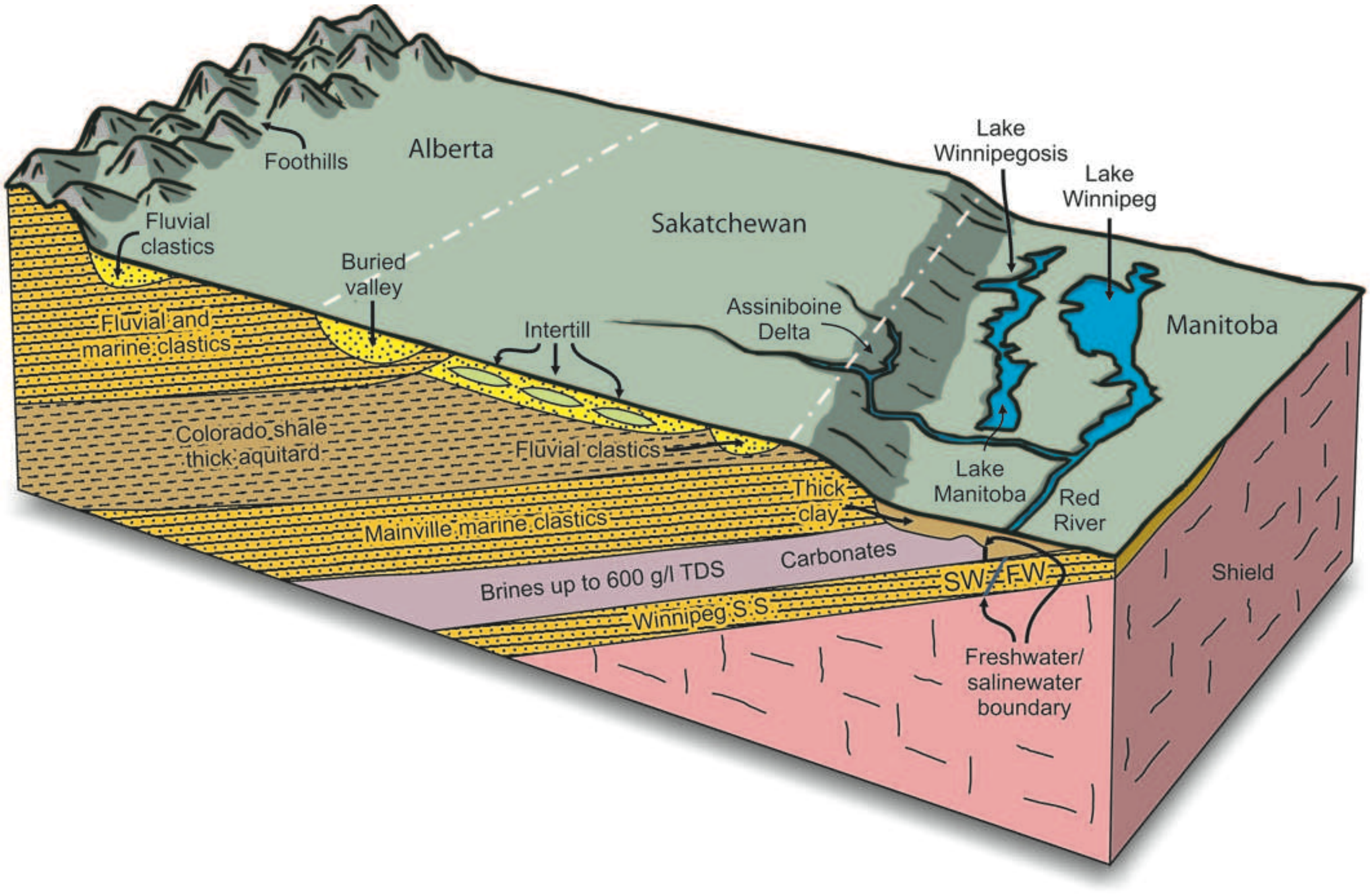


Figure 10.9 Schematic west to east cross section of the southern Plains Region showing distribution of main bedrock and surficial aquifers.

A general summary of the glacial history of the Plains Region can be found in Fenton et al. (1994). The thickness of drift cover varies extensively across the region, from zero in the unglaciated Cypress Hills to over 300 m in parts of Saskatchewan (Fenton et al., 1994). In general, drift is relatively thin in the Manitoba Lowlands, thick to very thick through Saskatchewan, while thinning toward western Alberta (Figure 10.10). The thickest accumulations of drift cover are typically found in buried preglacial valleys which today contain substantial groundwater resources.

10.2.6 Groundwater use in the Plains Region

Early regional hydrogeological studies were conducted in Manitoba and Saskatchewan (1930s to 1960s) by the Geological Survey of Canada. Although these studies mostly consisted of compiling inventory, they provided an early indication of which aquifers were being used for water supply. Manitoba expanded on this work by producing a series of 1:250,000 regional hydrogeology maps of the agricultural areas of the province from the 1970s to 1991 and is currently revising these maps. In Saskatchewan, the Saskatchewan Research Council (SRC) also carried out hydrogeological mapping on a 1:250,000 map sheet basis in the southern part of the province from 1964 to 1980. During the 1986–1999 period, the SRC prepared a series of 2nd-generation groundwater maps on a 1:100,000 scale showing individual bedrock and Quaternary aquifers (Empress Group aquifers between bedrock and the first till, inter/intra-till and surficial aquifers). In Alberta, the Alberta Research Council (ARC) conducted groundwater mapping, again on a 1:250,000 map

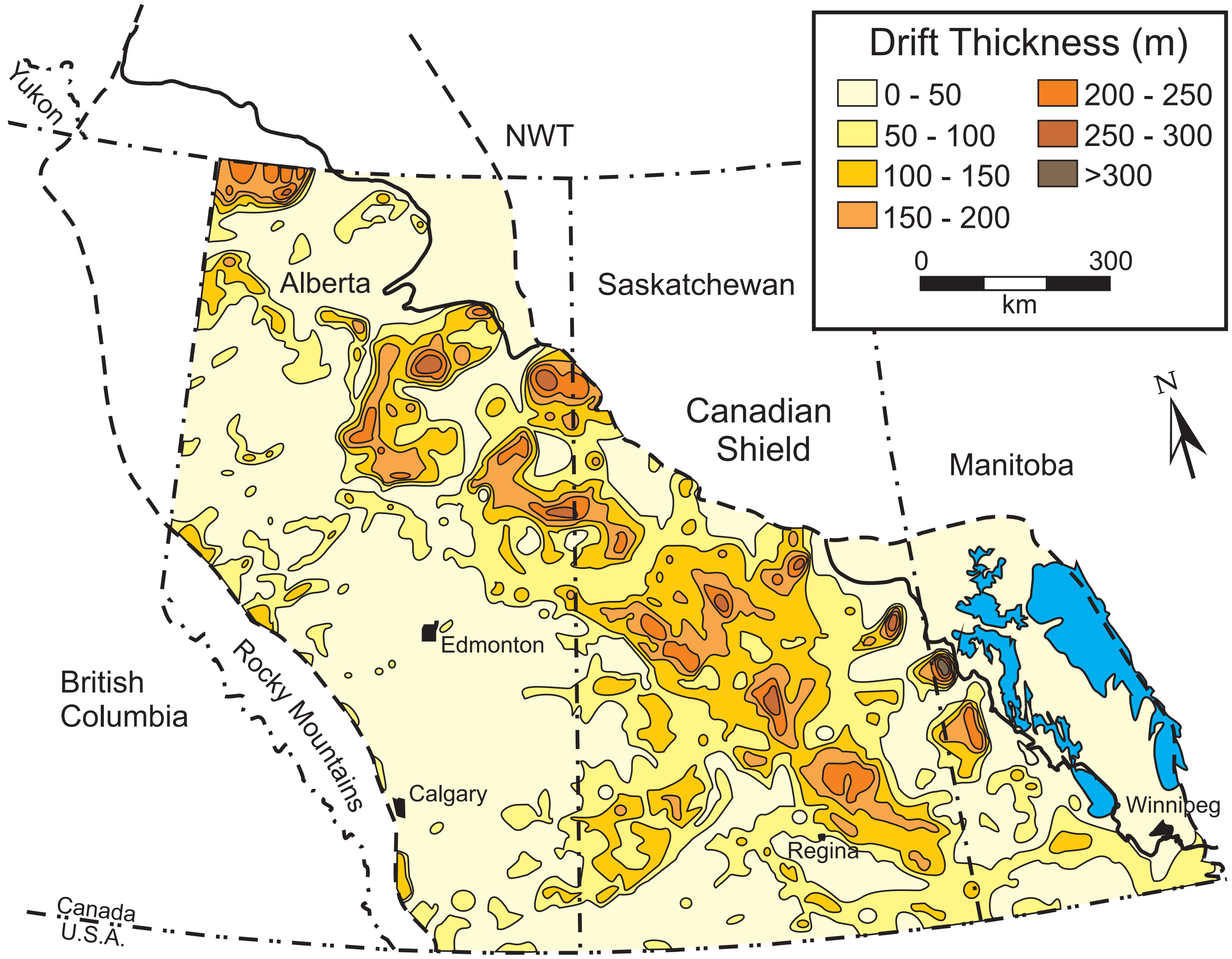


Figure 10.10 Drift thickness of the southern Plains Region (after Fenton et al., 1994).

sheet basis, from 1968 to 1982.

In addition, hydrogeological mapping and reports discussing the regional hydrogeology of all or part of the Plains Region were produced by a number of other agencies during this period, culminating with the 1967 Geological Survey of Canada's report entitled Groundwater in Canada. Maps and cross sections of areas along the Manitoba/Saskatchewan and Saskatchewan/Alberta borders were prepared by the Prairie Provinces Water Board (Tokarsky, 1985, 1986; Judd-Henrey et al., 1994, Judd-Henrey and Simpson, 2005) to show the location and extent of inter-provincial aquifers. Regional summaries of the hydrogeology of the Plains Region were prepared by Brown (1967), Lennox et al. (1988), Pupp et al. (1989, 1991) and Betcher et al. (1995). More recently, many groundwater studies have been conducted by provincial agencies. In addition, the Prairie Farm Rehabilitation Administration (PFRA) has sponsored numerous studies, including county-based groundwater reports. In recent years, there has also been a significant increase in university-based research into Plains Region groundwater systems.

The characterization of current groundwater use in the Plains Region is made difficult by the nature of the available data; however, a general overview of

TABLE 10.1 BREAKDOWN OF REPORTED WELL USE CATEGORIES BY PROVINCE SHOW THAT DOMESTIC WELLS ARE THE MOST COMMON WELLS IN THE REGION. (SOURCES: BRITISH COLUMBIA MINISTRY OF ENVIRONMENT, 2008; ALBERTA ENVIRONMENT, 2007; SASKATCHEWAN WATERSHED AUTHORITY, 2007; AND MANITOBA WATER STEWARDSHIP, 2007)

PROVINCE	DOMESTIC		MUNICIPAL		AGRICULTURAL LIVESTOCK IRRIGATION				INDUSTRIAL		OTHER			
	wells	%	wells	%	wells	%	wells	%	wells	%	wells	%	Total	%
British Columbia	826	52.91	13	0.83	0	0.00	3	0.19	26	1.67	693	44.39	1,561	0.49
Alberta	125,301	73.41	1,624	0.95	24,659	14.45	216	0.13	12,359	7.24	6,534	3.83	170,693	53.04
Saskatchewan	73,473	94.52	2,760	3.55	0	0.00	124	0.16	1,063	1.37	316	0.41	77,736	24.15
Manitoba	54,682	76.12	761	1.06	14,446	20.11	529	0.74	333	0.46	1,088	1.51	71,839	22.32
Total	**254,282**	**79.01**	**5,158**	**1.60**	**39,105**	**12.15**	**872**	**0.27**	**13,781**	**4.28**	**8,631**	**2.68**	**321,829**	

how the resource is used can still be provided. Water well databases have varying degrees of uncertainty that hamper accurate determinations of active well use. Table 10.1 provides a summary of water well usage determined for those wells that appear to be in active production. While production estimates can be derived from recommended pumping rates, this data is not available for a significant portion of the wells. Therefore, consumptive values can only be roughly estimated.

The majority of wells in the Plains Region (79%) are designated as supplying water for domestic water requirements of rural and urban populations. Although the term domestic use is not used consistently, livestock data for January 2007 combined with Alberta's consumption estimates was used to provide a rough estimate of the groundwater required for livestock use (12%). The total amount of water for domestic and livestock use represents 0.2 mm/year of recharge over the Plains Region agricultural crop and rangeland (Figure 10.11). This estimate is conservative, representing only 1,235 m^3/year of production from each of the domestic wells in the region, slightly less than the 1,250 m^3/year provided as a statutory right for household use in Alberta (Maathuis and van der Kamp, 2006).

Approximately 6% of the wells in the plains are used for municipal and industrial purposes. The number of licences and annual allocations (Maathuis and van der Kamp, 2006) provide a rough estimate of groundwater use for these two categories. The annual allocations are estimates of expected groundwater use and represent the upper limit of what might be extracted in a year, with actual production probably lower. Based on the number of wells designated as municipal or industrial (there is an average of 3 wells per licence, with an average allocation of 22,953 m^3/year per well), the average allocated production is 68,860 m^3/year per licence. The total estimated allocation for this use in the three provinces represents 0.3 mm/year of recharge over the Plains Region agricultural land (Figure 10.11a).

10.3 MAJOR AQUIFER TYPES AND PROPERTIES

There are two major aquifer types in the Plains Region: bedrock and Quaternary. Because most groundwater users extract water from the first producible zone encountered during drilling, the dominant aquifer type in any area corresponds to the nearest-to-surface aquifer system and does

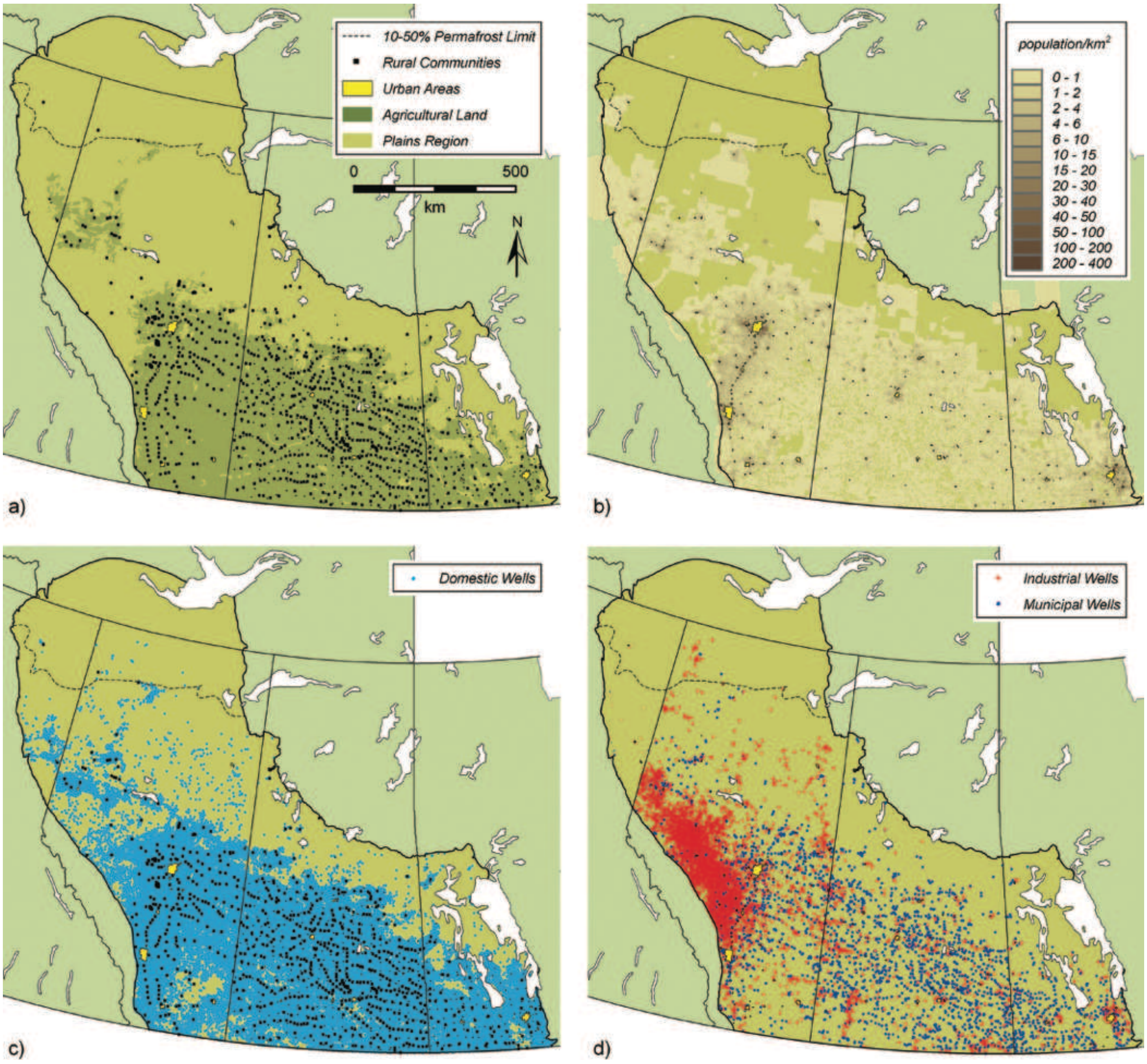


Figure 10.11 (a) Primary land use in the Plains Region, **(b)** Rural population density, **(c)** Domestic wells, and **(d)** Municipal and industrial wells showing close spatial coincidence, with the exception of industrial wells in Alberta that are located outside agricultural lands and areas of lower population density. Sources: Statistics Canada, Hydrogeo NR, J5707 (Government of Canada, 2007); AVHRR Land Cover Data, Canada (Government of Canada, 2009); Permafrost Map of Canada, Atlas of Canada, MCR 4177 (Government of Canada, 1995); Atlas of Canada 1,000,000 National Frameworks Data, Administrative Boundaries (Government of Canada, 2009); British Columbia Ministry of Environment, 2008; Alberta Environment, 2007; Saskatchewan Watershed Authority, 2007; and Manitoba Water Stewardship, 2007.

not preclude the possibility of deeper aquifers. Consequently, bedrock aquifers are dominant in Alberta and Manitoba where glacial drift is relatively thin, while Quaternary aquifers are the dominant groundwater supply source in the thick glacial drift regions of Saskatchewan.

Information in the form of lithology from drilling logs and well construction reports as well as designated aquifers in provincial databases provide an idea of whether groundwater is produced from unconsolidated Quaternary deposits or from bedrock. The data is recorded differently in each jurisdiction.

In the Plains portion of British Columbia, 32% of groundwater wells are installed in bedrock and 61% in unconsolidated deposits (British Columbia Ministry of Environment, 2008).

In Alberta, 84% of the wells draw water from bedrock aquifers and 16% from unconsolidated deposits (Alberta Environment, 2007).

Data for Saskatchewan water well drilling (Saskatchewan Watershed Authority, 2007) does not allow a distinction to be readily made. However, only 19% of well records include lithology data that can be classified as bedrock. In addition, the average top of bedrock lithology occurs at about 45 m (Saskatchewan Watershed Authority, 2007), while the average total well depth based on all available well drilling records is 37 m (Saskatchewan Watershed Authority, 2007). This information suggests that the majority of wells in Saskatchewan are installed in unconsolidated deposits.

In Manitoba, 90% of the well records provide a known aquifer type, with 61% of those wells in bedrock (78% in limestone or dolomite) and the remaining 39% in unconsolidated deposits (94% in sand and gravel) (Manitoba Water Stewardship, 2007).

Below we provide an overview of the major bedrock aquifers and then the overlying Quaternary aquifer systems within the Plains Region.

10.3.1 Bedrock aquifers

As discussed above, the prevalence of groundwater extraction from bedrock aquifers is related mostly to the thickness of overlying glacial drift. Bedrock aquifer usage is most significant where drift cover is thinnest, in southern Manitoba and Alberta. Bedrock aquifers in the plains can be divided into two large groups, carbonate and sandstone, each of which has distinct properties, groundwater production, and protection issues.

10.3.1.1 Carbonate Aquifers

Although Paleozoic rocks underlie the entire Prairie Region, they form freshwater aquifers only where they extend to the east and north of overlying Mesozoic and Cenozoic bedrock sediments (Figure 10.8). Paleozoic-age sediments are dominated by dolostone and limestone, with carbonate units separated by extensive shale, evaporitic or argillaceous beds. Gypsum or anhydrite beds are found locally, in the freshwater portion of these sediments, generally near the transition to saline groundwater, but in most areas, these units have been removed by erosion or dissolution. Groundwater quality in the Paleozoics is generally saline within the deeper parts of the basin, and fresh groundwater is found only in parts of Manitoba, a portion of east-central Saskatchewan, and northeastern Alberta. In Manitoba, these rocks are referred to as the Carbonate Aquifer System, while in Saskatchewan, they are called the Cumberland Aquifer. In this discussion, we will focus on the most extensively used carbonate aquifer that occurs in south-central Manitoba.

10.3.1.1.1 Carbonate Aquifer System of Manitoba

The Carbonate Aquifer System in Manitoba is formed by the erosional remnants of Paleozoic formations overlying the sandstone and shale of the Winnipeg Formation and extending east and north of overlying Jurassic and Cretaceous terriginous and evaporitic materials (Figure 10.12). The basal unit is the Middle Ordovician Red River

Formation, while the uppermost unit is the Middle Devonian Souris River Formation. Several widespread argillaceous units or beds have been identified in this sequence, and these form important aquitards, although the influence of these units is thought to decline to the north as they become less argillaceous.

Grasby and Betcher (2002) and Betcher et al. (1995) have provided an overview of regional groundwater flow systems throughout the Carbonate Aquifer in Manitoba. The areas lying generally to the east of the Red River, north of the Assiniboine River, east of Lakes Manitoba and Winnipegosis, then north of the Little Saskatchewan River contain fresh groundwater that encompasses an area of approximately 75,000 square kilometres. Areas to the west and south contain saline groundwater. A distinct water quality boundary appears to be controlled by lakes and rivers which form major physiographical lows (Figure 10.13) (Grasby and Betcher, 2002). By contrast, the deeper groundwater system of the Winnipeg Formation has a saline/fresh water boundary that appears less influenced by surface features (Ferguson et al., 2007).

The regional saline water system is believed to be driven by recharge occurring in upland areas of Montana, Wyoming and South Dakota (Downey, 1984), with discharge occurring as a series of spectacular saltwater springs and generalized seepage along the southern shore of Dawson Bay, along the Red Deer River and within Dawson Bay and Lake Winnipegosis (Cole, 1915; van Everdingen, 1971; Grasby and Londry, 2007; Grasby et al., 2010). This regional flow system, however, is largely a transient response to deglaciation and does not likely represent a long-term (millions of years) flow condition (Grasby et al., 2000; Grasby and Chen, 2005).

Two main intermediate to regional fresh water flow systems have been identified within the Carbonate Aquifer. In southeastern Manitoba, the piezometric surface of the aquifer system is elevated in the area of the Sandilands glacial upland (Figure 10.13). The erosional edge of the aquifer system lies just to the west of the upland area and may extend locally beneath the western part of the upland. Groundwater flow is west to north-westerly, away from the upland, with the aquifer system overlain by lacustrine clays of Lake Agassiz and glacial tills in this area. It would appear that the primary recharge zone for the freshwater portion of the aquifer system occurs near the Sandilands Upland. However, test drilling has shown that the sand/gravel aquifers in the Sandilands Upland and areas to the west are generally separated from the underlying Carbonate Aquifer System by glacial tills. It has been speculated that “recharge windows” may occur where the tills are absent. More recently, mass balance calculations and groundwater modelling indicate that generalized seepage through these relatively low-permeability tills may account for most of the recharge.

Groundwater discharge from this part of the Carbonate Aquifer System is less well understood than the recharge system. West of the Sandilands complex, the aquifer system is overlain by glacial tills and lacustrine clays that inhibit discharge. Prior to significant groundwater development from the aquifer system, groundwater levels through much of the area were above ground and only declined in response to the installation of large numbers of wells beginning in the late 1800s. Charron (1965) documented the progressive decline in flowing well conditions throughout the early- to mid-1900s. The pre-development flowing artesian conditions can perhaps be viewed more as a consequence of

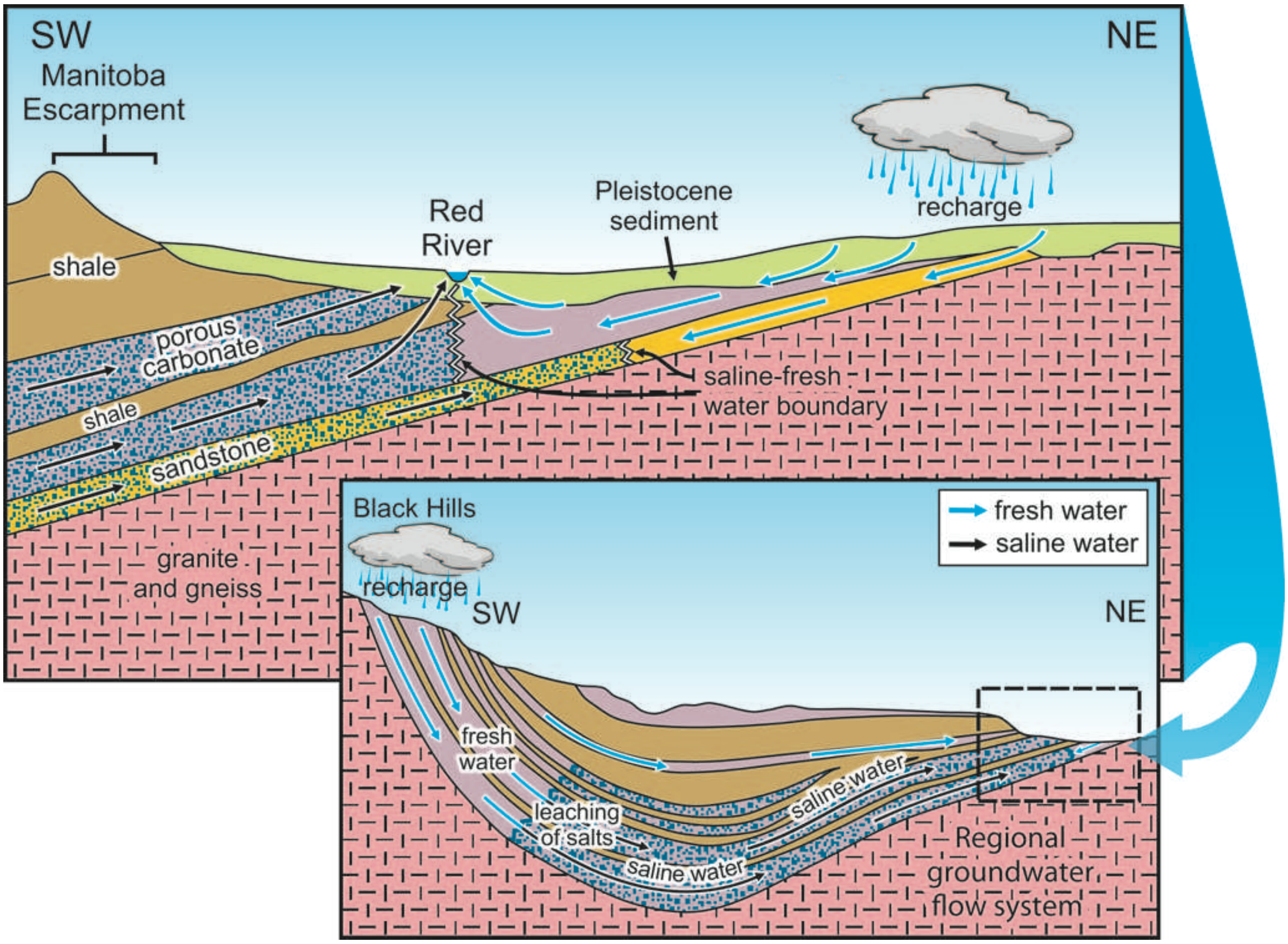


Figure 10.12 Schematic cross section showing fresh water-saline water boundaries in the Carbonate and underlying Winnipeg (Sandstone) Aquifers.

the lack of direct discharge points from this very permeable aquifer, rather than as an abundance of recharge, which may in fact be relatively low.

Grasby and Betcher (2002) observed that the Red River forms a major lateral flow and water quality boundary for the west- to northwest-directed groundwater flow system, indicating that the river is a groundwater discharge area. Bedrock outcrops occur along and perhaps directly beneath parts of the river between Winnipeg and Selkirk where direct discharge may take place; however, the hydraulic role of the river elsewhere is debated. The Red River Floodway, a large canal constructed around the east side of Winnipeg to divert floodwaters away from the city, has been an area of significant groundwater discharge since breakthroughs developed during construction in the early 1960s. Groundwater losses to the Floodway have been approximately 8,640 m^3/day to 17,280 m^3/day since the late 1960s.

A second intermediate to regional flow system has been identified in the Interlake area lying between Lakes Manitoba and Winnipegosis on the west and Lake Winnipeg on the east (Figure 10.13). A large groundwater mound has developed in the upland areas of the central Interlake with groundwater movement to the east, west and south of the mound. It is generally believed that recharge to this system occurs primarily in areas where overlying tills and clays are thin to absent;

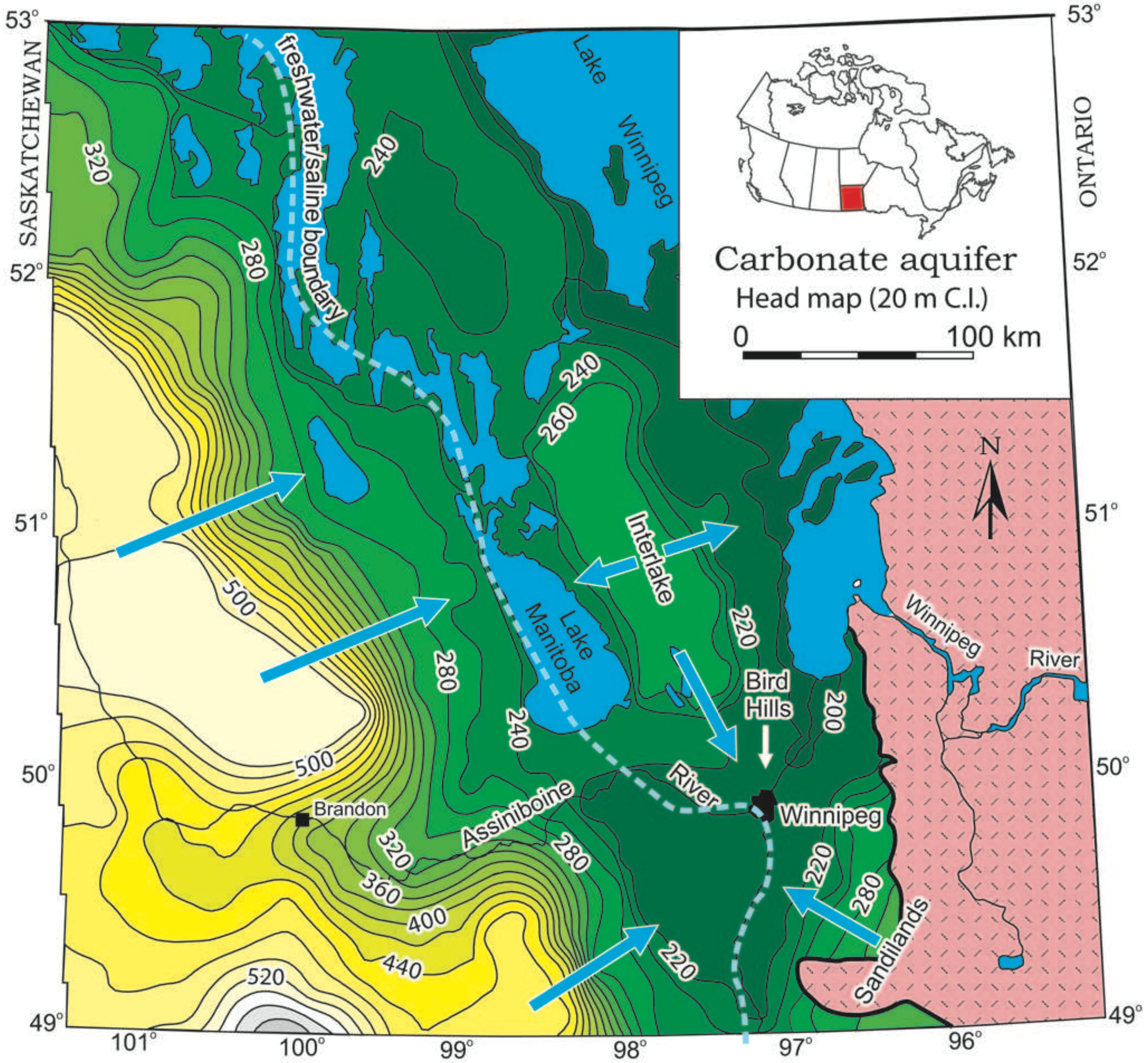


Figure 10.13 Regional hydraulic head in the Carbonate Aquifer of southern Manitoba.

however, the role of generalized seepage through large areas where the aquifer is overlain by relatively permeable glacial tills has not yet been evaluated in a quantitative fashion. Discharge occurs as springs and seepage along a number of rivers and perhaps into marshes, bogs and other wetlands, although many of these features may owe their presence more to underlying clays which restrict downward seepage. Flowing artesian areas are found along the western shore of Lake Winnipeg and the eastern shore of Lake Manitoba, indicating that these topographic lows are the terminal points of the regional system. The overburden, however, is quite thick in much of these areas and discharge must occur as very slow seepage.

More locally, a number of north-south trending glacial uplands east of Winnipeg also form focused recharge areas to the Carbonate Aquifer System, of which the Birds Hill upland, located just northeast of Winnipeg, is the most prominent. Groundwater

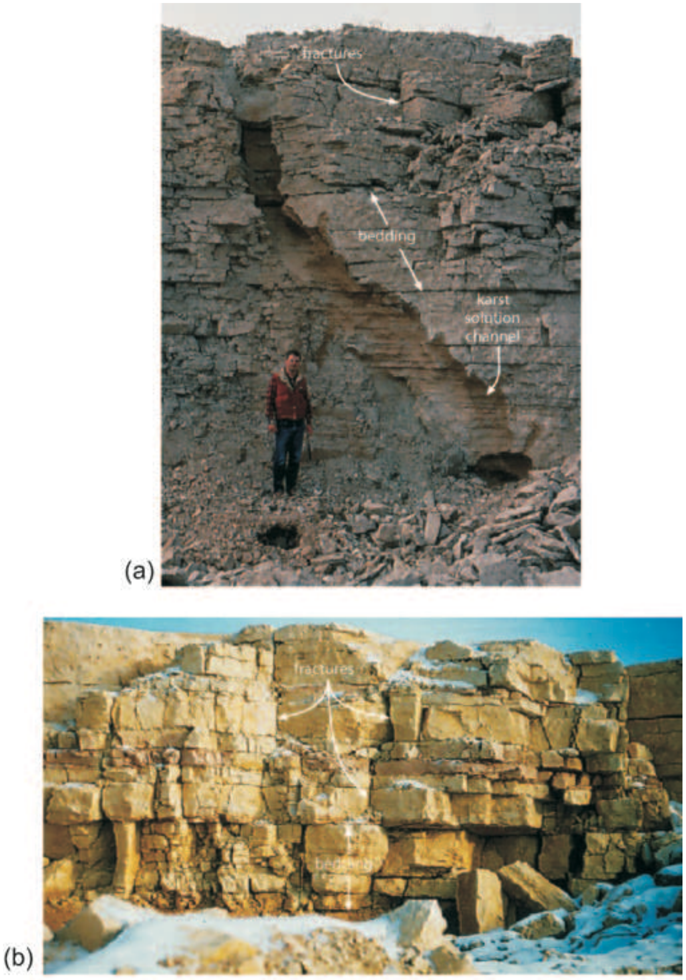


Figure 10.14 Field photographs of a quarry in the Carbonate Aquifer showing (a) bedding and well-developed karst features and (b) fracture sets.

in the Carbonate Aquifer, beneath and down-gradient from this upland, has anomalously low dissolved solids content, a sign of recharge to the aquifer through sand/gravel “windows”.

No published estimate of groundwater recharge rates has been made for any significant part of the aquifer system, although work is currently underway in southeastern Manitoba to develop a digital model that may provide some answers. The lack of long-term streamflow monitoring of most of the smaller rivers has been a significant impediment to evaluating groundwater recharge rates.

Porosity in the carbonates and argillaceous carbonates is formed by void pore spaces, sub-vertical joints and fractures, sub-horizontal bedding planes, and features developed through solution processes that have altered existing primary and secondary porosities and formed discrete porous features. Intergranular porosity averages 7% to 9% (Ferguson, 2004). The hydraulic interconnection of these pore spaces is uncertain, although these features may be significant in transmitting water over intermediate to long time scales.

Joints and fractures related to the regional stress regime (Bell and Grasby, 2012) are ubiquitous in the aquifer (Figure 10.14). Mapping of fracture orientations in bedrock exposures in the Interlake area by McRitchie (1996) has consistently identified three subvertical joint sets with orientations along east, north-east and north-west trends. Dissolution processes have enlarged some joints, fractures and bedding planes, while mineral precipitation processes have infilled or lined the sidewalls of existing fractures to a minor degree. A more significant impact of fracture lining or partial infilling is that it reduces the potential for exchange of fluids and dissolved species between fractures and the adjacent intergranular pore spaces over various time scales.

Glacial stresses are also believed to have caused significant modifications to the fracture network of the upper part of the carbonate rock (which has often been observed to be highly permeable), leading to the designation of the upper 10 m or so of bedrock as the Upper Carbonate Aquifer (Render, 1970). In some areas, particularly in the vicinity of Winnipeg and Selkirk, the upper, middle and lower portions of the local aquifer system have been identified (Render, 1970; Render, 1986) based on the intersection of permeable features in widely spaced boreholes at relatively common depth, and, in some cases, differences in groundwater quality and head.

Dissolution processes have also formed karst

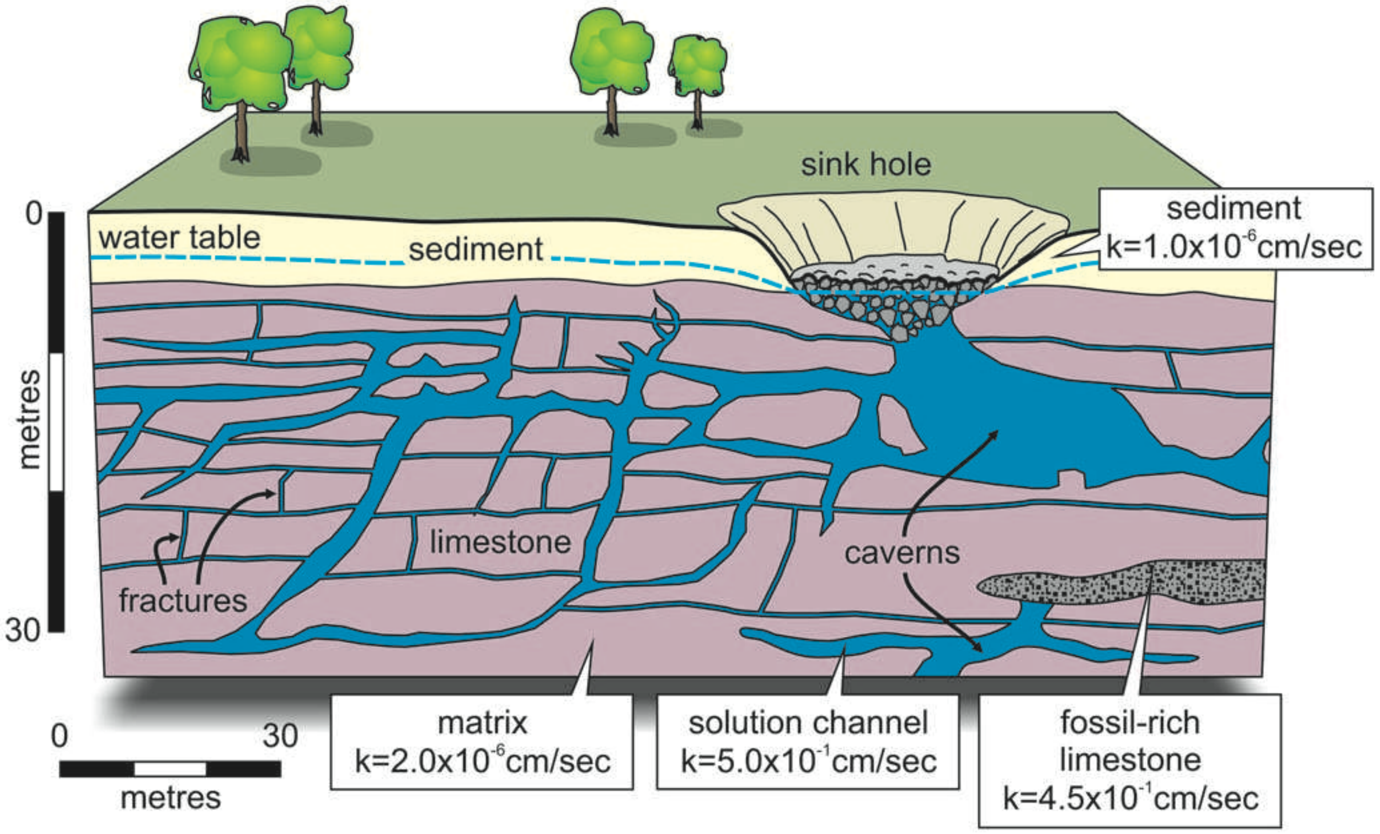


Figure 10.15 Diagram illustrating the hydraulics of the Carbonate Aquifer System.

features, such as sinkholes, tunnels and caves, while glacial loading/unloading and erosion have significantly modified near-surface fractures and pre-existing dissolution openings (Figure 10.15). Simpson et al. (1987) refer to three periods of intense karst development beneath the sub-Mesozoic, sub-Cretaceous and sub-Quaternary unconformities. Pre-Jurassic dissolution and infill features are quite pronounced in parts of southern Manitoba.

A number of water wells have also intersected thick karst infill sediments consisting of inter-bedded silica sands, silt and clay, often in association with lignite, which, in one case, was reported to be more than 100 m thick. Sediment-infilled karst features have been intersected in many parts of the Carbonate Aquifer at depths of 50 m to 100 m below the bedrock surface.

Not all karst features, however, have been infilled with younger sediments. Many boreholes have intersected large openings at depth within otherwise competent bedrock and large springs have been observed to discharge from circular bedrock openings up to several metres in diameter (Figure 10.15).

Reported yields from wells completed in the Carbonate Aquifer System show a broad range of aquifer properties. While wells have been drilled with yields of less than 6 m^3/day, most wells will produce at least 115 m^3/day, and yields in excess of 11,500 m^3/day have been reported. In some areas, drillers consistently report intersecting water-producing fractures at approximately the same stratigraphic interval, while in other areas, fracture intersects are much less predictable and nearby wells may be drilled to considerably different depths to produce sufficient water for household use. A fairly consistent feature is that if water-producing fractures are not encountered in the upper 30 m or so of bedrock (within the upper few metres of bedrock in some areas), extending the well depth will normally result in additional fractures being encountered, but yields from these deeper fractures may be only a few tens of cubic metres per day or less.

Kennedy (2002) compiled transmissivity data for the Carbonate Aquifer System in southern Manitoba using results from single-well and multiple-well pumping tests and estimates of transmissivity from specific capacity values supplied in water well drillers logs. She concluded that the natural logarithm of transmissivity follows a normal distribution with a mean of -7.2 corresponding to a transmissivity of approximately 62 m^2/day. The maximum transmissivity estimate was 34,700 m^2/day. Transmissivity values range over 12 orders of magnitude. Storativity values indicate the aquifer to be "semi-confined." Where pumping tests have been conducted with observation wells, the aquifer has responded in a classically confined fashion with little indication of leakage or dual porosity responses (over periods of 8 to 72 hours). Chen et al. (2011) examined the spatial trends in Kennedy's data set and concluded that highly transmissive zones in some areas appeared to have orientations similar to the overall trends in mapped bedrock joints and fractures. They concluded that dominant fracture systems influence the regional transmissivity patterns.

The hydraulics of the Carbonate Aquifer therefore consist of a complex and heterogeneous interconnected primary and secondary porosity. Groundwater flux is primarily through secondary joints and bedding planes which, in those areas where karst features have developed, serve to move water to dissolution channels through which large fluxes of groundwater may be transmitted. This can lead to localized high-vulnerability areas in the Carbonate Aquifer due to rapid contaminant transport (Figure 10.16). However, the rate of groundwater movement in these features will only be rapid where these channels are able to freely discharge to the surface. In large parts of southern and central Manitoba, discharge is severely restricted by glacial and lacustrine sediments that overlie the aquifer system's discharge areas. This is particularly apparent within the major lakes of Manitoba, which, although they occupy regional topographic lows, contain thick glacial and lacustrine sediments and likely do not form major volumetric discharge areas (Teller and Last, 1981; Forbes et al., 2000). Consequently, groundwater velocities within the aquifer system are likely quite slow through much of southern Manitoba. Transport rates estimated from the extent of contaminant plumes have indicated flow velocities in the order of a few tens of metres per year. In the central and northern Interlake area, velocities may be much higher because the overburden cover is generally much less and karst dissolution features are very prominent in some areas (e.g., the Grand Rapids area, Grice, 1964).

The role of intergranular porosity remains somewhat uncertain because the interconnection of primary pores is poorly understood and may vary based on the lithology of the various carbonate units. A slug test conducted in a "dry" hole with an open interval of 70 m in the Red River Formation just east of Winnipeg indicated a hydraulic conductivity of ~10^{-8} m/s, some of which may be attributed to unrecognized fractures intersecting the borehole. Nonetheless, if some of the intergranular pores are interconnected throughout the rock mass as a whole, they may contribute significantly to

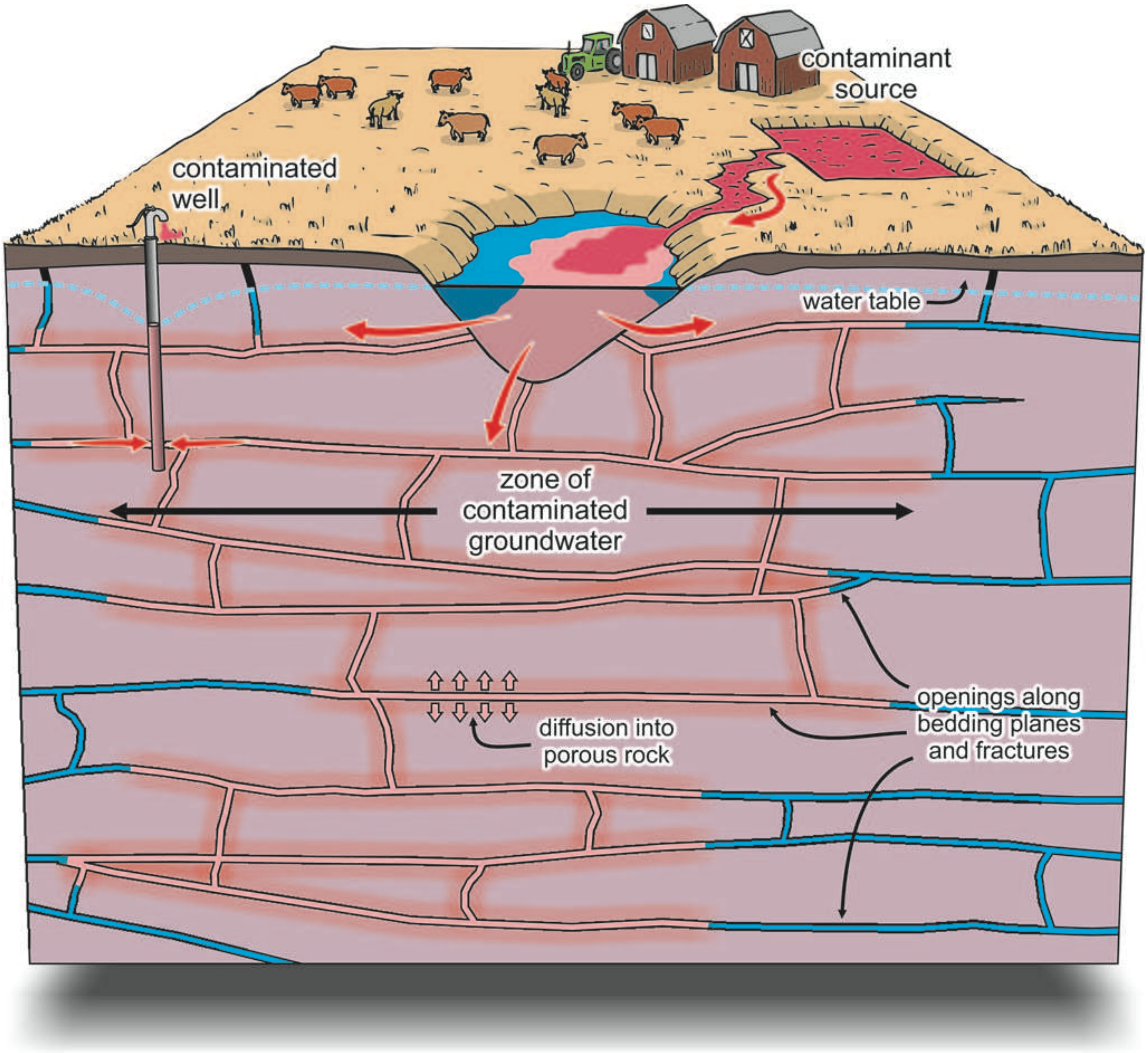


Figure 10.16 Schematic diagram illustrating the significant influence of fracture systems on contaminant transport within the Carbonate Aquifer.

the overall flux of groundwater through the aquifer system and may provide a dual porosity leakage to fractures during long-term pumping tests or groundwater withdrawal developments within the system.

The geochemistry of fresh groundwater in the Carbonate Aquifer is characterized as calcium-magnesium-bicarbonate type with a TDS (total dissolved solids) of 400 mg/L to 800 mg/L, typical of geochemical development in carbonate-rich terrains (Grasby and Betcher, 2002). The lower-TDS groundwater is associated with recharge areas in the Interlake and the Sandilands Upland, while elevated TDS contents and a transition to more sodium- and chloride-dominated groundwater occurs near the fresh water–saline water boundary. Localized regions of elevated-TDS, sulphate-rich groundwater are also found along the western edge of the Red River between Winnipeg and Selkirk, to the east of Winnipeg and in the Interlake area. These appear to be areas where leakage of water from the overlying clays provides

Figure 10.17 Outcrop of the silica sandstones of the Winnipeg Formation on Black Island, between the north and south basins of Lake Winnipeg. Note the variable cementing of the sandstones and the fracture-controlled discharge of groundwater from the well-cemented sandstones in the centre of the section.

a significant component of local recharge. Fresh groundwater in the Carbonate Aquifer is isotopically modern, with $\delta^{18}O$ values ranging from about –13‰ to –15‰, indicating that the active flow systems in the freshwater portion of the aquifer have removed residual Pleistocene water that would have been present at the end of the last glaciation.

10.3.1.2 Sandstone aquifers

There are a number of freshwater-bearing sandstone aquifers, ranging in age from Ordovician through Tertiary, found locally or regionally across the Prairie Provinces. Regional and provincial summaries of many of these aquifers have been provided by Brown (1967), Lennox et al. (1988), Betcher et al. (1995), Pupp et al. (1989) and Pupp et al. (1991). In this discussion, we deal with the major sandstone aquifers in the Plains Region, while recognizing that local freshwater-bearing aquifers do exist in other strata, such as Jurassic sandstones in Manitoba.

10.3.1.2.1 Winnipeg Aquifer

The oldest freshwater-bearing sandstone aquifer in the Prairie Region is within the Winnipeg Formation (Lower Ordovician) in southeastern and central Manitoba. The aquifer has a variety of names, such as the Upper Sandstone and Lower Sandstone aquifers (Render, 1970), the Winnipeg Formation aquifer (Betcher et al., 1995; Ferguson et al., 2007) and the Sandstone aquifer (Kennedy, 2002). In this discussion we use the term Winnipeg

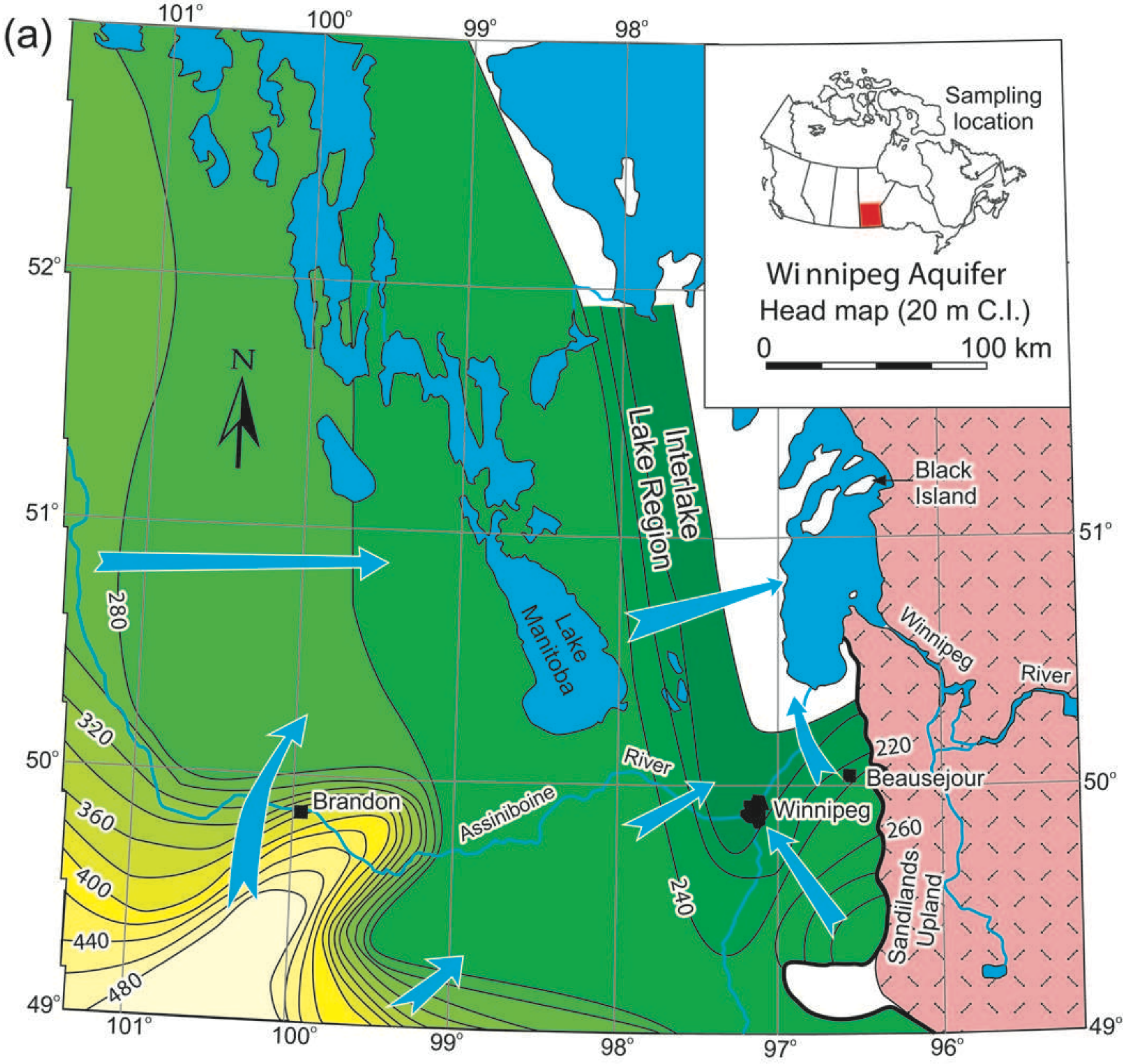


Figure 10.18 Hydraulic head for the Winnipeg Aquifer at 20 m contour intervals (after Fergusson et al., 2007).

Aquifer. This formation thins to the north and is not recognized as a significant freshwater-bearing unit in either Saskatchewan or Alberta. The geology has been discussed by many authors (Andrichuk, 1959; McCabe, 1978) and a recent summary of the hydrogeology of the formation in Manitoba has been provided by Ferguson et al. (2007). Outcrops of the aquifer are rare and confined to portions of a number of islands in the south basin of Lake Winnipeg (Figure 10.17).

The freshwater-bearing portion of the Winnipeg Aquifer in Manitoba sits directly on weathered Precambrian igneous and metamorphic rocks and is hydraulically separated from the overlying Carbonate Aquifer System by a shale aquitard in southern and central Manitoba (Figure 10.12). North of Lakes Winnipeg and Winnipegosis, geological test holes indicate that the upper shale is absent and that the sandstones are likely interconnected with the Carbonate Aquifer System. Based on the location of the fresh water–saline water boundary provided by Betcher (1986), the freshwater portion of the aquifer underlies an area of approximately 7,550 km^2 from the Canada/USA border to the northern Interlake (Figure 10.18).

Within this area, the dominant lithology is a grey-to-white, fine, variably cemented silica sandstone. Shale beds in the lower portions of the formation have been observed to confine basal sandstones to the extent that water level and water quality differences have been observed between the upper and lower sandstones. Visual observation and the responses of several pumping tests indicate that portions of the sandstones are fractured. Spring discharge can be observed from individual fractures in a well-cemented portion of the sandstone on Black Island (Figure 10.17). Betcher (1986) summarized the results from 20 single-well pumping tests carried out on wells and test holes completed in the aquifer. The hydraulic conductivity varied from 1.1×10^{-3} m/s to 3.2×10^{-6} m/s, reflecting the influence of local cementing and fracturing in the sandstones. The highest hydraulic conductivity was measured in a test hole where it is believed that the fractures were intersected in a cemented layer of sandstone.

Betcher (1986), Betcher et al. (1995) and Ferguson et al. (2007) have described two separate intermediate to regional groundwater flow systems within the freshwater portion of the Winnipeg Aquifer (Figure 10.18). In southeastern Manitoba, the Winnipeg Formation subcrops near the Sandilands Upland and a series of smaller upland areas near the southeastern tip of Lake Winnipeg. Hydraulic head and groundwater quality information indicate that these areas form the dominant recharge zones for the aquifer, with groundwater movement occurring westward to northwest (Figure 10.18).

Interestingly, these two freshwater recharge areas are separated by a "tongue" of saline groundwater stretching from Winnipeg to the subcrop area east of Beausejour. Betcher (1986) speculated that prior to emplacement of the Sandilands and other uplands near the end of the last glaciation, saline groundwater extended to the subcrop area throughout much of southeastern Manitoba. With the establishment of these glacial uplands, and the higher heads they imposed on the subcrop area, fresh groundwater influx occurred beneath or near these areas, driving the saline water to the north and west by the advancing "modern" freshwater fronts. East of Beausejour, where there is no upland area over the subcrop of the Winnipeg Formation, saline groundwater continues to extend to the subcrop area.

A second regional flow system is found in the Interlake area. Saline groundwater occurs in the western Interlake and advances to the east, driving fresh water out of the system. Isotopic evidence suggests that subglacial meltwater was injected into the system during glacial periods, advancing several tens of kilometres to the west (Ferguson et al., 2007). With the removal of subglacial excess heads, the natural system of west-to-east flow has been re-established (Grasby and Chen, 2005).

Little work has been done to examine how discharge occurs from the Winnipeg Formation. In southeastern Manitoba, a number of erosional channels have been mapped where scouring has penetrated through the Carbonate Aquifer and the upper shale of the Winnipeg Formation. These features may form limited pathways for discharge of groundwater from the system. However, piezometric surface maps for both southeastern

Manitoba and the Interlake region indicate that Lake Winnipeg forms the dominant regional discharge area for groundwater flow systems within these areas. This is somewhat puzzling because geophysical studies have shown thick clay sediments overlying bedrock within Lake Winnipeg, excluding areas such as Hecla, Black and Deer Islands. It may be that the observed slow rates in advancement of the water quality fronts reflect a very diffuse seepage of discharging groundwater through these clays. This situation has changed, at least in the southeastern part of the system, with the construction of deep bedrock water wells beginning in the late 1800s. Betcher and Ferguson (2003) estimate discharge of about 1,500 m^3/day from the Winnipeg Formation into the overlying Carbonate Aquifer through interconnecting boreholes. This appears to have led to significant head reductions in this part of the aquifer and may account for the loss of a significant percentage of recharge to the aquifer.

The quality of fresh groundwater in the Winnipeg Aquifer shows considerable variation.

In the eastern Interlake, where residual Pleistocene water has not been flushed from the aquifer, the groundwater is sodium-mixed anion type with a TDS of 1,000 mg/L to 1,300 mg/L. Chloride concentrations range from 300 mg/L to 500 mg/L and sulphate from 200 mg/L to 300 mg/L. This reflects mixing of very fresh Pleistocene water with residual saline groundwater likely held in lower-permeability portions of the aquifer.

In southeastern Manitoba, isotopically modern groundwater extends westward from the Sandilands Upland before transitioning to sodium chloride type water along the fresh water–saline water boundaries to the west and north. Near the eastern recharge area, the groundwater is $Na\text{-}Ca\text{-}Mg\text{-}HCO_3$ type with TDS concentrations ranging from 200 mg/L to 300 mg/L, but gradually increasing down the flowpath to 300 mg/L to 400 mg/L. Calcium and magnesium concentrations initially rise as the TDS increases, but then decline dramatically to very low concentrations east and south of the saltwater boundaries. In these areas, the groundwater is $Na\text{-}HCO_3$ type with very low hardness, reflecting cation exchange processes in the parts of the aquifer where saline groundwater has been flushed more recently by recharging fresh modern water (Ferguson et al., 2007). This naturally soft water has been a drilling target for more than a century, allowing water users to escape the problems of hard water from the overlying Carbonate Aquifer. Water analyses reveal elevated fluoride and boron concentrations in these soft water zones.

10.3.1.2.2 Mannville Aquifer

The Mannville Aquifer is formed by sandstone beds within the Lower Cretaceous Mannville Formation (equivalent to the Inyan Kara Formation in North Dakota and the Swan River Formation in Manitoba) which forms the basal Cretaceous sedimentary unit of western Canada. The Mannville was deposited unconformably on an eroded Jurassic or Paleozoic surface in a fluvio-deltaic environment. Sediments consist of variably cemented sandstone, siltstone, shale and coal, with individual beds apparently having little lateral continuity.

In much of the Plains Region the Mannville aquifer is either too deep for water supply development or yields saline water. Only in a fringe along the boundary with the Precambrian Shield, where the Mannville Group forms the bedrock surface and is overlain by Quaternary deposits, may it yield potable water (Pupp et al., 1989; Christopher, 1984).

Sandstone beds within the Mannville Formation also form freshwater-bearing aquifers in parts of west-central Manitoba (Rutulis, 1984).

Studies in Manitoba and Saskatchewan, where the formation may be as much as 150 m thick, have shown the upper part of the aquifer to contain relatively fresh water, although water quality generally declines with depth in an irregular fashion (Betcher, 1991). Well yields are highly variable, consistent with the lithologic heterogeneity. Betcher (1991) summarized reported well yields in the Swan River area of Manitoba as ranging from 7 m^3/day to 650 m^3/day, for an average of 130 m^3/day.

In Manitoba, freshwater recharge to the Mannville Formation occurs along the eastern and northern edges of the Manitoba Escarpment (Rutulis, 1984) through leakage from overlying Quaternary sediments with regional groundwater movement toward the east to northeast. Discharge occurs to rivers and creeks in the Swan River area where outcrops of the formation have been mapped. In most areas, however, the sandstone beds are overlain by low-permeability materials, and interaction with the surface environment is inhibited.

Groundwater quality in the Mannville Aquifer in Manitoba is characterized by extreme changes, both spatially and vertically. Betcher (1991) reports TDS values varying between 316 mg/L and 15,000 mg/L, with rapid variations found over short lateral or vertical distances. This is believed to reflect the limited extent of individual sandstone units and their separation by low-permeability, clay-rich materials. Shallow sandstone units have generally been flushed of residual saline groundwater, while in the deeper units, flushing is severely impeded. Fresh groundwater consists of two major types: (1) Ca-Mg-HCO_3 in those areas where flushing of saline groundwater and replacement by "modern" water has occurred, and (2) Na-mixed anion groundwater typically with low hardness in those sandstone units where much of the saline water has been flushed, but cation exchange sites remain charged with Na. In Saskatchewan, there is little groundwater quality information available. In northwest Saskatchewan, the aquifer yields Na-Cl or Na-HCO_3-type waters with TDS in the 650 mg/L–7,750 mg/L range (Maathuis, 2008).

Water from the Mannville Group is used in some oil-producing areas for enhanced oil recovery. Well yields range from 5 m^3/day to 3,200 m^3/day, but are typically in the 86 m^3/day to 430 m^3/day range. Data on the hydraulic conductivity of the Mannville Group aquifer is scarce. Lissey (1962) reports an in situ hydraulic conductivity of 1.6×10^{-6} m/s at a site near Regina. Meneley et al. (1979) report a value of 2×10^{-4} m/s for a Mannville Group sand in northeastern Saskatchewan.

10.3.1.2.3 Milk River Aquifer

The Milk River Aquifer is an important groundwater source for southern Alberta (Figure 10.19). The aquifer has been the subject of a number of hydrogeological studies, including Meyboom (1960), Schwartz and Muehlenback (1979), Domenico and Robbins (1985), Phillips et al. (1986), Hendry and Schwartz (1990), as well as an international study on the use of isotope tracers in groundwater studies (Fröhlich et al., 1991).

This is a transboundary aquifer covering over 10,000 km^2 and extending 100 km northward from the recharge zone in exposed outcrop belts around the Sweetgrass Hills. The aquifer is characterized by 30 m to 75 m thick sandstone dipping northward from the recharge zone and overlain by up to 120 m of confining marine shales of the Pakowki Formation. The massive marine sandstones of the Milk River Aquifer diminish northward and transition into shale, limiting the northern extent of the aquifer. Previous work has suggested that the water of the Milk River Aquifer has a complex history of original marine water being displaced by freshwater recharge after the formation was exposed to surface ~ 50 Ma ago due to erosional unroofing (Hendry and Schwartz, 1990). This initial freshwater influx was later altered by deposition of glacial drift over the recharge belt, imparting a new, more sulphate-rich water chemistry onto the more modern-day recharge water, creating distinct compositional zones along the flow gradient within the aquifer. Meyboom (1960) determined transmissivity values, based on shut-in tests on 45 wells, ranging from 0.15 m^2/day to 30 m^2/day.

The Milk River Aquifer has been used as a water source since the early 1900s. Over time, numerous wells were drilled and, later, a significant number of them abandoned. Meyboom (1960) identified 409 wells installed in the aquifer, of which 192 had flowing water. A recent survey identified 1,027 wells, of which 442 were inactive (43%), and 41 of the inactive wells were flowing. A reclamation and conservation plan was recently implemented to protect water quantity and water quality. A total of 101 wells, 22 of which were flowing, were sealed by cementing (Printz, 2004). Monitoring data are being collected, but the impact of well decommissioning on the aquifer has not yet been assessed.

10.3.1.2.4 Judith River Aquifer

The Late Cretaceous Judith River Formation extends from southern Alberta into southwestern Saskatchewan and the United States. The formation crops out in Montana and locally in Alberta and Saskatchewan. However, over most of its extent, it is overlain by the Bearpaw Formation, Tertiary

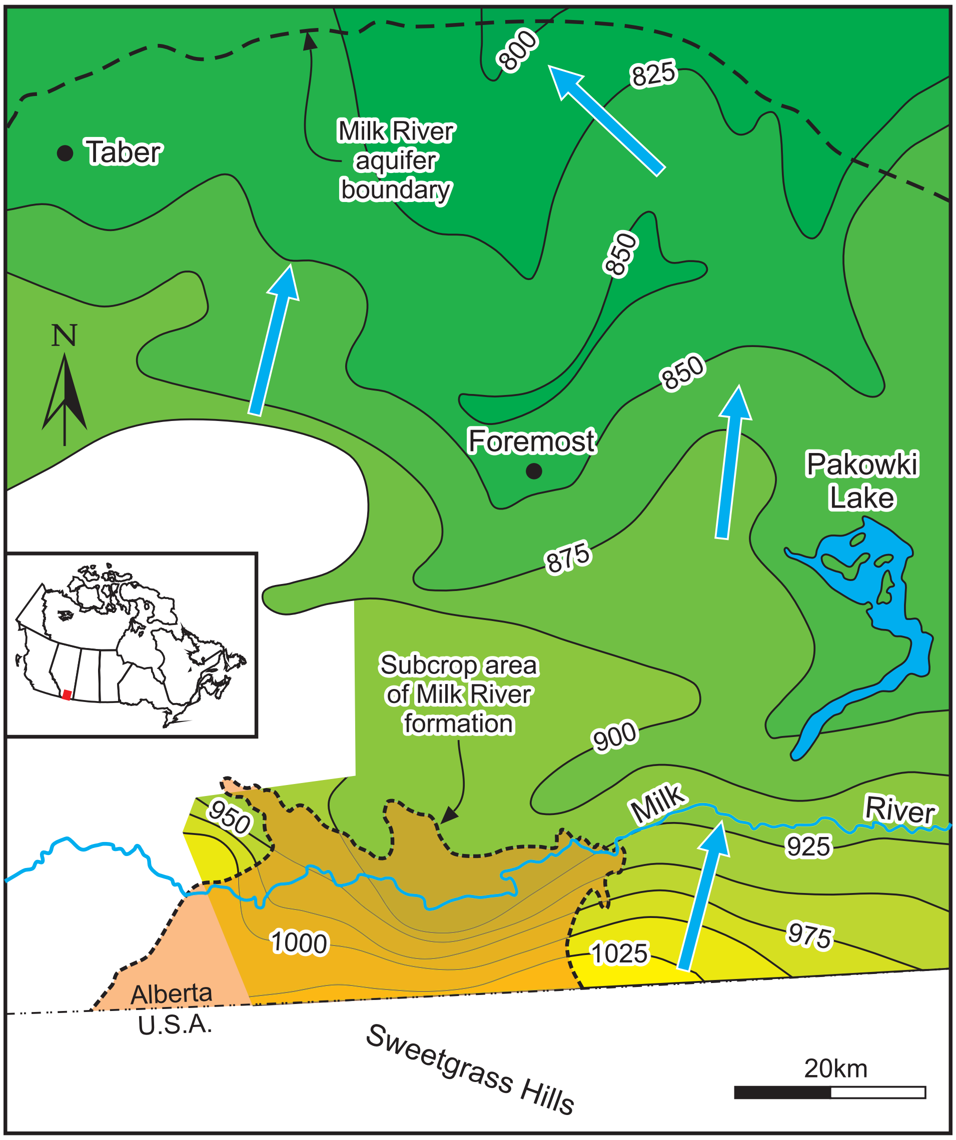


Figure 10.19 Location and extent of the Milk River Aquifer along with contoured head values (shown at 25 m contour interval).

sediments, and Quaternary deposits (Figure 10.8). In Alberta, in areas where the Bearpaw Formation is absent, the Judith River Formation may be overlain by the Horseshoe Canyon Formation.

Descriptions of the geology of the Judith River Formation and its subdivisions can be found in McLean (1971), Eberth and Hamblin (1993), Dawson et al. (1994), and Hamblin and Abrahamson (1996). The Judith River Formation is an eastward-thinning sedimentary wedge composed of non-marine and marine, multi-coloured sandstones (very fine to medium-grained), silts and clays with carbonaceous and concretionary zones deposited in a deltaic environment (McLean, 1971), including alluvial, lacustrine, aeolian, lagoonal, swamp, beach and marine sediments. The lower part of the Judith River Formation was deposited in a more marine environment, whereas the upper portion represents a more continental depositional environment (Dawson et al., 1994). The depth at which the Judith River Formation is encountered may range from zero at the outcrop edge to 635 m in southwestern Saskatchewan. Its thickness ranges from zero at its erosional or depositional edges to 125 metres. Individual sand units within the formation are less than 15 m thick, and commonly only a few metres thick. It is difficult to trace individual sand layers and silt and clay beds over more than a few kilometres (McLean, 1971).

The regional hydrogeology of the Judith River Aquifer has been described by Kewen and Schneider (1979), Whitaker (1982a, b), Maathuis and Simpson (2007a, b, c, d) and Pupp et al. (1989). The Judith River Aquifer is recharged directly by infiltrating precipitation and surface water in those areas where the aquifer crops out in Montana. Over much of its extent, however, the aquifer is overlain by aquitards formed by the silts and clay units of the Bearpaw Formation, as well as Quaternary unconsolidated sediments. Consequently, downward flow through these overlying aquitards limits vertical recharge to no more than a few millimetres per year.

Whitaker (1982a) suggests that the maximum hydraulic conductivity of Judith River Aquifer sand beds could be 15 m/day (≈ 1.7 × 10^{-4} m/s), but that the average hydraulic conductivity for the fine to medium-grained sands would likely be no more than 5 m/day (≈ 5.8 × 10^{-5} m/s). Hydraulic conductivity in the 0.1 m/day-to-5 m/day (≈ 1.2 ×10^{-6} to 5.8 × 10^{-5} m/s) range can be taken as a general characteristic for the Judith River Aquifer sands.

Pupp et al. (1989) indicate that in Alberta, this aquifer unit generally yields sufficient water for domestic supplies, and that some zones yield enough water for municipal and industrial purposes. In Saskatchewan, the aquifer is also used as a source of domestic/farm, municipal and industrial water. In southwestern Saskatchewan, water from the aquifer is used for enhanced oil recovery. Wells for this purpose may yield up to 600 m^3/day (Maathuis and Simpson, 2007a). Although this aquifer is a highly complex formation, under pumping conditions the entire structure will, in complex ways, act as a single aquifer unit because of interaction between sand units.

The quality of water in the Judith River Aquifer in Saskatchewan has been described by Maathuis (2008). Both the quality of the water and the water type are highly variable. The TDS may range from 725 mg/L to 12,250 mg/L, median 2,000 mg/L. Locally, the aquifer yields small amounts of natural gas and is known to yield brownish-coloured water. Pupp et al. (1989) provided some water quality data for the aquifer in Alberta.

10.3.1.2.5 Eastend to Ravenscrag Formations

During the Late Cretaceous to Miocene, non-marine sands and silts were deposited in an advancing delta and alluvial deltaic plain across the Plains Region (Whitaker et al., 1978), including the Late Cretaceous Eastend, Whitemud, Battle and Frenchman Formations, the Tertiary Ravenscrag, Turtle Mountain and Paskapoo Formations, the Oligocene Cypress Hills Formation and the Miocene Wood Mountain Formation. Locally, these units can all form large aquifer systems.

The Eastend Formation is composed of greyish and greenish sandstone, siltstone, and mudstone, with thin coal seams in the upper part. The Whitemud is composed of kaolinitized, white sandstone and mudstone, separated by a carbonaceous zone and overlain by purplish shale of the Battle Formation. The Frenchman Formation is composed of sandstone and mudstone. The Ravenscrag Formation is comprised of sandstone, siltstone, mudstone, and coal. Christiansen (1983) states that the bottom portion of the Eastend Formation consists of blanket sands. The Frenchman, Ravenscrag and Paskapoo Formations were deposited by rivers meandering over swampy floodplains and are characterized by fine to medium-grained channel sands. The Tertiary Cypress Hills Formation is composed of conglomerate, gravel, sand and silt (Vonhof, 1965a, b; Vonhof, 1969). Leckie and Cheel (1989) interpreted the formation as a braidplain deposit. It unconformably overlies the Ravenscrag Formation (or Eastend to Ravenscrag Formations) or directly overlies the Bearpaw Formation. The Wood Mountain Formation has been described by Whitaker (1965, 1967), Vonhof (1969) and Leckie et al. (2004). The present occurrences of the Miocene Wood Mountain Formation in the Wood Mountain area are erosional remnants of an originally much more extensive deposit. The formation consists of gravel and sand up to 30 m thick deposited in a braided river system environment.

The Eastend-Ravenscrag Aquifer is formed by the sediments of the Eastend, Whitemud, Battle, Frenchman and Ravenscrag Formations. In southwestern Saskatchewan, it also includes the aquifers formed by the Cypress Hills and Wood Mountain Formations, where these formations overlie the Eastend-Ravenscrag Aquifer. The thickness of the aquifer ranges from zero (0) metres at its erosional edges to 290 metres beneath the Cypress Hills in southwestern Saskatchewan. This transboundary aquifer extends into the United States.

Regional hydrogeology of the Eastend-Ravenscrag Aquifer has been described by Meneley (1983), and Maathuis and Simpson (2003, 2007a, b, c, d). West of 103°W, large portions of the aquifer are exposed at the ground surface or covered by a thin layer of glacial drift. In this area, the aquifer can be considered a tabular mass overlying an impermeable base formed by thick siltstones and mudstones of the Bearpaw Formation. The aquifer is unconfined and recharge occurs over virtually the aquifer's entire extent. The area is characterized by significant topographic relief. In a general sense, groundwater flow will be from the central parts of the aquifer toward its erosional edges. However, because of the topographic relief, flow will also discharge into river and creek valleys dissecting the landscape. In the southeastern part of Saskatchewan (east of the 103°W), there is less topographic relief and the aquifer is generally covered by several tens of metres of glacial drift, mainly till. The aquifer in this part of Saskatchewan is semi-confined.

Using analyses of specific capacities, Meneley (1983) derived hydraulic conductivity values in the 1 $\times 10^{-5}$ to 7 $\times 10^{-5}$ m/s range for sandstones in the Frenchman and Ravenscrag Formations. Based on reported values, the hydraulic conductivities of the Eastend-Ravenscrag sandstones are probably 1.1 $\times 10^{-5}$–1.1 $\times 10^{-4}$ m/s, typical for the fine to medium-grained sandstones of the aquifer. Coal within the Ravenscrag Formation may be fractured, making coal layers a potential target for well completion. However, there is no actual data on the hydraulic conductivity or transmissivity of fractured coal layers. There is also no information on the transmissivity or hydraulic conductivity of the gravels within the Cypress Hills and Wood Mountain Formations, although the literature suggests that the hydraulic conductivity of gravels can range from hundreds to thousands of metres per day (e.g., Freeze and Cherry, 1979).

Meneley (1983) estimated that the yield of individual wells may be in the order of 50 m^3/day to 500 m^3/day. Wells screened across multiple zones within the aquifer may yield higher volumes. Because of the complex lithological settings of the aquifer, pumping-induced drawdowns will not show radial flow patterns. The presence of the more permeable channel sands causes drawdowns along the axes of these channels (i.e., elongated drawdowns).

Water quality data for the Eastend-Ravenscrag Aquifer and the Cypress Hills Aquifer have been discussed by Dyck (1980) and Maathuis (2008). Water in the Cypress Hills Formation is commonly either Ca/Mg-SO_4 or Ca/Mg-HCO_3 type. The sum of ions ranges from 125 mg/L to 4,500 mg/L, but typically is less than 1,000 mg/L.

Within the Eastend-Ravenscrag Aquifer, the water quality changes from west to east. The highest-quality water is found in the western part, where the aquifer is unconfined. In this area, the sum of ions is typically less than 1,500 mg/L. In the eastern part, the sum of ions in the water is typically in the 1,500 mg/L to 3,000 mg/L range. The type of water is variable, but in the southeastern region, sodium is typically the dominant cation.

In Manitoba, erosional remnants of the Eastend-Ravenscrag are recorded as sandstones within the Upper Cretaceous and Tertiary Boissevain and Turtle Mountain Formations within and immediately adjacent to the Turtle Mountain upland of southwestern Manitoba: These sandstones encompass an area of approximately 1,100 km2 (Figure 10.8) in Manitoba and extend south into the United States, as another transboundary aquifer. These units are equivalent to the Eastend-Ravenscrag Aquifer of southeastern and south-central Saskatchewan and the Fox Hills and Hell Creek aquifer systems of North Dakota.

The Boissevain Formation overlies grey, non-calcareous shale of the Coulter Member of the Pierre Shale and consists of sandstone with minor amounts of mudstone and siltstone, averaging about 30 m in thickness where it has not been eroded (Bamburak, 1978). In North Dakota, Randich and Kuzniar (1984) report that sandstone comprises approximately 18% of the total formation thickness, with individual sandstone beds ranging in thickness from 0.6 m to 25 m. The Boissevain Formation is overlain by up to 158 m of non-marine siltstone, sandstone, and mudstone, grading upward to silty mudstone with minor thin fine-grained sandstone forming the Turtle Mountain Formation (Bamburak, 1978). Lignite beds are common in the lower part of the formation and were mined sporadically from 1883 to 1943 (Bannatyne, 1978). It is interesting to note

that groundwater seepage from sandstone aquifers was a serious problem for some mining attempts. Bedrock units have been deeply incised in places and are unconformably overlain by up to 120 m of Quaternary deposits.

In most areas, sandstone aquifers of the Boissevain and Turtle Mountain Formations are confined by overlying low-permeability materials. However, outcrops occur locally along the flanks of Turtle Mountain, providing unconfined conditions. Recharge to the bedrock units occurs primarily as a result of seepage through overlying Quaternary deposits, but direct recharge is also found in local areas of outcrop, particularly in the Turtle Mountain Formation (Halstead, 1959). Springs have been reported around the base of Turtle Mountain (Johnston, 1934; Kohut, 1972) and in a ravine where outcrops of the Boissevaine Formation occur (Elson and Halstead, 1949).

Rutulis (1978) suggested that groundwater flow would generally be from south to north in Canada with discharge along the flanks of Turtle Mountain. However, Western Ground-Water Consultants (1982) suggested a regional north-to-south movement of groundwater. This observation is consistent with studies in North Dakota indicating regional groundwater movement toward the Souris River valley (Randich and Kuzniar, 1984). It is likely that local to intermediate groundwater systems have developed along the flanks of Turtle Mountain in response to topographic changes, and that groundwater movement in these areas would be from higher elevations to discharge areas in topographic lows.

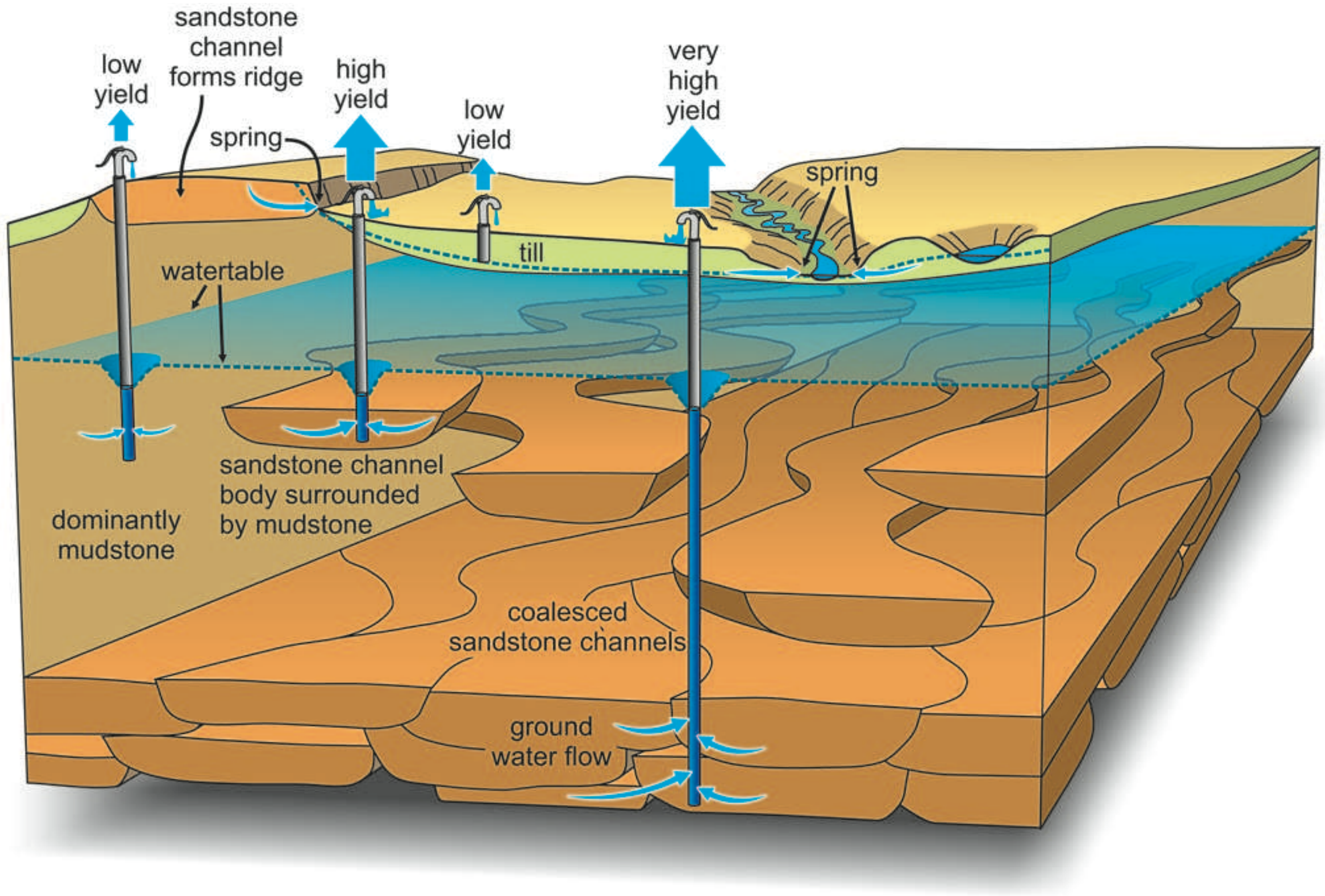


Figure 10.20 Conceptual hydrogeological model for the Paskapoo Aquifer, illustrating isolated sand channels encased in mudstones.

Yields from wells completed in the Boissevain and Turtle Mountain Formations are quite variable, with excellent supplies sufficient for most rural residential or small agricultural operations obtained whenever thicker sand beds are intersected, and poor yields where finer-grained sediments are found (Elson and Halstead, 1949). Well yields from equivalent formations in North Dakota are about 9 m3/day to 260 m^3/day from the Fox Hills aquifer system and less than 86 m^3/day from the Hell Creek aquifer system (Randich and Kuzniar, 1984). Western Ground-Water Consultants (1982) conducted a test drilling program in the Canadian portion of Turtle Mountain in 1981 and suggest that well yields from the formations decline with a fining of grain size from north to south. Their studies indicate that yields up to 475 m^3/day may be possible along the northern flank of Turtle Mountain, although the sustainability of the resource was not evaluated.

Groundwater quality analyses for samples from the Boissevain and Turtle Mountain Formations have been presented by Elson and Halstead (1949), Halstead (1959) and Western Ground-Water Consultants (1982). The groundwater is Ca-Mg-(Na)-HCO_3-(SO_4) type with TDS ranging from about 850 mg/L to 2,500 mg/L. Sodium concentrations are variable, but typically range from 150 mg/L to 500 mg/L, while sulphate concentrations generally exceed 200 mg/L and are more than 1,000 mg/L in some areas. Chloride concentrations in groundwater are generally less than 50 mg/L, although Na-Cl-type groundwater is reported in equivalent units in the North Dakota portion of Turtle Mountain.

10.3.1.2.6 Paskapoo Aquifer System

The Paskapoo Formation of southern Alberta is an extensive Tertiary fluvial mudstone and sandstone complex covering ~65,000 km2 (Figure 10.20). It forms the westernmost and most extensive erosional remnant of Tertiary deposits equivalent to those in Saskatchewan and Manitoba. Roughly one third of wells in Alberta are located within the Paskapoo outcrop belt and 96% of these penetrate bedrock. The number of wells completed in the Paskapoo (~64,000) makes this Formation the most significant groundwater supply in the Plains Region. Many previous studies have examined localized areas of the Paskapoo (Farvolden, 1961; Meyboom, 1961, 1967; Tóth, 1962, 1966; and Ozoray & Barnes, 1978) and included research into nested flow systems by Tóth (1962, 1963). A recent study of the Paskapoo Aquifer System was conducted by Grasby et al. (2008, 2010).

The Paskapoo Formation ranges in thickness from zero up to 800 m and is comprised of light grey, thick-bedded sandstone, with greenish sandy siltstone and mudstone, deposited in non-marine environments. In the Plains, the strata dip westward at <1º. Although commonly referred to as sandstone because of the tendency of sand channels to form outcrops, the Paskapoo is greater than 50% siltstone and mudstone. Background literature and detailed measured sections of Paskapoo rocks in cores and outcrops within the Calgary to Red Deer region are provided in Hamblin (2004, 2007a, b, c).

The Paskapoo Formation sits on top of the coal-bearing upper Scollard Formation. This surface is overlain successively by the Haynes Member and the Lacombe Member (described below), which together make up the bulk of the Paskapoo Formation. In some northern and western locations, there is some evidence that an additional (later) sequence is present (Dalehurst Member), but these deposits have not been studied in detail.

The basal Haynes Member (Demchuk and Hills, 1991) is characterized primarily by vertically stacked, multi-storey, medium-grained channel sandstone bodies, which form a distinctive, regionally extensive, laterally continuous unit up to 150 m thick. It includes only minor and discontinuous mudstone layers (10%–30%) and sandstones (70%–90%), although it appears that the thick sandstones do not extend southward to the vicinity of Calgary. The overlying Lacombe Member (Demchuk and Hills, 1991) is very widespread and characterized by thinly inter-bedded channel and splay sandstone, overbank siltstone and mudstone and minor coal, and is up to 300 m thick. This unit represents the bulk of the near-surface Paskapoo rocks for much of its area plus some isolated, thick channel sandstone aquifer units and many thinner isolated, splay sandstone aquifer units (30%–50%), all encased in the dominant aquitard overbank deposits (50%–70%). The uppermost Dalehurst Member (Demchuk and Hills, 1991) is characterized by inter-bedded, fine-grained sandstones, grey mudstones and at least five thick coal seams. The geometry of the sand channels within a mudstone matrix ensure complex groundwater movement through the Paskapoo Formation (Burns et al., 2010a, b).

Paskapoo sandstones are predominantly litharenites with major framework grains including quartz, feldspar and rock fragments (mainly chert, volcanic, metamorphic and sedimentary) (Grasby et al., 2007) (Figure 10.21). Diagenetic production of clays through alteration of feldspars and rock fragments is a significant process reducing sandstone permeability. Calcite cement is also

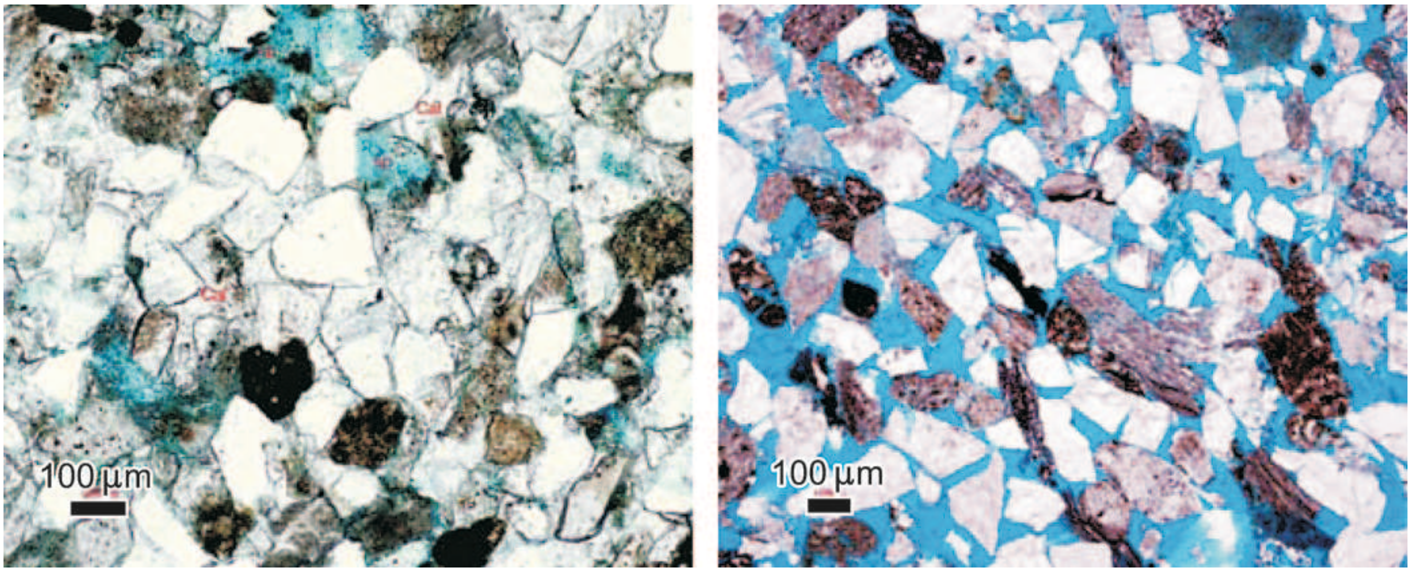


Figure 10.21 Thin section of Paskapoo sandstones illustrating (on left) well-cemented sands with little porosity (in blue) and (on right) poorly cemented sands with high porosity.

observed to occlude intergranular pore spaces, particularly near redox boundaries between the upper weathered and lower unweathered portions of the aquifer, where calcite cement can be pervasive (Grasby et al., 2009).

Both porosity and permeability of sandstones in the Paskapoo Formation show significant variation. Measured helium porosity values show a broad range from 4.2% to 32.5%, with an average of 19.2% ± 7.3. Porosity is generally highest in coarser-grained sandstones. Estimated porosity from petroleum well sonic logs (4%–28%) (Chen et al., 2007b) is consistent with the range measured from core samples.

Hydraulic conductivity is generally low (average 1×10^{-5} m/s for 159 measurements). Diagenesis of rock fragments appears to reduce hydraulic conductivity by generating clay minerals that occlude pore necks (Grasby et al., 2007). A bimodal distribution is observed, representing higher-permeability, coarse-grained sandstones and lower-permeability, fine-grained sandstones and mudstones. Permeability values are generally highest in association with thick coarse channel sands. Fractures are thought to significantly enhance permeability in some sandstones (Farvolden, 1961; Tóth, 1966) and probably mudstone units as well.

The piezometric surface in the Paskapoo mimics regional topography. Indications are that there are no confined regional-scale flow systems here, and groundwater is dominated by local-scale flow systems. This theory is consistent with observations suggesting that recharge occurs over most of the Paskapoo outcrop area as a result of downward infiltration through overlying glacial drift. The aquifer system is characterized by a general downward directed flow system (Grasby et al., 2008, 2010).

Although there are few long-term monitoring wells not affected by nearby pumping, an examination of historical trends for this aquifer shows that reported water levels have increased over the last 40 years (Figure 10.22). This fact may suggest a general lowering of the regional water table. Some high-volume-production wells providing municipal water supplies have recently been abandoned because of local reductions (Wozniak et al., 2008). These observations suggest that more work is needed to effectively quantify sustainable production from this important aquifer system.

10.3.1.3 Fractured shale aquifers

Shale is generally considered an aquitard. In parts of southwestern Manitoba and southeastern Saskatchewan, (Figure 10.8), however, the Odanah Member of the Pierre Shale is highly siliceous and fractured, such that it forms a large-scale aquifer. In outcrops, layers of hard, brittle, heavily fractured shale are found inter-bedded with layers of soft, less fractured shale and thin but continuous layers of yellow bentonite. Seepage faces have been observed at the point of contact between the fractured siliceous layers and underlying bentonite beds. Drillers' descriptions of the unit are similar to what is seen in outcrops, i.e., generally described as "layers of soft and hard shale." The Odanah Member is as much as 240 m thick (Bannatyne, 1978; Figure 10.23) in southwestern Manitoba, but becomes increasingly less siliceous and more bentonitic with depth. The Odanah is underlain by the Millwood Member, which is a soft bentonitic shale with little reported groundwater production potential. The contact between the two members is often reported as being very abrupt.

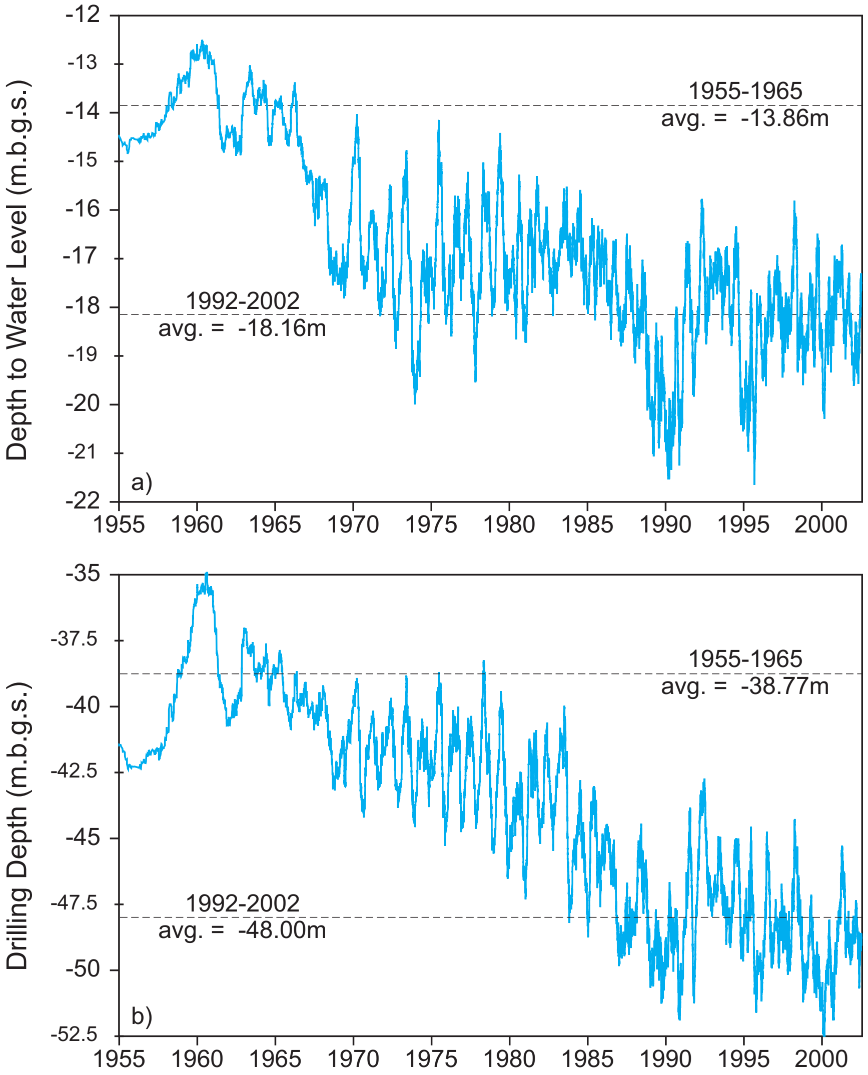


Figure 10.22 Plot showing historical changes in average drilling depth and water levels.

Through much of its outcrop area, the Odanah Member occurs as a series of rounded hills known as the Pembina and Tiger Hills in southern Manitoba. In some parts, the hills appear to be large blocks of bedrock that have been scoured and transported significant distances by glacial ice sheets. To some degree, these physiographic features may divide the aquifer or parts of the aquifer into a series of non-interconnected units. Given these lateral boundaries, the occurrence of groundwater primarily in fracture porosity, and the vertical separation of the aquifer by bentonite layers, it would be expected that any attempts to withdraw substantial amounts of groundwater would lead to dewatering of the local portion of the aquifer. Unfortunately, long-term monitoring information is not available for any of the larger water supply developments, but dewatering would certainly be a concern.

Well yields from the Odanah Aquifer are

Figure 10.23 Photograph showing the Odanah Aquifer in Southwestern Manitoba. Note the seepage occurring at the top of thin bentonite beds forming icings. The extent of the Odanah Member in Saskatchewan is limited (see Figure 10.8). Wells are known to have been completed in this unit for domestic/farm water supplies, but there is no information on hydraulic properties, yields and water quality.

generally less than 43 m^3/day, but in exceptional cases, yields of 860 m^3/day or more have been reported. The aquifer has been developed as a source of municipal water supply in a few locations, but the lack of predictability in well yield and generally poor water quality have hindered additional development.

Betcher (1997) provided a summary of water quality in the aquifer in Manitoba based on regional sampling of private wells. TDS varied from less than 500 mg/L to more than 6,000 mg/L, averaging 1,770 mg/L. TDS values tended to increase with well depth, although there was considerable scatter. Groundwater in shallow wells (<15 m) was typically Ca-Mg-HCO_3-(SO_4) type trending toward increased NaCl and SO_4 and a decline in Ca and Mg with depth. Sodium concentrations exceeded 300 mg/L in many of the deeper wells.

10.3.2 Quaternary aquifers

Quaternary aquifers are unconfined to highly confined sand or sand and gravel units that occur in the sediments between the bedrock surface and the present ground surface. Quaternary aquifers (Figure 10.24) in ascending order include aquifers between bedrock and the first till, inter- and intra-till aquifers, and surficial aquifers. Aquifers between bedrock and the first till are often referred to as Empress Group aquifers and include the preglacial buried-valley aquifers. Inter-till aquifers can be buried-valley or sheet/blanket. Surficial aquifers

TABLE 10.2 HYDRAULIC CONDUCTIVITIES OF TILLS IN THE PRAIRIES

SITE	FORMATION	HYDRAULIC CONDUCTIVITY (M/S)	REFERENCES
Warman	Sutherland till, unfractured	$10^{-10} – 10^{-11}$	Keller (1987), Keller et al. (1988, 1991), Fortin et al. (1991), Remenda et al. (1996)
Dalmeny	Floral till, fractured	5×10^{-9}	
	Floral till, bulk	3.2×10^{-10}	
Birsay	Battleford till, Unfractured	5.4×10^{-11} - 2.7×10^{-11}	Shaw and Hendry (1998)

include those formed as inwash (deltaic sediments deposited in icebound glacial lakes by extra-glacial rivers) or outwash (silt, sand and gravel washed out from a glacier by meltwater sediments) during the final deglaciation of the Prairies and alluvial deposits. Quaternary aquifers do not necessarily represent a single hydrostratigraphic unit, but they can be comprised of stratified sediments of different ages.

Throughout the Plains, Quaternary aquifers are a major source of domestic, municipal and industrial water supplies. Tills (an unsorted and unstratified mixture of clay, silt, sand, gravel and boulders directly deposited by glaciers) and silts and clays form aquitards. Table 10.2 provides a summary of reported hydraulic conductivities of tills in the Prairies.

10.3.2.1 Confined Quaternary aquifers

Inter-till, intra-till and buried-valley aquifers are major sources of groundwater within the Prairie

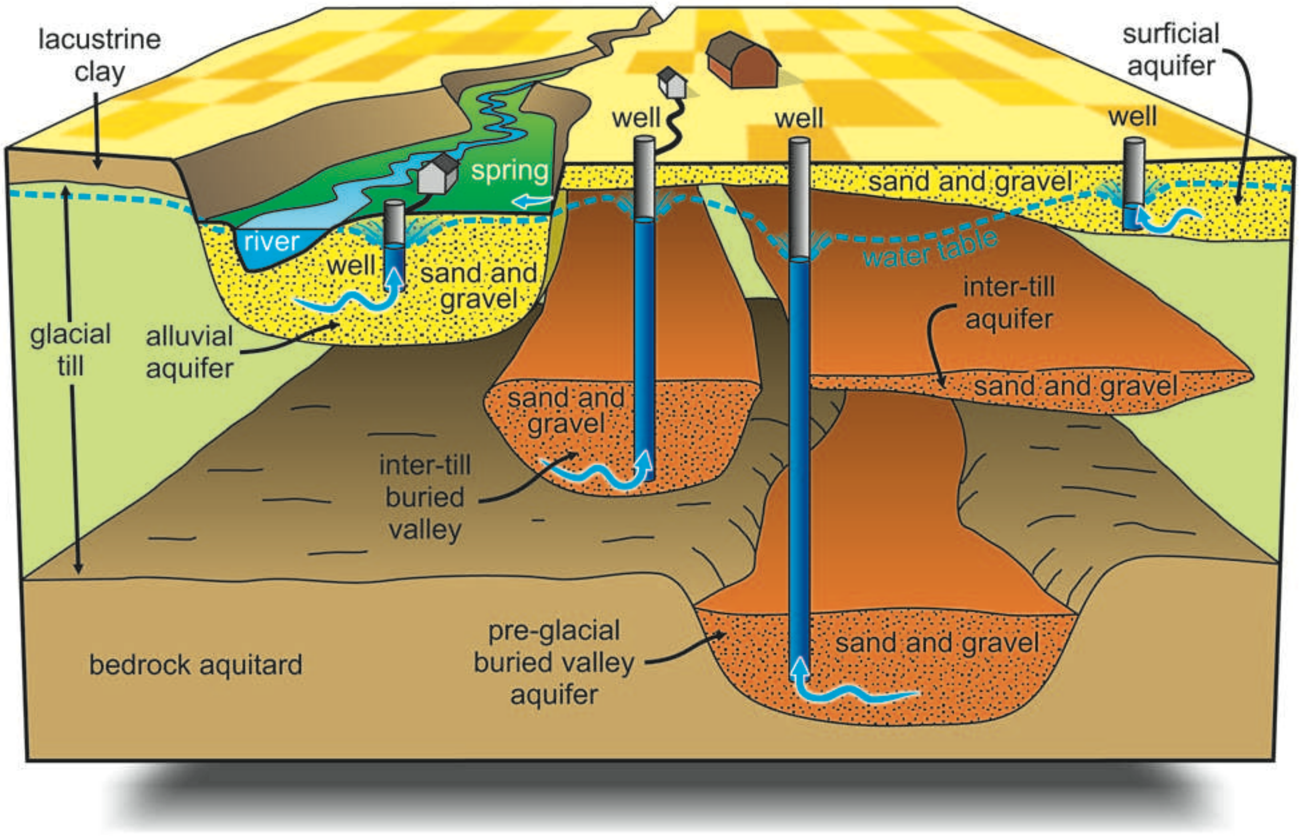


Figure 10.24 Block diagram of Quaternary aquifers.

Region. Considerable effort has been devoted to mapping major buried-valley aquifers, particularly in Saskatchewan where these aquifers can provide significant rates of supply. Less effort has been devoted to mapping the occurrence and extent of inter-till and intra-till aquifers, which are locally important.

10.3.2.1.1 Buried-valley aquifers

Buried-valley aquifers are common in the glaciated terrain of North America (e.g., Betcher et al., 2005; Russel et al., 2004; Maathuis and Thorleifson, 2000; Shaver and Pusc, 1992; van der Kamp, 1986). In the Prairies, the term "buried-valley aquifer" commonly refers to aquifers occupying preglacial valleys, although the term is also used in Manitoba to refer to aquifers occupying valleys scoured by glacial meltwater. At the end of the Tertiary, an extensive network of river systems was present in the bedrock surface of the Prairie landscape. Prior to the onset of glaciation, Tertiary sediments (quartzite and chert gravel) were deposited in many of these valleys, forming the lower portion of the fill. The upper, and generally thicker, portion of the fill consists of preglacial sands and gravels which contain igneous, carbonate and metamorphic clasts (e.g., Christiansen, 1992). Significant silt and clay beds can be found locally. In Saskatchewan and Alberta, these stratified deposits are referred to as the Empress Group (Whitaker and Christiansen, 1972; Christiansen, 1992). There is no specific stratigraphical name for the fill deposits in Manitoba, although Empress Group sediments are less common. During the first and subsequent glaciations, these stratified sediments, several tens of metres thick, were covered by glacial drift, mainly till. The thickness of the glacial drift overlying these preglacial buried-valley aquifers is commonly in the 60-metre to 90-metre range. These aquifers are typically semi-confined to highly confined.

Current knowledge of the extent of buried valley aquifers varies across the Plains Region, as shown in Figure 10.25. In Saskatchewan, the preglacial buried valleys have been mapped in detail. In Alberta, the main buried valleys are known, but only parts of them have been mapped in detail (for example, the buried-valley aquifers in the Cold Lake area, e.g., Parks et al., 2005). Several buried-valley aquifers have been identified in Manitoba (Betcher et al., 2005).

The largest of these buried-valley aquifers in the Prairie Provinces is the Hatfield Valley Aquifer in Saskatchewan. In contrast to the older preglacial valleys, this valley was cut into bedrock by fluvial erosion during the advance of the first continental glacier. It was filled with stratified sediments (Empress Group) before it was covered by drift of the first and subsequent glaciations (Christiansen et al., 1977). The aquifer traverses Saskatchewan from the northwest Alberta border to the southeast Manitoba border and continues into both provinces. It is approximately 550 km long and up to 30 km wide and is typically between 30 m and 50 m thick. The thickness of the overlying confining layer, mainly consisting of tills, averages about 90 m (e.g., Maathuis and Schreiner, 1982a, b; Schreiner and Maathuis, 1982).

Typically, there are no surface expressions of preglacial buried valleys: with the exception of a few areas, their location does not coincide with that of present-day major rivers. Preglacial buried-valley aquifers are longitudinally extensive, but there is increasing evidence that they are not continuous, and that continuity is interrupted by transverse low-transmissivity barriers (Maathuis, 2005; van der Kamp and Maathuis, 2002; Shaver and Pusc,

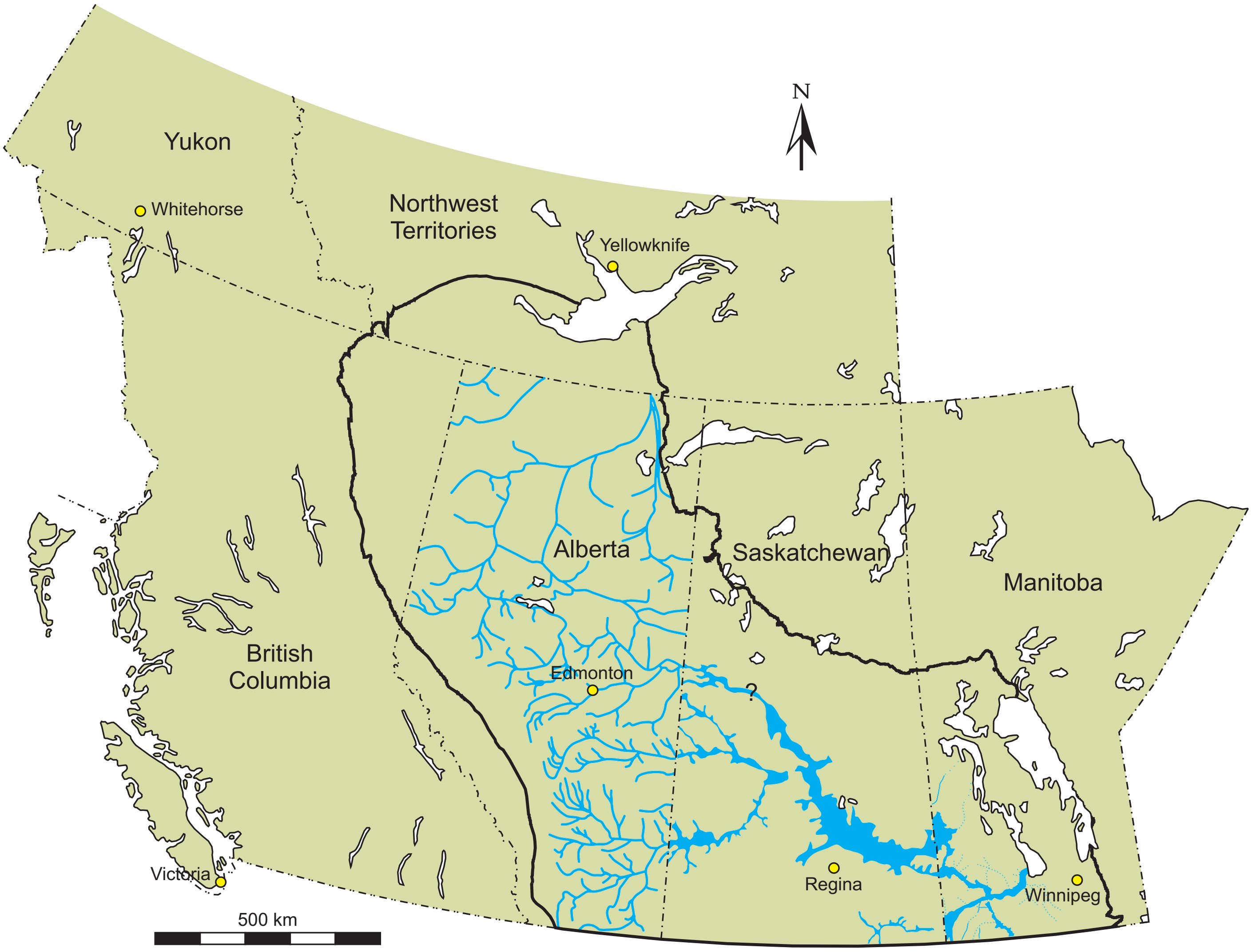


Figure 10.25 Locations of (preglacial) buried valley aquifers in the southern part of the Plains; no data on BC and NWT (after Maathuis and Thorleifson, 2000; and Toop and Betcher, unpublished data).

1992; Meneley, 1970). It remains a matter of speculation as to what causes these transverse barriers, which can be identified if monitor wells have been installed throughout the aquifer. When not stressed by pumping, large hydraulic head differences between wells indicate the existence of these transmissivity barriers. In other cases, presence of a barrier and/or barriers becomes apparent only when there are significant withdrawals from such aquifers (e.g., Maathuis, 2005). It has been noted that barriers are rarely found during exploratory drilling.

Buried-valley aquifers in the Prairies are not limited to aquifers formed by the preglacial valleys. They may also occur throughout the sequence of Pleistocene sediments, formed as subglacial or as proglacial meltwater valleys. These valleys were filled with stratified sediments and subsequently covered by tills or, in a few cases, outcrop at the ground surface. Compared to the preglacial buried-valley aquifers, these aquifers tend to be of limited longitudinal extent; nevertheless, they are an important source of local water supply.

Recharge to the deep buried-valley aquifers depends on their geological setting. When incised into Cretaceous/Tertiary siltstones and mudstones recharge occurs by vertical seepage through the overlying aquitard, formed predominantly by till units, or by lateral seepage from the surrounding bedrock. Given the thick aquitard (more than 30 m) and the low vertical hydraulic conductivity of the tills, recharge to these preglacial buried-valley aquifers is typically only a few millimetres per year. Deep buried-valley aquifers incised into low-permeability bedrock aquifers are also recharged by lateral flow from these sediments and can act as a drain for the adjacent bedrock aquifer.

The preglacial buried-valley aquifers often discharge into present-day valleys. For example, the Hatfield Valley Aquifer discharges into the North Saskatchewan River and the Qu'Appelle and the Assiniboine River Valley near the Manitoba border (Meneley, 1972). The main discharge for the Battleford and Tyner Valley aquifers is the North Saskatchewan River just north of Saskatoon (Meneley, 1970). Discharge from the shallower Pleistocene buried-valley aquifers is poorly documented. These aquifers may discharge into present-day valleys as generalized seepage or as springs.

The water quality in preglacial buried-valley aquifers is highly variable and depends on the aquifer's setting. If buried-valley aquifers are recharged solely by vertical flow through the overlying tills, then the water quality is controlled by till water geochemistry. If the recharge is from bedrock, the quality of the water in the buried-valley aquifer will be a mixture of till water and bedrock aquifer water.

The water quality in Saskatchewan's preglacial buried-valley aquifers has been described by Maathuis (2008) as highly variable, both in terms of concentration and composition. The water is often Ca/Mg-SO_4 type or Na-SO_4 type with a TDS in the 1,000 mg/L to 3,000 mg/L range. Betcher et al. (2005) noted that water quality in Manitoba's buried-valley aquifers is also highly variable.

Recent significant groundwater withdrawals from two of the preglacial buried valleys in Saskatchewan provided invaluable information on the unique behaviour of these aquifers (Maathuis, 2005; Maathuis and van der Kamp, 2003; van der Kamp and Maathuis, 2002). Key discoveries in this work include recognition that buried-valley aquifers are of finite extent and bounded on all sides by low-permeability units. They can be considered "bucket"-type aquifers. Because of their hydrogeological setting (long, narrow, highly transmissive and bounded on all sides), pumping-induced drawdowns in buried-valley aquifers may extend over tens of kilometres on each side of a production well or well field. The drawdown cone in a bucket-type aquifer is created initially within the well field area, but as pumping continues, the water levels will drop throughout the entire area by about the same amount. Additional recharge to the aquifer is induced by the drawdown of the water levels within the aquifer. This drawdown will continue until pumping balances the lateral and vertical recharge. When the pumping rate exceeds the maximum possible recharge, the water levels will continue to drop indefinitely until pumping becomes impractical. Once pumping has ceased, there is a rapid infilling of the drawdown cone in the well field area by lateral flow toward the pumping centre. A general flattening of the water levels occurs and, throughout the aquifer, there are similar amounts of residual drawdown. The rate of recovery decreases with time, as with any type of semi-confined aquifer. Depending on the hydrogeological setting, complete recovery may take up to several decades. Reliable estimates of the maximum sustainable pumping rate can only be made if long-term pumping and water level data are available.

These observations show that, while significant volumes of water can potentially be obtained from preglacial buried-valley aquifers, these aquifers must be managed carefully because of their peculiar behaviour. Such characteristics not only are valid for the preglacial buried-valley aquifers, but also apply to Pleistocene buried-valley aquifers.

10.3.2.1.2 Confined Quaternary aquifers

Inter-till and intra-till aquifers are major sources of groundwater within the Prairie Region. Intra-till aquifers are formed by aqueous sorting of glacial deposits, and are often associated with eskers or moraines. Individual aquifers generally have a limited extent, although the glacial feature itself may be quite impressive. Inter-till aquifers are formed by similar processes, but are found in sediments between till sheets or at the till-bedrock point of contact. Again, while individual aquifers may have limited extent, the overall extent of the inter-till deposits can be considerable and is often a target for test drilling or water wells.

While considerable effort has been devoted to mapping major buried-valley aquifers, less effort has been devoted to mapping the occurrence and extent of locally important inter-till or intra-till aquifers. In many cases, the presence of these aquifers is only known through water well logs, but in places where development has occurred, there may be more extensive information, such as test drilling and pumping test results and data resulting from monitoring of development impact. A number of municipal well fields have been established in intra-till sand and gravel aquifers in parts of southern and central Manitoba.

In most instances, these aquifers are highly confined by overlying and underlying glacial tills, but some of them, or portions of them may extend to the surface or nearly to the surface, providing an unconfined or partially confined area where more direct interaction with the surface or shallow subsurface can occur (see discussion of the Winkler Aquifer in Box 10-1). Typically, these are areas where most of the recharge water enters the aquifer. When the aquifer is highly confined, however, limited isotopic analysis and age dating reveal that the groundwater is very old, probably dating back to the time of deposition, indicating very, very slow groundwater movement through the surrounding low-permeability tills.

10.3.2.2 Unconfined sand and gravel aquifers

Unconfined sand and gravel aquifers are composed of glaciofluvial, glaciolacustrine, fluvial and alluvial materials deposited after the retreat of the Wisconsinan Ice Sheet. Major aquifers are formed by inwash or outwash (Christiansen, 1979, 2005). Some of these deposits may have been modified by later aeolian action (e.g., Great Sand Hills in southwestern Saskatchewan). The extent of major deposits of unconfined sand and gravels in the Prairies is illustrated in Figure 10.26 , which is based on published surficial geology maps. Although many of these deposits do form aquifers, others may not have sufficiently saturated thicknesses to provide water for household needs.

Major unconfined sand and gravel aquifers in the Plains Region are located in the Great Sand Hills in southwestern Saskatchewan, in the deltas along the Saskatchewan River (e.g., Prince Albert and Nipawin) and in Manitoba's Oak Lake and Assiniboine deltas.

Unconfined sand and gravel aquifers are bounded at the bottom by an aquitard and at the top by the water table. They receive recharge directly from precipitation. Discharge from these types of aquifers

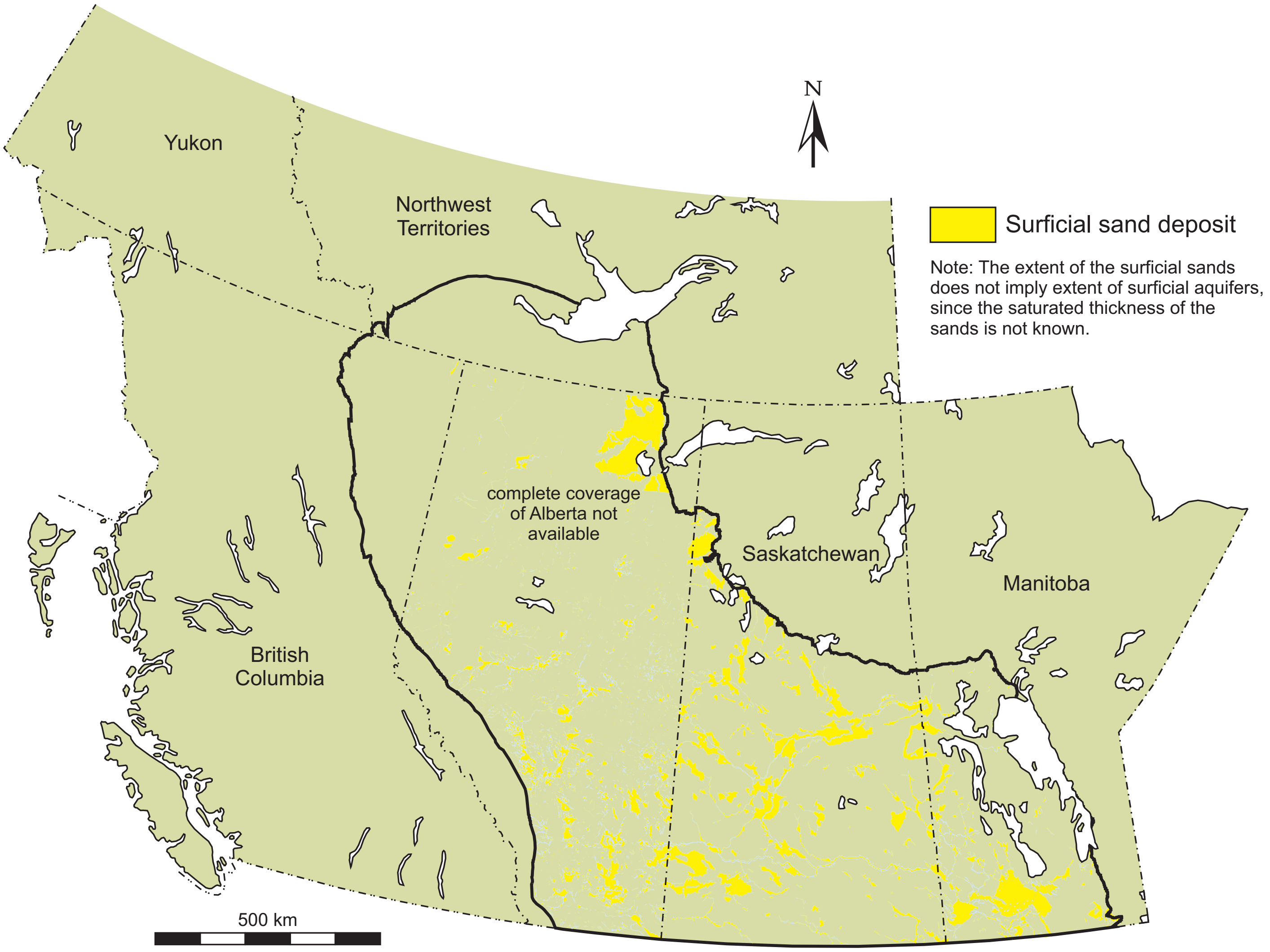


Figure 10.26 Extent of surficial sands and gravels in the southern part of the Plains; no data on BC and NWT (after Maathuis and Thorleifson, 2000).

is by evapotranspiration and through springs and seeps. A hydrograph showing typical water level response in a surficial aquifer is shown in Figure 10.27. Recharge occurs primarily in the spring or during the early summer by infiltration of snowmelt and seasonal rains, with a smaller rise also occurring in the fall in those years where precipitation is sufficient. Summer recharge events are relatively uncommon on the Plains, but may occur in response to significant storm events or after a series of storms. Annual recharge rates have been estimated for a number of surficial aquifers. Render (1997) estimated an annual average recharge rate for the Assiniboine Delta Aquifer in Manitoba to be ~52 mm based on an analysis of streamflow records in a small sub-basin within the aquifer.

Most shallow aquifers in southern Manitoba experienced a gradual decline in groundwater levels through the 1970s and 1980s, followed by a gradual but consistent rise in groundwater levels starting in about 1991.

Surficial and alluvial aquifers provide water supplies for domestic/farm use and locally for towns, villages, irrigation and acreages. The yield of these aquifers varies, but in some circumstances, may exceed several hundreds of m^3/day and be suitable for irrigation and other high-production uses (see discussion of the Assiniboine Delta Aquifer below). Surficial sand and gravel aquifers that are connected hydraulically to surface water bodies (e.g., wells installed in alluvial aquifers) may potentially yield significant volumes of water. However, in these cases, the yield is largely derived from induced recharge from surface water and the aquifer merely performs a transfer function. The quality of the water in sand and gravel aquifers is normally excellent. Water is typically Ca/Mg-HCO_3 type with a TDS of less than 1,000 mg/L.

Across the Plains Region, there is a significant percentage of shallow, wide-diameter bored wells. Typically, these wells, commonly less than 30 metres deep, are completed in fractured tills or in thin sand and gravels seams that have a very limited extent within the till. Many of these wells are water table wells, although in areas with a significant downward or upward vertical gradient, the "static" water in these wells may be below or above the water table. The yield of these types of wells is typically low, but often sufficient for domestic use. The quality of the water is variable, but often poor because it is usually till water (i.e., high content of Ca, Mg and SO_4). These wells are susceptible to contamination from the ground surface and a significant percentage of them have high concentrations of nitrates.

10.3.2.2.1 Assiniboine Delta Aquifer

We are discussing the Assiniboine Delta Aquifer (ADA) in greater detail because it is the largest and most representative aquifer of its type within the region. The ADA is a 4,000 km^2 sand and gravel deposit laid down where the ancestral Assiniboine River flowed eastward into glacial Lake Agassiz (Render, 1988, Figure 10.28). The sands and

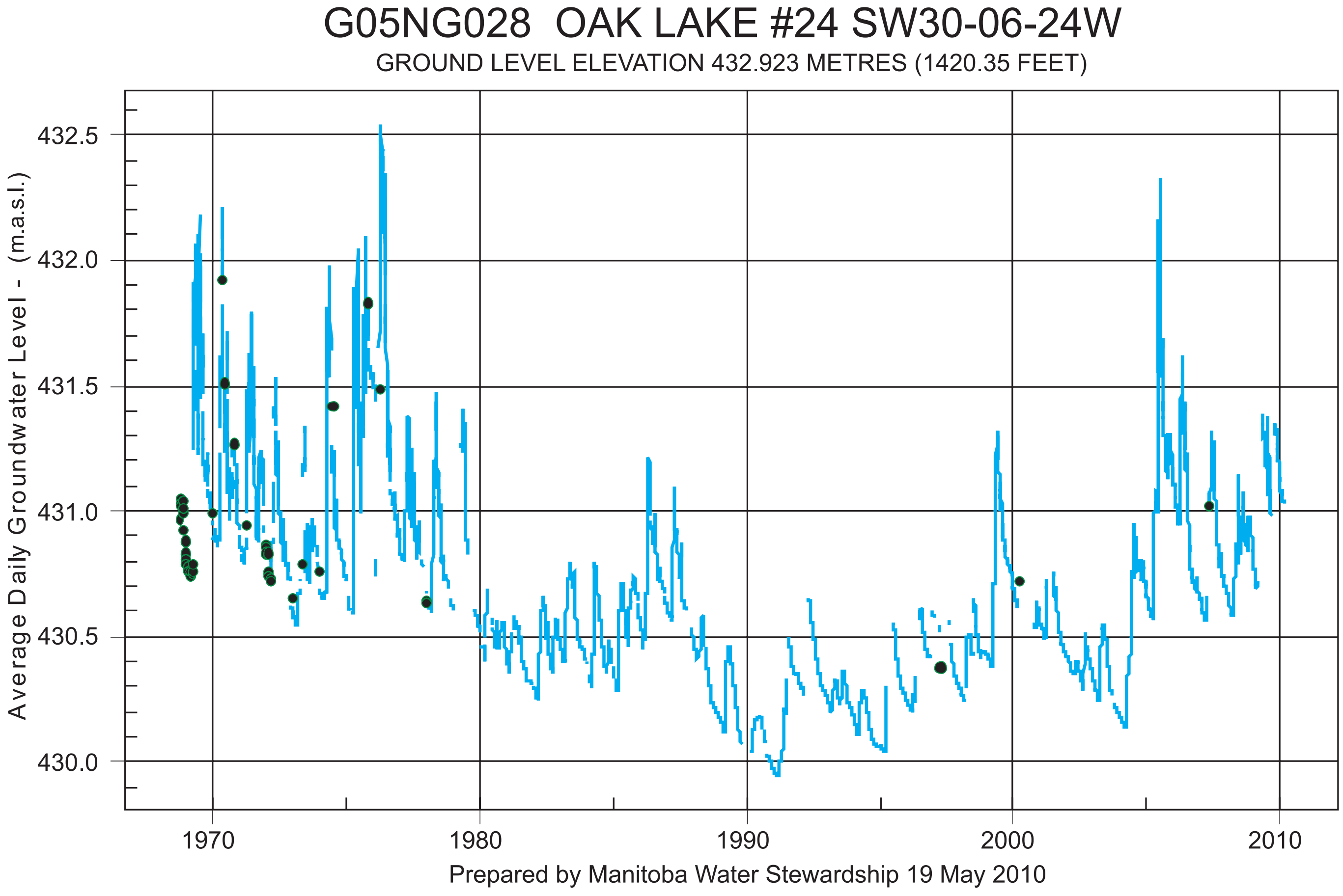


Figure 10.27 Hydrograph for a monitoring well unaffected by pumping in the shallow unconfined Oak Lake Aquifer of Southwestern Manitoba.

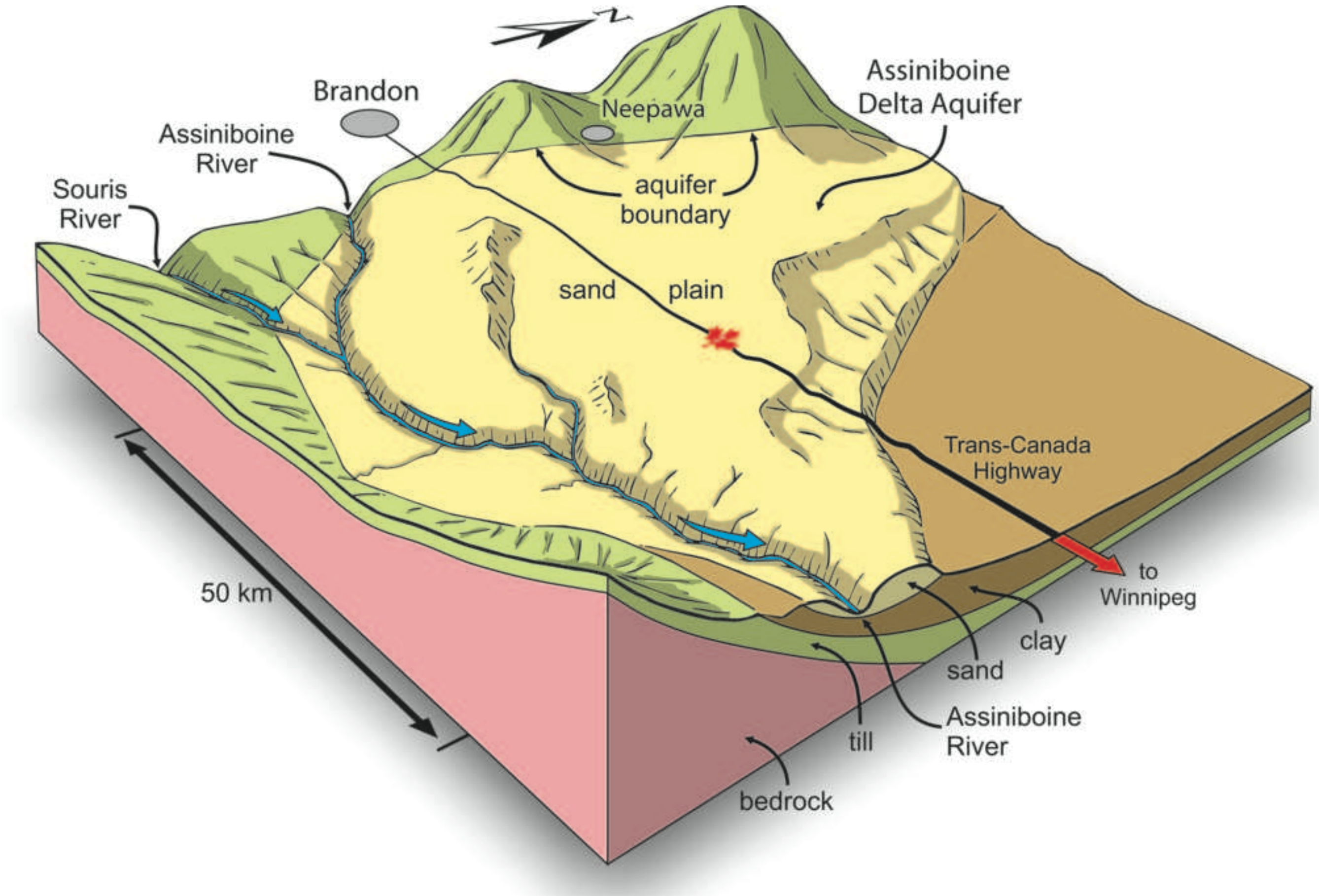


Figure 10.28 Block diagram of the Assiniboine Delta Aquifer.

gravels forming the aquifer are exposed at surface through most of its extent, but some parts are overlain by relatively thin clay deposits. The ADA averages about 18 m in thickness, but sometimes exceeds 30 m. Grain size varies from very fine sand to coarse gravel, with the coarser deposits generally found in the western part of the aquifer. In the Brandon area, there are very coarse gravel and boulder deposits which were left along the spillway of the ancestral Assiniboine River as it flowed toward Lake Agassiz. The aquifer is underlain by thick deposits of silt, clay and till. Regional-scale groundwater flow is generally directed toward the Assiniboine River, although smaller-scale flow systems discharge to a number of smaller creeks. Depth to the water table is quite variable and may be as much as 20 m or more beneath some areas of dune development.

Render (1988) summarized the available information on aquifer transmissivity. The transmissivity is greatest in the coarser deposits of the western parts of the aquifer, where values may exceed 1.43×10^{-2} m^2/s, it then declines toward the east and the aquifer's boundaries. These high transmissivities have allowed the development of high-capacity wells for irrigation use in parts of the aquifer. Storage coefficient values range from 0.0006 to 0.001, and specific yield values from 0.11 to 0.39.

Until the mid-1970s, the aquifer was used primarily for small towns, domestic and farm water supplies. Over the past few decades, however, there has been increased demand for groundwater withdrawals specifically for irrigation purposes. The aquifer is a major source of irrigation water supply for Manitoba's potato industry as well as a vital source of baseflow for the Assiniboine River. There are future plans for significant development to support the expansion of irrigation systems based on the aquifer and the extension of municipal water supplies to surrounding water-shortage areas.

In 1993, a well drilling program was implemented to allow further aquifer definition and instrumentation to a level suitable for detailed groundwater potentiometric surface mapping and measurement of hydrologic properties. Based on this work, the aquifer was divided into 13 subbasins in order to enable segmental assessment of groundwater and surface water hydrology: a detailed hydrologic budget was prepared. An extensive monitoring network has been developed within the ADA (rain gauges, snow accumulation, soil moisture, groundwater levels and creek flows). To date, management of the aquifer has provided sustainable development for domestic, municipal, agricultural, industrial and irrigation uses. The annual sustainable yield of the aquifer is estimated to be 1.34×10^8 m^3 of water. Slightly less than one-half of this amount (6.27×10^7 m^3) has been made available for non-domestic purposes. Of this latter amount, about 3.32×10^7 m^3 is currently licensed, mostly to persons using the water for irrigation purposes. About 7.13×10^7 m^3 has been reserved for domestic and environmental protection purposes.

Chemical water quality within the aquifer is generally good to excellent. TDS range typically between 200 mg/L and 500 mg/L, and are of a calcium-magnesium-bicarbonate type. Nitrate concentrations in the aquifer are variable and can be high. Nitrate-N findings in excess of the Canadian Drinking Water Quality (CDWQ) guideline of 10 mg/L are not uncommon, especially in shallower groundwater.

10.4 GROUNDWATER QUALITY

10.4.1 Major ion chemistry

Groundwater in the Plains Regions has significant variations in geochemistry. This is well demonstrated by springs in the region, which range from those with nearly pure fresh water to those with over 300,000 mg/L of total dissolved solids (TDS). Salinity within the sedimentary basin underlying the Plains Region increases progressively with depth, and in some of the deepest parts are in excess of 600,000 mg/L TDS. The amount of dissolved salts in groundwater is largely a function of the history of that water. The highly saline waters in the deep portions of the sedimentary basin are remnants of evaporating oceans (Connolly et al., 1990) 100s of millions of years old. Saline water has also formed where fresh water entering the basin through regional recharge systems encountered buried salt deposits at depth (Grasby et al., 2003; Grasby and Chen, 2005). This water is seen returning to the surface as brine springs in west-central Manitoba and Northern Alberta. Most potable groundwater within the region overlies these deeper brines, occurring at the near surface (<400 m).

Potable water across the Plains Region exhibits a broad range of chemistry and quality, as a function of the geology of the aquifers and their local environments. In south-central Manitoba, for example, groundwater in the carbonate aquifer is generally of excellent quality. However, dissolution of carbonate minerals within the aquifer through dedolimitization reactions generates Ca-Mg-rich hard water. Water within the underlying Winnipeg Formation sandstones, not in contact with carbonate minerals, is $Na\text{-}HCO_3$-dominated as a result of ion exchange processes (Ferguson et al., 2007).

Surficial sand aquifers are composed mainly of quartz with minor amounts of limestones, dolomites, and igneous and metamorphic rock fragments. Dominant geochemical processes in such aquifers are the generation of carbonic acid (H_2CO_3) within the soil zone, and the dissolution of limestones and dolomites. The result is calcium-, magnesium- or bicarbonate-dominated water with minor sodium and sulphate. The TDS in such water is low, often less than 1,000 mg/L.

The chemical evolution of the major ion chemistry of groundwater in tills has been the subject of many studies. In Saskatchewan, studies were carried out by Rutherford (1967), Rozkowski (1967), Davison and Vonhof (1978), Keller (1987), Keller et al. (1988, 1991), Mermut and Arshad (1987) and van Stempvoort et al. (1994). Relevant studies conducted elsewhere in glaciated prairie environments include those by Grisak et al. (1976), Wallick (1981), Groenewold et al. (1983), Hendry et al. (1986, 1989) and Grasby et al. (2010). These studies have determined that the chemical characteristics of water in fractured tills in the near subsurface, and thus the characteristics of the water quality in shallow confined aquifers, are formed in the unsaturated zone as a result of chemical processes active since the final deglaciation. Within the unsaturated zone, and to some extent at greater depth, chemical evolution occurs through (1) generation of organic and carbonic acids (H_2CO_3); (2) dissolution of carbonates, generating calcium, magnesium, and bicarbonate; (3) oxidation of reduced sulphur, generating hydrogen (H) and sulphate (SO_4); (4) dissolution of gypsum which produces calcium and sulphate; and (5) cation exchange, resulting in the loss of dissolved calcium and magnesium and the gain of dissolved sodium.

Keller's (1987) study of hydrochemical evolution within an 18 m thick fractured till at the Dalmeny site near Saskatoon revealed large differences in chemical evolution over lateral distances of tens of metres. Virtually all of the reduced sulphur in the first few metres of till beneath a slough in a depression at this site had been oxidized to sulphate. This sulphate was removed downward into the aquifer because of the concentrated downward flow beneath the slough. The water quality in the till beneath the slough was characterized by calcium-bicarbonate-type water with relatively low sulphate concentrations. In the non-depression areas, where the water table was relatively deep, all of the reduced sulphur had been oxidized, but because of the small vertical flow rate, the oxidized sulphur remained in the unsaturated zone as gypsum. Downward movement of sulphate-rich water and dissolution of gypsum will occur only after extreme infiltration events and perhaps under irrigation conditions. In such settings, water is calcium/magnesium-sulphate type and has high TDS (up to 5,000 mg/L). Keller (1987) attributes these lateral differences in chemical evolution to the high bulk hydraulic conductivity of the till at the Dalmeny site and the resulting groundwater flow regimes.

In settings where a thin fractured till overlies a thick-till aquitard with low bulk hydraulic conductivity, the main geochemical processes taking place in the thin fractured till are the same as listed above. However, since there is little downward flow, water in the thin till is characterized by high TDS (up to 15,000 mg/L) and high sulphate concentration (up to 10,000 mg/L).

Thick (> 25 m) unweathered and unfractured, near-surface tills contain pore water introduced during or shortly after glaciations. Hydrochemical processes within such till units are diffusion-dominated with negligible advection (e.g., Remenda et al., 1996; Shaw and Hendry, 1998; Hendry and

Wassenaar, 2000). These geochemical processes have been active since the Holocene, and were probably also active during interglacial periods between Pleistocene glaciations, as evidenced by buried weathering zones containing gypsum at the top of older till units.

In coal/lignite-bearing formations, such as the Judith River and the Ravenscrag Formations, sulphate reduction can also be an important process. Van Stempvoort et al. (2005) showed that bacterial sulphate reduction may play a role in bio-attenuation of fugitive natural gas in groundwater within the Plains Region. The reduction of nitrate by oxidation of organic matter (denitrification) within aquifers can also be important (e.g., Trudell et al., 1986).

Groundwater recharges through Laurentide till imparts SO_4-rich water chemistry to underlying bedrock aquifers (e.g., the Milk River Aquifer; Hendry and Schwartz, 1990). Similarly, the abrupt east-to-west transition from high- to low-sulphate groundwater in the Paskapoo Aquifer is coincident with the boundary of the overlying till, between igneous/metamorphic-dominated till derived from the east and the carbonate-dominated till derived from the Cordillera to the west (Grasby et al., 2010). This suggests that recharge through till plays a dominant role in setting the initial geochemical conditions of underlying bedrock aquifers.

10.4.2 Trace element concentrations

Locally, groundwater in the Plains contains naturally occurring concentrations of trace elements that exceed drinking water guidelines. Of particular concern are arsenic, boron, barium, fluoride, selenium and uranium because exceedances of these elements are more widely distributed than other trace elements. The following discussion is based primarily on recent compilations carried out in Manitoba (Betcher et al., 2003, and subsequent unpublished updates) and Saskatchewan (Maathuis, 2008). No similar regional presentations are known for Alberta.

Arsenic concentrations in excess of the current drinking water guideline (0.01 mg/L) are widely reported across both Saskatchewan and Manitoba. In Manitoba, elevated arsenic concentrations are commonly found in groundwater from confined inter- or intra-till sand/gravel aquifers where the confining tills developed from glacial movement over Cretaceous shale. Erickson (2005) reported a similar relationship between elevated arsenic concentrations in groundwater and the footprint of "Northwest Provenance" tills in the upper Midwest of the United States. Northwest Provenance tills are considered to have the Riding Mountain and Winnipeg areas as their provenance and have been found to contain "significant fractions of both carbonate and shale, and a large fraction of fine-grained material" coupled with organics entrained from periglacial forests.

In the Winkler aquifer, a sand and gravel body deposited along the eastern flank of the Manitoba Escarpment and overlain by lacustrine clay for most of its extent, elevated arsenic is found in groundwater from many municipal and private wells. Recent sampling has also identified elevated arsenic in the deeper (anoxic) groundwater of some unconfined sand aquifers in south-central and southwestern Manitoba. Arsenic speciation analysis has not been done. Arsenic concentrations greater than 0.01 mg/L are rarely found in samples from bedrock aquifers within the province. A number of municipalities have recently installed treatment facilities in order to facilitate arsenic removal to concentrations below the drinking water guideline.

In Saskatchewan, Maathuis (2008) has examined arsenic results reported from more than 4,300 wells. The average arsenic concentration was approximately 0.006 mg/L, with arsenic concentrations exceeding the current Canadian guideline of 0.010 mg/L in 14.9% of the samples. No correlation was reported between arsenic concentration and either well depth or aquifer type.

Boron is rarely found at concentrations above the current drinking water guideline (5 mg/L) in Manitoba, but elevated groundwater concentrations (>2.5 mg/L) are found in in parts of the Winnipeg and Swan River sandstones and in groundwater from some wells completed into the Odanah Shale aquifer. Higher boron concentrations are generally found in groundwater with elevated salinity. Boron concentrations also exceed 5 mg/L in groundwater from a number of wells in the Gypsumville area (Desbarats, 2009). The geology of this area is very unusual, with uplifted Precambrian basement, gypsum and red beds resulting from a meteorite impact (McCabe and Bannatyne, 1970) and from subsequent Jurassic deposition.

Maathuis (2008) reports an average boron concentration in groundwater samples from Saskatchewan to be 0.41 mg/L, with very few samples containing more than 5 mg/L.

Elevated barium concentrations are found in two distinct areas of Manitoba. In the southeastern part of the province, elevated barium concentrations are found in groundwater from the Winnipeg Aquifer along a distinct NW-SE trend about 15 km wide and running for about 30 km northwest of the subcrop area (Underwood et al., 2009). To the south of this zone, anomalously high barium concentrations are found in groundwater from wells installed in the Carbonate aquifer or wells installed as open hole-type across both the Carbonate and the Winnipeg Aquifers. Barium concentrations in excess of 10 mg/L have been found in these areas (the current Canadian drinking water guideline for barium is 1 mg/L). Barium solubility may be elevated as a result of very low sulphate concentrations in recharge waters or due to bacterial sulphate reduction (Underwood et al., 2009). Barium has also been found to exceed the drinking water guideline in some wells installed in the unconfined Assiniboine Delta Aquifer. Sulphate concentrations are typically very low in this aquifer, but localized zones of detrital coal within the aquifer matrix may also cause the development of both strongly reducing conditions, and further declines in sulphate concentrations.

In Saskatchewan, about 0.5% of the wells produce water with a barium concentration in excess of 1 mg/L with a maximum reported value of 1.9 mg/L. No relationship has been reported between barium concentration and aquifer type or geochemical controls that may result in lower sulphate concentrations.

Fluoride concentrations have been found to exceed the drinking water guideline value of 1.5 mg/L in groundwater from a number of bedrock aquifers in Manitoba, particularly the Winnipeg Aquifer in southeastern Manitoba and along the western shore of Lake Winnipeg, and the Swan River Aquifer near Porcupine Mountain. Elevated fluoride concentrations are associated with cation exchange reactions near fresh water–saline water boundaries or with mixed fresh and saline groundwater as found in the Interlake. Fluoride concentrations are also above drinking water guidelines in some wells within the Carbonate aquifer, particularly near the fresh water–saline water boundary on the eastern side of the south basin of Lake

Manitoba and to the west of Lake Winnipeg, and near Dauphin, where water quality in the aquifer is brackish. Fluoride concentrations exceeding 15 mg/L have been found locally in groundwater from granitic rocks of the Lac du Bonnet batholith in southeastern Manitoba (locally, concentrations may exceed 15 mg/L) and from the disturbed bedrock units found in the Gypsumville area, although the reason for this is disputed (Leybourne et al., 2008; Desbarats, 2009).

In Saskatchewan, elevated fluoride concentrations are found in groundwater from the Judith River Aquifer in the southwestern part of the province and also from Bearpaw sands in the Riverhurst area from the Gravelbourg Valley Aquifer. As in Manitoba, elevated fluoride concentrations are found in the Mannville Aquifer in northeastern Saskatchewan.

Uranium concentrations greater than the drinking water guideline of 0.02 mg/L are found locally in southern Manitoba. A study carried out by Betcher et al. (1988) examined the uranium content of groundwater in a portion of southeastern Manitoba east of Beausejour. An average uranium concentration of 115.6 µg/L was found in samples from wells completed into Precambrian rock aquifers (primarily the Lac du Bonnet batholith) with concentrations as high as 2,020 µg/L. Groundwater in a number of sand and gravel aquifers in the area were also found to contain elevated uranium concentrations where leaching of uraniferous water from overlying lacustrine clays was occurring. Uranium concentrations over the drinking water guideline have also been found in groundwater from the Winkler Aquifer (confined sand and gravel), the Odanah shale aquifer and in a few wells completed into the Carbonate aquifer.

Uranium concentrations in Saskatchewan average 0.011 mg/L with about 14.5% of samples containing more than the current Canadian guideline (0.020 mg/L). Maathuis reports that most elevated uranium is found in samples from wells completed to relatively shallow depth (<25 m), but he does not discuss which aquifers these represent.

Although elevated selenium concentrations have been reported in Saskatchewan, limited sampling in Manitoba has not revealed significant issues. In Saskatchewan, concentrations up to 0.58 mg/L have been reported with samples from 7.9% of wells exceeding current Canadian guidelines (0.01 mg/L). As with uranium, the higher selenium concentrations appear to be found primarily in shallow wells.

BOX 10-1 SALINE INTRUSION

Intrusion of saline water into freshwater-bearing aquifers is a common concern along coastal regions. Saltwater intrusion occurs naturally because of the higher density of saline water and it may become a serious issue in coastal regions where there are substantial freshwater withdrawals. Climate change can also introduce increasing intrusion problems because of rising sea levels and potential declines in fresh groundwater head.

Saltwater intrusion may also be a serious issue in aquifers lying far from the ocean where saline groundwater or brines occur within many aquifers adjacent to freshwater zones. An interesting example is found in south-central Manitoba's Winkler Aquifer. This sand and gravel aquifer lies adjacent to the Manitoba Escarpment and is highly confined by overlying lacustrine clays, except at its northern extent where the aquifer outcrops within an area of about 500 hectares. This outcrop area and adjacent regions of thin clay cover form the principle recharge areas for the aquifer. Render (1987) estimated the annual recharge rate to be approximately 416×10^3 m^3/year, although it is interesting to note that this recharge estimate was made at the end of a long period of groundwater decline.

Fresh groundwater is found in the upper part of the northern extent of the aquifer and is underlain by saline water. Test drilling has revealed that the aquifer may locally be in hydraulic connection with sandstones of the Swan River Formation, which, in this area, are occupied by saline groundwater containing total dissolved solids (TDS) of approximately 20,000 mg/L. The fresh water–saline water system is thus in a dynamic equilibrium between the volume of the aquifer occupied by fresh water and intrusion/extrusion of saline water with the Swan River sandstones.

Although the aquifer was developed as a source of freshwater, beginning in the late1800s, there was little intensive pumping, other than a cannery well in the City of Winkler, until the early 1960s, when the city began to develop the aquifer as a source of municipal water supply. Through the 1980s and early 1990s, the City installed 10 production wells, while additional production wells were installed by adjacent municipalities. By the mid-1990s, the estimated rate of fresh groundwater withdrawal was about $1070–1340\times10^3$ m^3/year, perhaps three times the average freshwater recharge rate (Phipps and Betcher, 2007). Groundwater levels in the aquifer were also observed to have declined through the mid-1970s into the early 1990s (Figure 10.29). Monitoring wells in the vicinity of pumping centres began to record increases in the salinity of deeper groundwater within the aquifer (Figure 10.30), raising concerns of salinization to the extent that the water quality would no longer be potable. Responses to this concern have included reducing the pumping rates in some of the higher-capacity wells, cycling of pumping among the various production wells serving the City of Winkler, and reduction or withdrawal of the amount of water allocated by water rights licences issued by the province. Current groundwater withdrawals (2007) are estimated to be less than 800×10^3 m^3/year, which is still about twice the estimated recharge rate to the aquifer.

Since the early 1990s, groundwater levels in the aquifer have risen and stabilized at an elevation near the levels observed during the early 1960s (prior to significant development). The trend of rising water levels is similar to what has been seen in confined aquifers in many other parts of Manitoba and reflects a return to a wetter climate than what

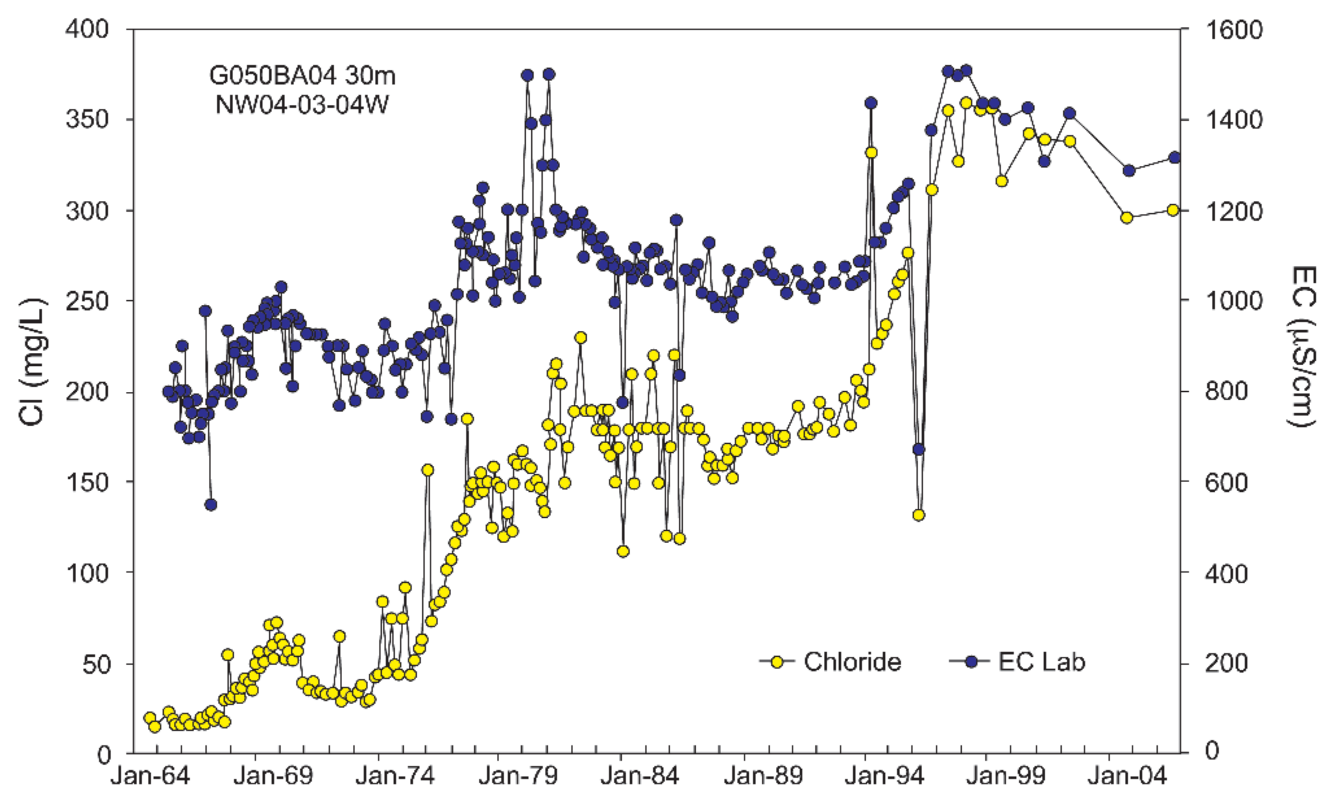


Figure 10.29 Chloride and conductivity for observation well G05OB004, 30 m depth, in the central portion of the Winkler Aquifer.

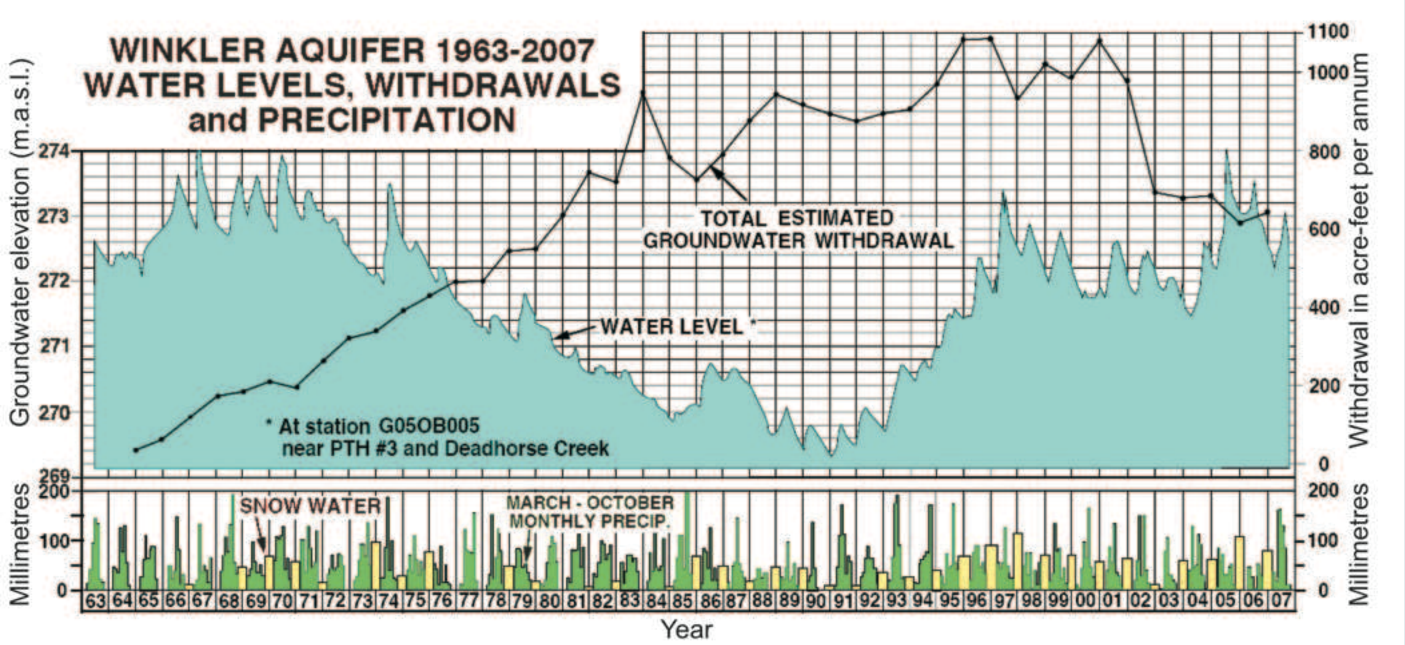


Figure 10.30 Groundwater levels in the Winkler Aquifer for the period 1963 to 2007. Estimates of withdrawal rates from the aquifer and precipitation are also shown.

was experienced during the 1980s. While groundwater withdrawals have been reduced and aquifer levels have risen, the salinity increases observed over the past 35 years have only stabilized, indicating the need for intensive management of the aquifer in order to minimize further salinization.

BOX 10-2 THE ESTEVAN VALLEY AQUIFER SYSTEM—A LONG-TERM CASE STUDY OF THE BEHAVIOUR OF BURIED-VALLEY AQUIFERS

The Estevan Valley Aquifer System is unique in that it has been the subject of groundwater resource evaluations for over four decades. It is a major preglacial buried-valley aquifer in southeastern Saskatchewan (Figure 10.31). The system consists of the preglacial Yellowstone, Missouri and "Northwest" channels. In the vicinity of the City of Weyburn, the Northwest Channel is referred to as the Weyburn Valley channel. The extension of the preglacial Missouri and Yellowstone River valleys into Saskatchewan was speculated on as early as the 1910s (Beekly, 1912; Bauer, 1915). Meneley et al. (1957), using oil, coal and water well information, prepared a bedrock topography map for the Weyburn-Estevan area. This map defined the location of the preglacial Missouri, Yellowstone and Estevan River valleys in southeastern Saskatchewan.

The preglacial valleys were incised into low-permeability bedrock siltstones and sandstones formed by the Eastend to Ravenscrag Formations, and locally into the siltstones and mudstones of the Pierre Shale. They were filled with predominantly coarse-grained sediments of the Empress Group, up to 80 m thick. Over most of its extent, the aquifer consists of a lower and upper unit, separated by a clay and silt layer. It is overlain by a 60 m–80 m thick aquitard composed mainly of clay-rich

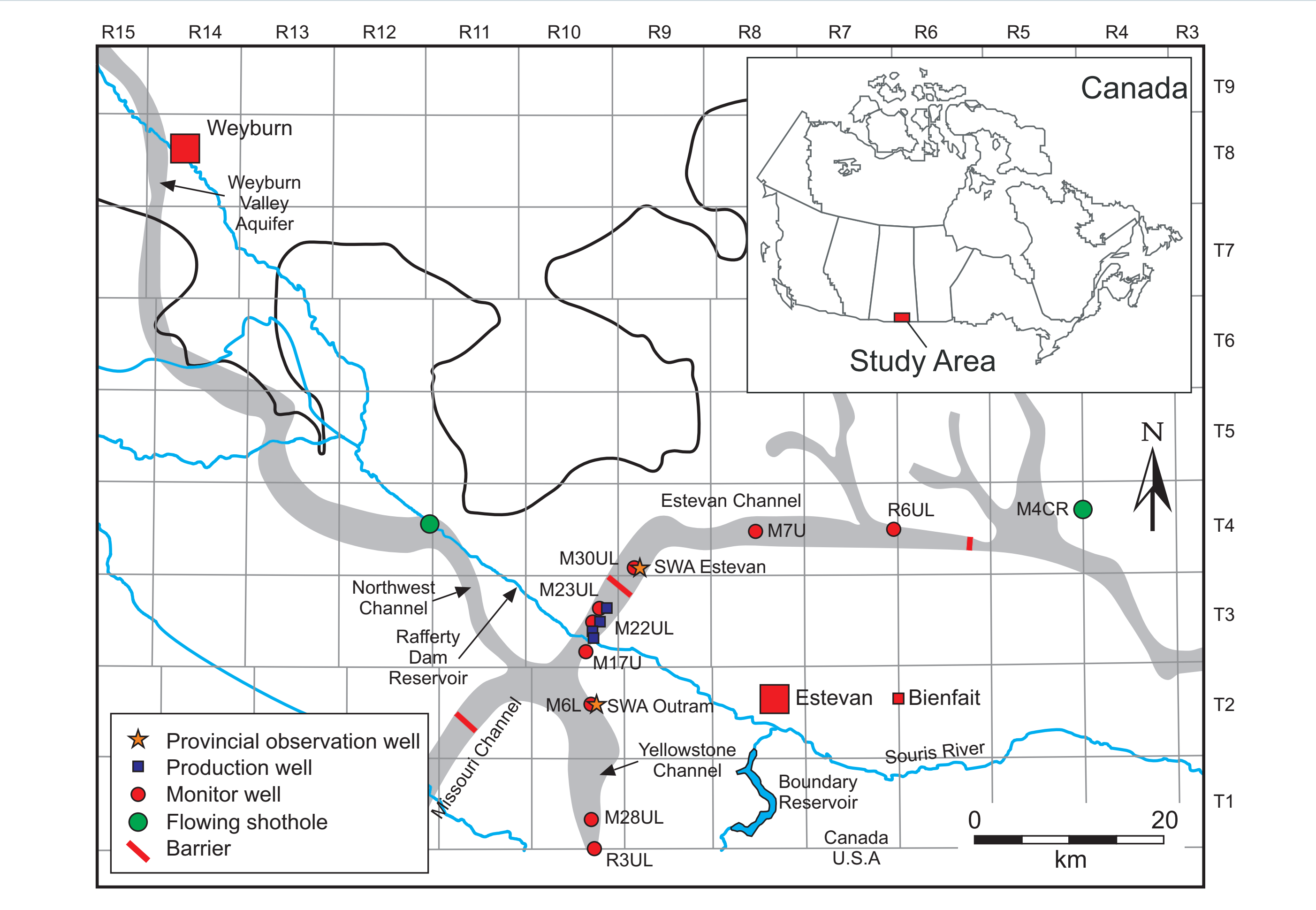


Figure 10.31 The Estevan Valley Aquifer System in southeastern Saskatchewan.

till. Within Saskatchewan, the aquifer is at least 70 km long and up to 4 km wide. It extends well into northwestern North Dakota and northeastern Montana, making it a transboundary aquifer.

The first major study was done in the mid-1960s as part of the search for a groundwater supply source for a proposed heavy water plant in the Estevan area. This study involved the drilling of a production well and observation wells, the conducting of a seven-day pumping test and the construction of an electrical analog model. Walton (1970) documented the study in his book.

The Midale flowing shothole (NE16-24-4-12-W2) was a significant hydrogeological event documented by Meneley and Whitaker (1970). This shothole was drilled into the Estevan Valley Aquifer System on November 20, 1965, and water flowed until May 20, 1966, when the hole was plugged. The drawdown caused by the flow and the subsequent slow recovery affected water levels over large distances and provided the first indication of the peculiar behaviour of water levels in stressed buried-valley aquifers.

In 1959, the Boundary Dam power plant, located about 6.5 km south of the City of Estevan, was commissioned. The cooling water supply for the plant comes from the Boundary Dam reservoir. It became evident during the early 1980s that consumption demands on the Boundary Dam Reservoir were such that only short periods of below-normal water flow could be tolerated. Lacking an alternative source of surface water (water from the Rafferty Dam and other reservoirs was not available at the time), a groundwater source had to be found. A large number of studies, including testhole drilling and pump tests, led to the development of a well field and the establishment of a large network of observation wells. The well field consisting of four production wells installed in the Estevan Valley Aquifer is located in the area between observation wells M22UL and M23UL (see Figure 10.31).

From September 16, 1988, until May 24, 1994, a total of 21,338 dam^3 (1 dam^3 = 1,000 m^3) was pumped, corresponding to an average annual pumping rate of 3,750 dam^3/year (about 118 L/s). Near the end of pumping, the observed drawdowns in the well field were in the 45 m to 50 m range and were very close to the top of the aquifer. If pumping had continued, the water level in the aquifer would have dropped below the top of the aquifer and the pumping rate of 3,750 dam^3/year would have been unsustainable. At the Canada-USA border, 23 km away from the centre of the well field, the drawdown was 20 m.

The development of the drawdown cone is shown in Figure 10.32 in the form of a longitudinal profile through the Yellowstone and Estevan channels (R3UL, M28UL, M17UL, M22UL, M23UL, M30UL, M7U and R6UL; see Figure 10.31 for locations).

Figure 10.32 shows the development of large drawdowns (up to 45 m) in the centre of the well field (M22UL). The development of a large hydraulic gradient between M22/23UL and M30UL, because of the presence of a blockage, can be observed, as well as the development of a strong lateral gradient in the Yellowstone channel from the border to the centre of the well field. A systematic and virtually equal amount of additional drawdown along the entire length of the aquifer during the May 1990–September 1992 period occurred, followed by a partial recovery of water levels in the centre of the well field in October 1993, owing to a decreasing pumping rate, coupled with a continuation of drawdowns at distances further from the pumping centre.

The recovery of water levels, depicted in Figure

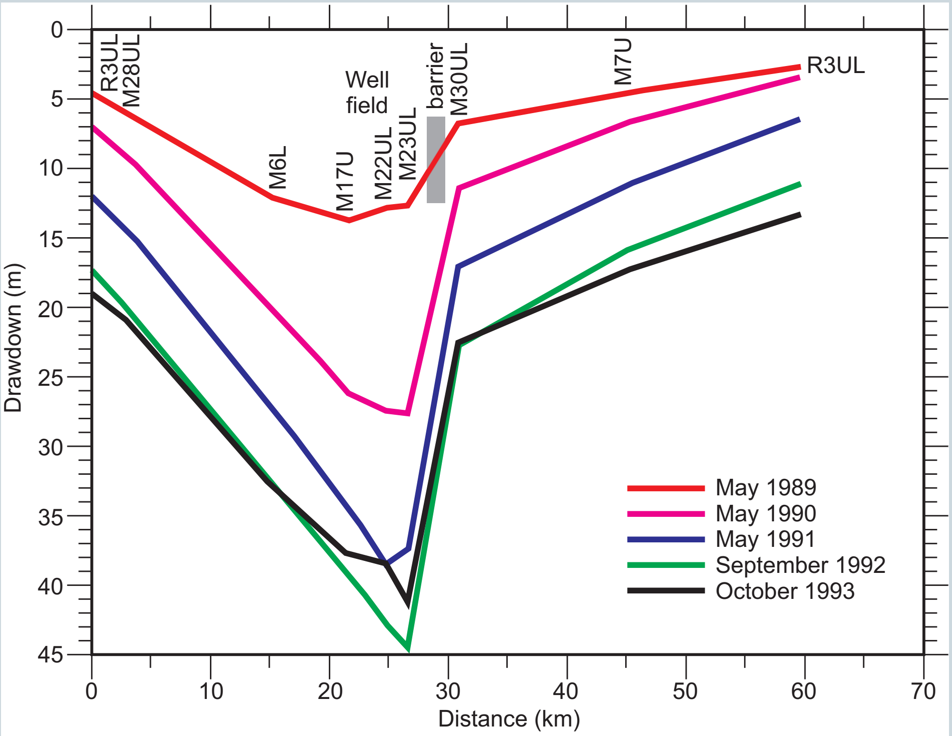


Figure 10.32 Development of the drawdown cone in the Estevan Valley Aquifer.

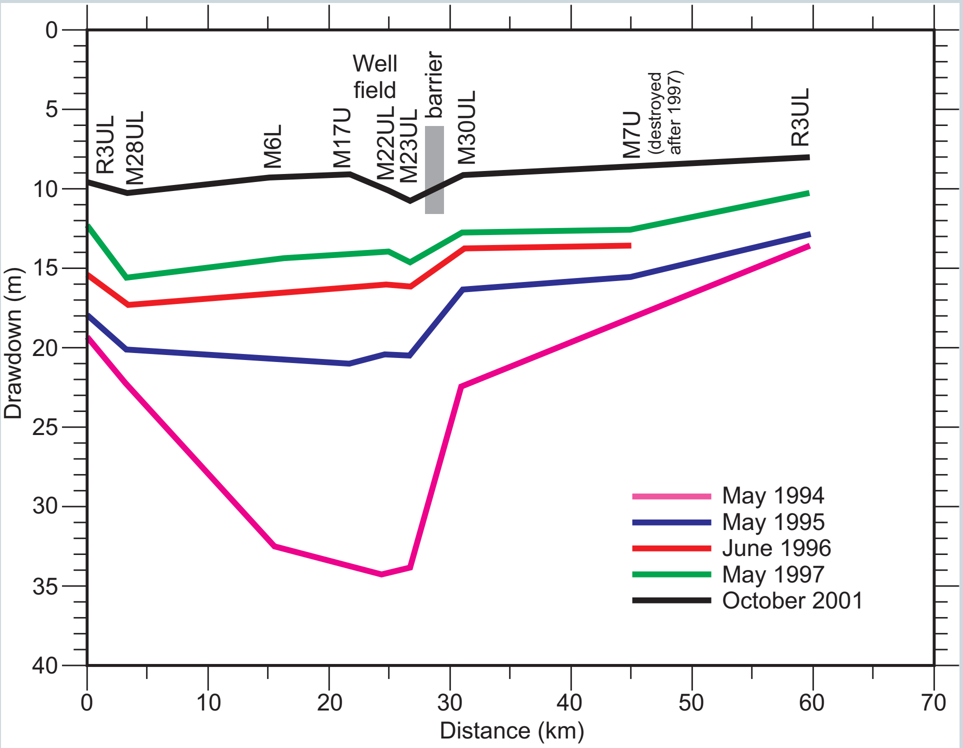


Figure 10.33 Residual drawdowns in the Estevan Valley Aquifer after pumping stopped.

10.33 as residual drawdowns, shows a rapid infilling of the drawdown cone in the well field during the first few years after pumping ceased: this was caused by lateral flow toward the centre. Subsequently, there was a general flattening-out of the water levels with similar amounts of residual drawdowns throughout the entire aquifer.

In 2007, 13 years after pumping stopped, the residual drawdown in the aquifer is still in the 6 m–8 m range, as illustrated in Figure 10.34 (which shows the long-term hydrographs for provincial observation wells SWA Estevan and Outram).

The slow recovery of the water levels merely indicates that recharge to the Estevan Valley Aquifer is small, only a few millimetres per year. As the rate of recovery decreases over time, complete recovery cannot be expected to occur for some considerable time to come.

Over the decades, various estimates have been made of the safe or sustainable yield of these aquifers (Maathuis and van der Kamp, 2003). These estimates were based on the results of an analog model (Walton, 1965, 1970), on image well theory (Meneley 1972; Puodziunas, 1977), on numerical modelling (van der Kamp, 1985) and on analyses of actual performance (Van Stempvoort and Simpson, 1994; Maathuis and van der Kamp, 1989 and 1998). Sustainable yield estimates ranged from 20,000 dam^3/year during the 1970s to 2,400–2,800 dam^3/year in 1998. The estimates decreased as more actual performance data became available.

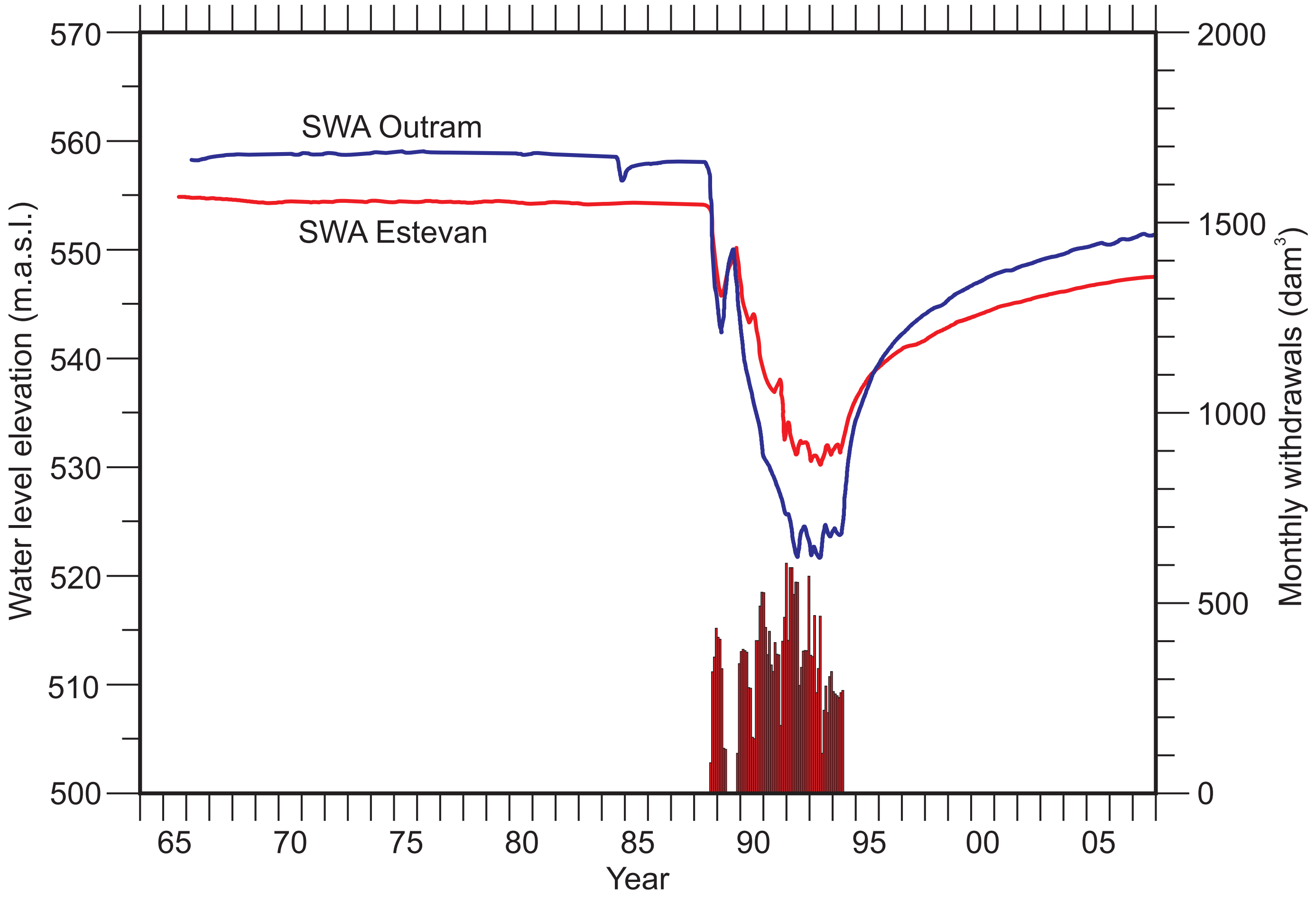
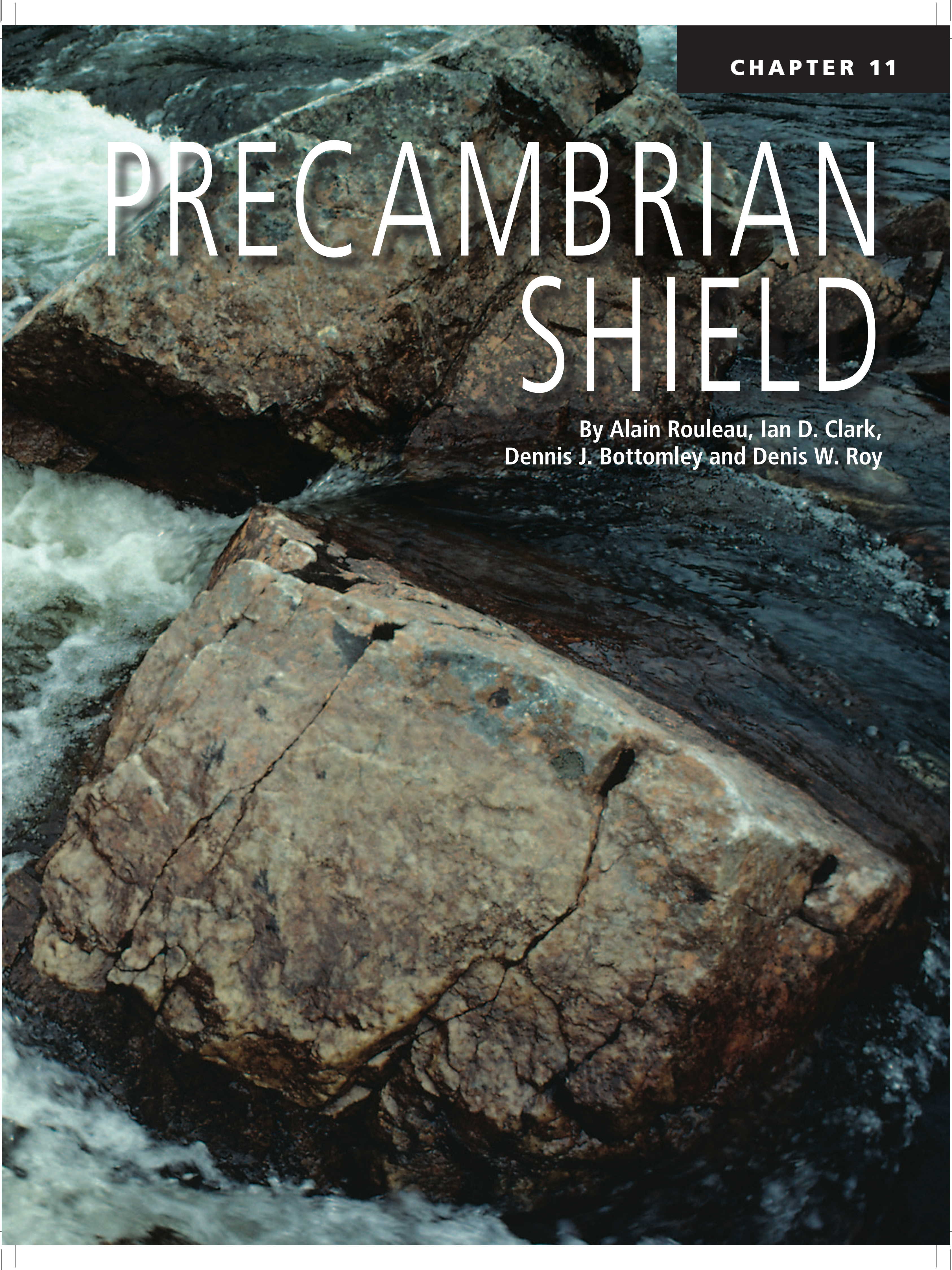


Figure 10.34 Hydrographs for SWA Estevan and Outram observation wells and pumping history from the Estevan Valley Aquifer.

The lessons learned from the Estevan Valley Aquifer case show that buried-valley aquifers have limited safe yields and can only be pumped at high rates for short periods of time. Furthermore, drawdown will extend over tens of kilometres and recovery will take a very long time (up to decades). This case has also demonstrated that realistic sustainable yields can only be determined when long-term water level and pumping records are available, a fact which applies to all types of aquifers.

PRECAMBRIAN SHIELD

By Alain Rouleau, Ian D. Clark,
Dennis J. Bottomley and Denis W. Roy



11.1 INTRODUCTION

11.1.1 Physiography

The Precambrian Shield region extends from the Northwest Territories to Labrador, across northern Saskatchewan, and constitutes most of the surface area of Manitoba, Ontario and Québec. The general physiography of this region is that of a peneplain at an elevation typically ranging from 500 to 1,000 m. This region has been subjected to many erosional cycles following the Precambrian orogenies. It is underlain almost entirely by Precambrian igneous and metamorphic bedrock and minor areas of sedimentary rock. The bedrock is typically covered by thin layers of glacial and post-glacial sediments.

11.1.2 Population

Most of the largest cities in Manitoba (Winnipeg), Ontario (Toronto and Ottawa) and Quebec (Montreal and Quebec City) are located immediately south of the Shield region. Nevertheless, major population centres are located within the southern part of the Shield, including Sault-St-Marie, Timmins, Sudbury, Rouyn-Noranda, Gatineau, and Saguenay. Mining and forest-based industries, particularly lumbering and paper-making, constitute important groups whose economic activities are scattered over many areas of the Shield. Hydroelectric power generation is also important in some areas, as well as some industries requiring high energy input such as aluminium manufacturing in Quebec's Saguenay region. Tourism, as well as agriculture in lowland areas, are other important activities in a number of areas of the region.

11.1.3 Climate and hydrography

Canada's Shield region includes a large surface area embracing 6 of the 15 different ecozones set out in the Ecological Framework for Canada (Environment Canada, 2005): these are the Boreal Shield, the Hudson Plains, the Taiga Shield, the Southern Arctic, the Northern Arctic, and the Arctic Cordillera. The last three ecozones are located in the Arctic and are discussed in Chapter 15 as the permafrost groundwater region. The Boreal Shield ecozone is further described in Urquizo et al. (2000), including its ecological and the socioeconomic settings. These ecozones are further subdivided in a number of ecoregions. The portion of the Shield region covered in this chapter experiences a moderate moisture regime; with precipitation and temperature decreasing significantly from south to north. At a given latitude, temperatures are lower near and across Hudson Bay. The northern half of the region is underlain by a sporadic or discontinuous superficial layer of permafrost.

11.1.4 Groundwater and human activities

Even in the most populated areas, groundwater is not used in large quantities because of the wide availability of surface water (i.e., lakes and streams). Groundwater is mostly drawn from permeable glacial and proglacial deposits, and is used by municipalities and industries. Mine drainage constitutes the main groundwater withdrawal from the crystalline basement formations in the Canadian Shield (Rouleau et al., 1999). As a result, mine drainage creates the characteristic hydrogeological problem in the bedrock basement formations of the Shield (Charron, 1967; Brown, 1970). The problem of radioactive waste disposal has also motivated a number of hydrogeological studies, particularly in Manitoba and Ontario's plutonic rocks (Farvolden et al., 1988).

Prior to about 1980, few detailed investigations had been conducted into the hydrogeology and geochemistry of groundwaters in crystalline rocks of the Canadian Shield. Most information on groundwater in the Shield is found in water-well records on file with the provincial Ministry of the Environment or the Ministry of Natural Resources, various consultants' reports on groundwater potential for communal or private wells (for potential rural residential subdivisions or light industry, for instance), and occasional reports on groundwater quality of inflows at various mine sites. This situation began to change dramatically in the late 1970s when Atomic Energy of Canada Ltd. (AECL) became interested in the Shield as a potential geologic repository for the subsurface disposal of fuel waste from nuclear power generating stations, waste that is presently being stored on surface. At that time, however, little information was available on the hydrogeological suitability of the Shield for the storage of such material. AECL established research sites at its nuclear facilities at Whiteshell in southeastern Manitoba, and at Chalk River in eastern Ontario. It also set up sites near the community of Atikokan in northwestern Ontario, and at East Bull Lake in central Ontario (35 km east of Elliot Lake). Furthermore, AECL constructed an underground research laboratory at a depth of about 400 m at the Whiteshell site. The lab was constructed to collect more detailed information on the subsurface conditions than data provided from borehole drilling and geophysical testing on the surface. AECL also supported various studies into the collection of information on the hydrogeological conditions at several operating mines on the Shield. This type of work was also done by the Canadian Nuclear Safety Commission in order to independently verify the geologic safety of AECL's disposal concept.

11.2 GEOLOGY

Compilations of the geology of Canada's Precambrian Shield have been provided by Lucas and St-Onge (1998), and by Thurston et al. (1991) for Ontario, and Hocq (1994a) for Quebec. A comprehensive thematic review of Precambrian research over the World is presented in Eriksson et al. (2004); the work includes many papers discussing parts of the Canadian Shield.

11.2.1 Bedrock geological provinces

The Canadian Shield is subdivided into geological provinces according to deformation style and age (Stockwell, 1962), a subdivision which has been reinterpreted in a plate tectonic framework by Hoffman (1988, 1989; Figure 11.1). Every province generally comprises belts of stratified or banded rocks that have been metamorphosed and deformed to various degrees, as well as bodies of intrusive and highly metamorphosed rocks. Most provinces of the Canadian Shield host *greenstone belts* composed of volcano-sedimentary rocks that have been submitted to many deformation phases and are metamorphosed to the greenschist facies (and lower amphibolite facies). These belts are normally bounded by intrusive bodies, mainly granitic in composition, and various types of gneisses. Minor amounts of alcaline rocks, including carbonatites, occur throughout the Shield. The two principal geological provinces south of the discontinuous permafrost line are Superior (Archean in age) and Grenville (Middle Proterozoic in age) Provinces (Figure 11.2). The former provides a good example of the distribution of greenstone belts within an Archean Province, while the latter, being the youngest in the Canadian Shield, may herald the present-day mountain ranges with deep crustal roots in the Earth mantle.

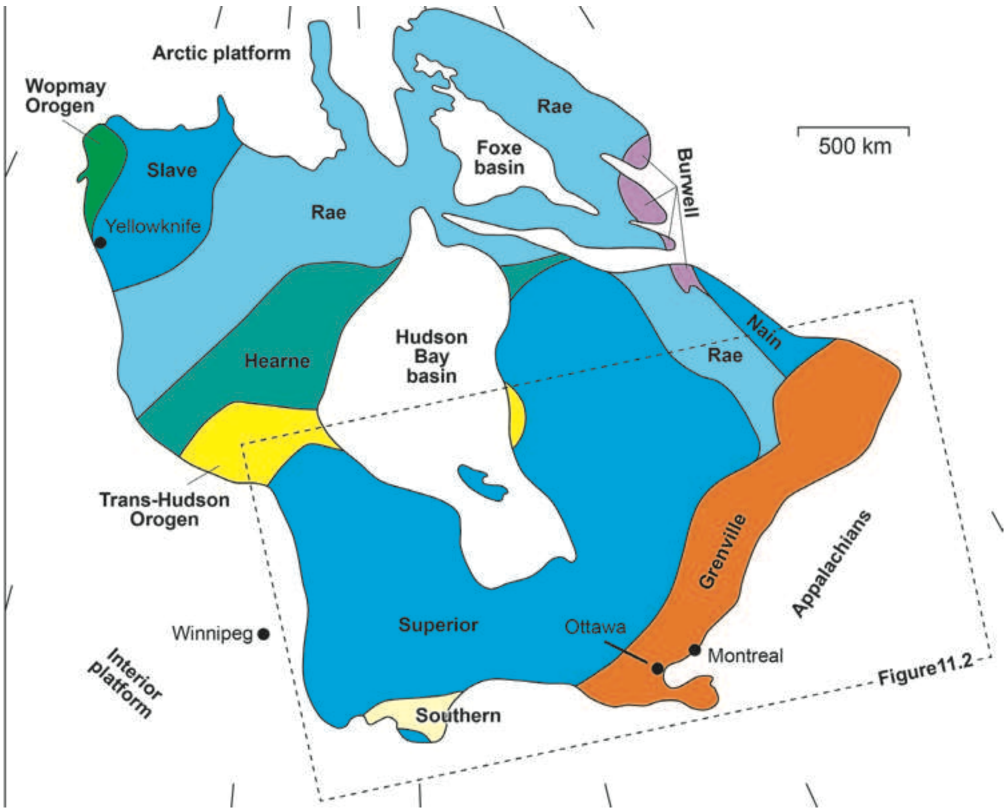


Figure 11.1 Schematic pre-drift restoration of the principal geological provinces of the Canadian Shield (adapted from Hoffman, 1989).

The Superior Province is Late Archean in age (2.85 to 2.5 Ga) and occupies the central part of the Canadian Shield (Hocq, 1994b; Card and Poulsen, 1998). This geological province is further divided into sub-provinces based on various contrasts concerning rock type, metamorphism, structure and age (Card, 1990; Figure 11.2). Numerous metal mines (Cu, Zn, Ni, Fe, Ag, Au) are located within the Superior Province, particularly in the Abitibi Subprovince (Hocq and Verpaelst, 1994). Most of these mines contain gold-bearing quartz veins or volcanic massive sulphides deposits (Chartrand, 1994).

The Grenville Province (Rivers et al., 1989; Easton, 1992; Hocq, 1994c; Davidson, 1998) is the latest Precambrian geological province accreted to the Canadian Shield, in its southeastern part (Figure 11.2). The surface of this geological province features highly deformed rocks that were metamorphosed (upper amphibolite and granulite facies) at more than 25 km deep in the crust. They were first intruded by large quantities of magmatic rocks (such as the anorthosite and charnockite suite) that crystallized under high temperature, and secondly by late grenvillian granites.

Subhorizontal layers of sedimentary rock, Paleozoic and Mesozoic in age, cover the Canadian Shield platform on its border, e.g., the St. Lawrence and Hudson Bay Lowlands, and the Interior platform to the west. Metamorphic and plutonic bedrock within the Canadian Shield itself is covered unconformably in places by subhorizontal outliers of sedimentary rocks. These are remnants of stratigraphic units of a much larger extent which have been deposited unconformably over the crystalline bedrock during a number of distinct episodes of sea invasion during the Proterozoic and Paleozoic eras. Proterozoic sedimentary rock includes the Cobalt Group (part of the Huronian Supergroup; Bennet et al., 1991) in the Lake Timiskaming area, as well as the Otish and the Mistassini Basins, all in the southeast side of the Abitibi Subprovince (Hocq, 1994b). Paleozoic rock outliers are found within the tectonic depression of the Saguenay graben (Avramchev, 1993; Desbiens and Lespérance, 1988), as well as in the Lake Timiskaming area on top of the Huronian Supergroup (Johnson et al., 1992), and in most parts of the Hudson Bay Basin.

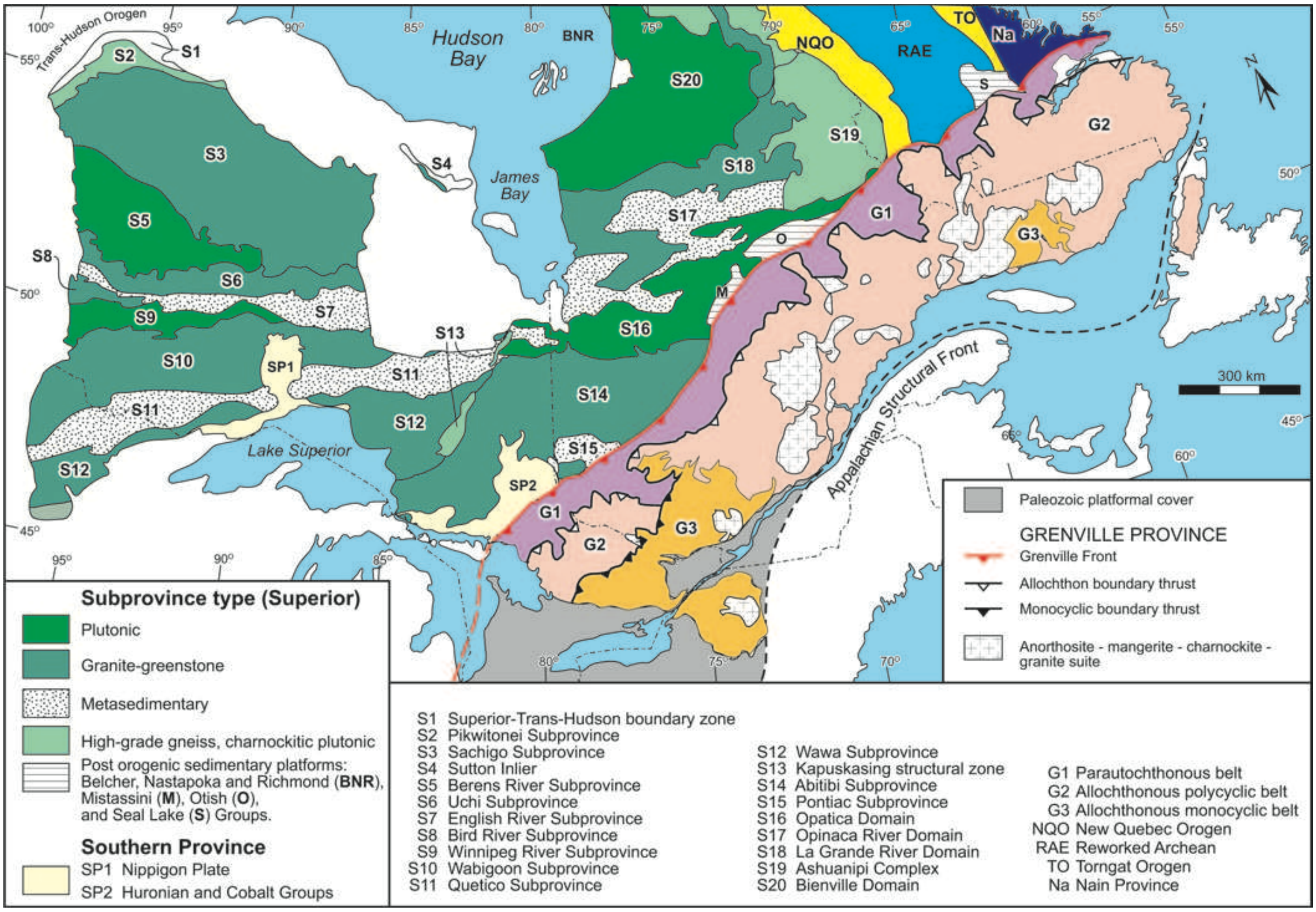


Figure 11.2 The Grenville and the Superior geological Provinces and their subdivisions based on structure, lithology, and metamorphism (adapted from Card and Poulsen, 1998; Rivers et al. 1989).

11.2.2 Quaternary deposits

The bedrock here is covered in most parts by Quaternary sediments. Quaternary overburden deposits over most of the Canadian Shield, except along stream and river valleys, are generally relatively thin and often absent. Moreover, where present, the overburden is predominantly glacial till which is typically too low in permeability to be a potential aquifer for a municipal water supply. Glacial and proglacial deposits also include moraines and eskers, as well as fluvial deposits and sediments left by glacial lakes or post-glacial seas. Extensive glaciofluvial sand and gravel deposits are present in some areas of Quebec and northern Ontario. More recent deposits include alluvia and organic sediments (peat) in wetlands (Vincent, 1989).

As described by Roy et al. (2006), eskers could be located in flat-lying uplands, such as in Abitibi (Veillette, 1986) and the Larder Lake area, but also in valley bottoms, as along the Peribonka River, which drains into Lake Saint-Jean (LaSalle and Tremblay, 1978)

Large outwash deposits are found at many locations in the southern margin of the Precambrian Shield. Deltaic systems have been formed by rivers that discharged to seas that invaded parts of the southern margin of the Shield at the end of the last glaciations. These seas include the Champlain Sea in the St. Lawrence Lowlands, and the Laflamme Sea in the Saguenay-Lake-Saint-Jean area.

11.3 HYDROGEOLOGICAL CONTEXTS

Simard and Des Rosiers (1979) have subdivided the

Precambrian Shield in southern Quebec into four hydrogeological units, mostly based on geographical location and geology, but also on the specific capacity of wells estimated from the *Système d'information hydrogéologique* (SIH) database (MDDEP, 2006). Table 11.1 summarizes water well data from the Precambrian bedrock; the statistics on well depth, yield and specific capacity are estimated for a total of 708 wells from the SIH data base, whereas the groundwater quality is based on a total of 20 water samples from as many wells. All of these hydrogeological units are qualified as low-permeability by Simard and Des Rosiers (1979), since the water wells generally yield less than 2.7m^3/hr. The statistics on well yield shown in Table 11.1 are biased toward high values because of the presence of overlying permeable granular deposits frequently encountered in valleys.

Many different hydrogeological units have been defined by Roy et al. (2006) for the southern part of Quebec, including the Precambrian Shield area, both for the bedrock and for the surficial unconsolidated deposits. Many of these units are applicable to the overall extent of the Shield. For the bedrock in the Precambrian Shield, Roy et al. (2006) have defined three other types of possible hydrogeological unit (types E, F, and G), in addition to those mentioned in Table 11.1 (types A, B, C, and D). Type E corresponds to faults or fault zones that are present at numerous locations in the Precambrian Shield. These zones are often expressed at surface by linear topographic depressions and lineaments; and they are often characterized by a high fracture density and increased permeability. Moreover, permeable granular deposits are often present in the bottom of valleys corresponding to fault zones. Many authors (Simard and Des Rosiers, 1979; Sylvestre, 1981; McCormack, 1983) have suggested that the presence of these deposits induces a better groundwater recharge and contributes to a higher yield of wells in valleys, even those wells in the fractured bedrock.

Mapping of faults and fault zones has been carried out mostly as part of tectonic studies. Card and Poulsen (1998) presented a map showing many of the major fault zones in the Superior Province. A map in DuBerger et al. (1991) depicts many lineaments in a large portion of the Grenville Province surrounding the epicentre of the Saguenay 1988 earthquake. A number of examples of lineament

TABLE 11.1 CHARACTERISTICS OF WATER WELLS IN THE PRECAMBRIAN BEDROCK IN SOUTHERN QUEBEC GROUPED IN FOUR HYDROGEOLOGICAL UNITS (AFTER SIMARD AND DES ROSIERS, 1979)

GEOGRAPHIC AREA	TIMISKAMING	ABITIBI	SAGUENAY-LAKE-SAINT-JEAN	ELSEWHERE
Hydrogeological unit	A	B	C	D
Rock types	Metasedimentary	Metavolcanic Metasedimentary Acidic intrusive	Anorthosite Acidic intrusive	Acidic intrusive gneiss
Number of wells	48	267	41	352
Mean yield (m^3/hr):	5.4	5.9	2.8	4.1
Mean depth (m)	67	69	62	39
Mean specific capacity (m^3/hr/m)	0.278	0.343	0.123	0.326

analysis, using remote sensing over the Canadian Shield, are discussed in Short (2002). Roy et al. (2006) have compiled data for many set of large structural discontinuities in the Precambrian Shield (including dyke swarms and faults) with their age and orientation. Not all lineaments, however, correspond to structures that are efficient groundwater conduits. A study by Gleeson and Novakowski (2009) in the Tay River watershed in southern Ontario suggests that structures corresponding to lineaments often act as watershed-scale hydraulic barriers. The low-gradient Tay River flows over exposed and fractured bedrock of the Grenville Province or a thin veneer of coarse-grained sediments; groundwater discharge rates to the river are low, indicating that the groundwater and surface water system may be largely decoupled in this watershed when compared to watersheds underlain by porous media (Gleeson et al., 2009).

The type F of Roy et al. (2006) corresponds to metamorphosed Proterozoic carbonate rock units found in many places in the Precambrian Shield, e.g., southwest part of the Grenville Province. Karstic networks have developed in places within these marble and crystalline carbonate units, creating highly permeable flow channels. Finally the type G hydrogeological unit defined by Roy et al. (2006) corresponds to remnants of a subhorizontal platform cover of sedimentary rock.

11.3.1 Context 1: Greenstone belts, metasedimentary, gneissic and intrusive crystalline rock (most of the Shield)

The hydrogeological units of types B, C, D, E and F defined above are included within the hydrogeological context 1 (Figure 11.3) described in this section.

Greenstone belts, gneissic basement and plutons are comprised of plutonic and metamorphic rocks often termed crystalline rocks. An important characteristic of crystalline rocks is their relatively low primary porosity and rock matrix permeability, except where weathered (Trainer, 1987). These rocks, unless fractured, commonly yield only a small supply of water to wells. The hydrogeology of crystalline rocks in the Canadian Shield is known mostly at mining sites and hydroelectric power plants, and at a few sites where field research has been conducted in relation to radioactive waste storage.

Studies conducted at these sites indicate that the rock is fractured more or less extensively, with fracture spacing ranging from metres to tens of metres or more (e.g., Raven 1986; Raven and Gale, 1986; Stevenson et al., 1996, among others). If the fractures are connected within a network, then this connectivity will allow groundwater circulation even though the rock matrix has very low permeability.

Although groundwater flow in Shield bedrock is highly restricted, fracture permeability can represent an important aquifer for rural water supply. The Quaternary aquifers at the AECL Chalk River Laboratories (CRL) in Eastern Ontario are underlain by granitic gneiss doming the 1.4 Ga Algonquin Batholith in the Central Gneiss belt of the Grenville Province. Here, regional bedrock relief is on the order of 100 m. Raven (1986) demonstrated a highly complex and non-homogeneous fracture network in the upper 100 m with bulk vertical hydraulic conductivities up to 4.4×10^{-5} m/s, and over 100 times greater than the radial hydraulic conductivity.

Many authors have observed that the degree of fracturing generally decreases with depth from surface. In most geological settings, including the Precambrian Shield, this decrease occurs in parallel

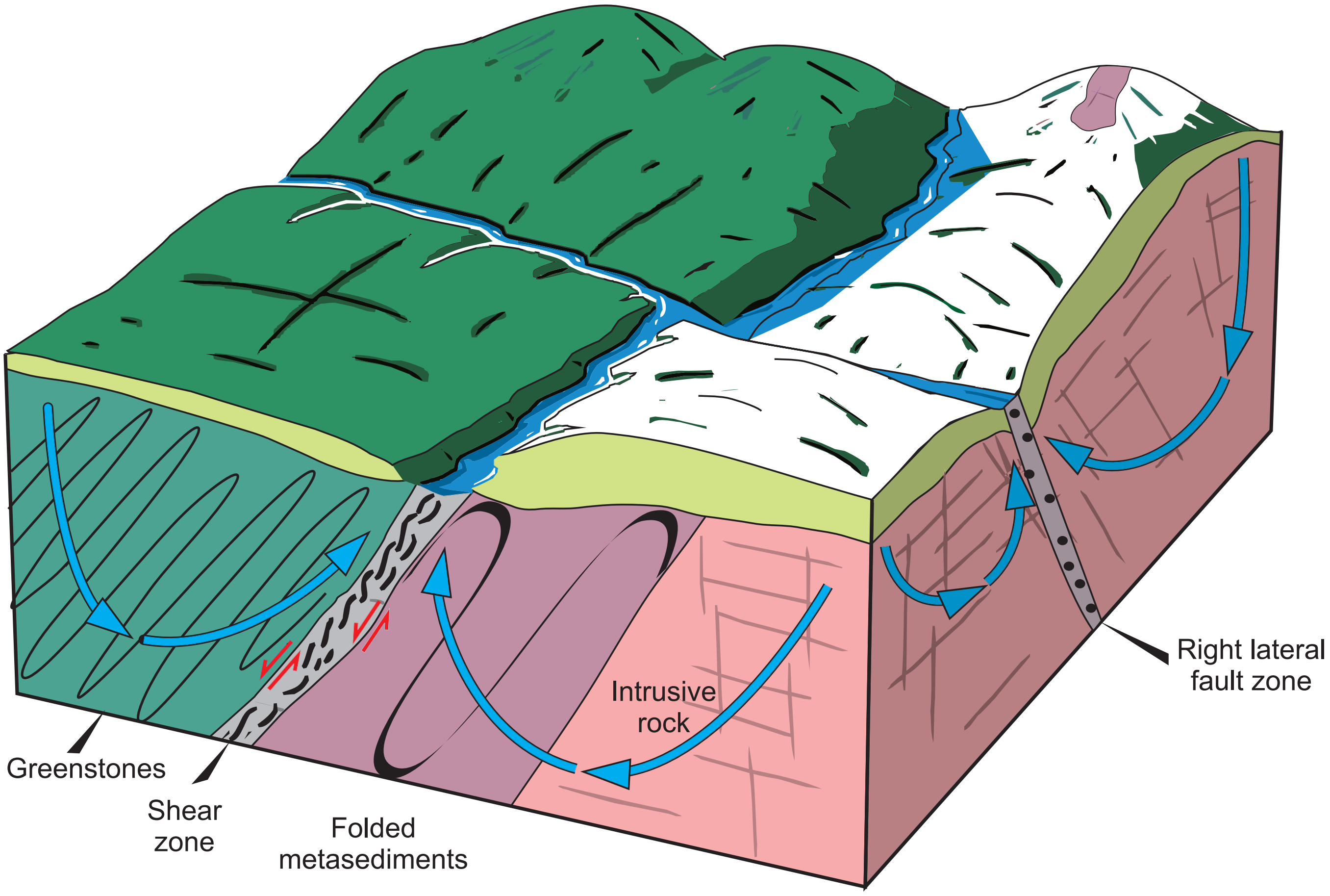


Figure 11.3 Hydrogeological context in the Precambrian Shield consisting of greenstone belt , metasedimentary and intrusive rocks, showing a shear zone offset by a fault zone, and surface lineaments.

with a decrease in rock mass permeability. (Gale et al., 1982; Gustafson and Krásný, 1994). A higher permeability near the surface can be due to a higher fracture density related to stress release, or to weathering and mineral dissolution in fracture planes. Farvolden et al. (1988) and Lemieux et al. (2008b) point out that a log-linear decrease can usually be observed in the first 400 m and that the deeper hydraulic conductivity values tend to be variable depending on the fractures or faults intercepted. Additionally, a progressive increase in effective stress results in fracture closure with depth.

The hydrogeological properties of a structural discontinuity may vary considerably along its plane (Raven and Gale, 1986) even at the same depth. One example is provided by data from the Underground Research Laboratory at Pinawa (Manitoba), where detailed characterization of the in situ geomechanical stress and the hydrogeological properties of the rock mass along a major subhorizontal fault zone allowed the identification of a significantly lower-permeability segment of that structure, corresponding with higher values of normal stress; that location constituted a better emplacement for a future excavation in order to reduce groundwater inflow (Davison et al., 1993).

11.3.2 Context 2: Same as context 1, with a platform cover of Proterozoic or Paleozoic age

The areas of crystalline bedrock in the Canadian Shield covered by subhorizontal remnants of sedimentary rock units constitute a distinct

hydrogeological environment. Hydrogeological units of types A of Simard and Des Rosiers (1979; Table 11.1) and G of Roy et al. (2006) are both included in the hydrogeological context no. 2 defined here. These sedimentary rock units may constitute valuable aquifers provided their saturated zone is sufficiently thick. In any case, the presence of a relatively permeable sedimentary rock cover favours groundwater recharge to deeper aquifer systems. As an example, a water well installed in a remnant of an Ordovician carbonate unit provides an important supply of drinking water to the town of Saint-Félicien near Lake Saint-Jean (Verreault, 2003).

11.3.3 Context 3: Quaternary aquifers of granular material

In lowlands areas of the Canadian Shield, and at its southern border, Quaternary sediments deposited during and after the Wisconsinian glaciation include significant units of granular material which constitute major aquifer systems. Various types of Quaternary granular aquifers are illustrated schematically in Figure 11.4, using the Saguenay-Lac-Saint-Jean (SLSJ) region as an example. The regional physiography, deeply affected by the Saguenay graben, has controlled the placement and formation of these granular deposits in lowland areas.

The Quaternary granular aquifers includes glacial and glaciofluvial as well as post-glacial prograding alluvial and delta plains sediments deposited in lowlands, and on bedrock uplands and plateaus. Figure 11.4 illustrates important glaciofluvial aquifers located at the border of the

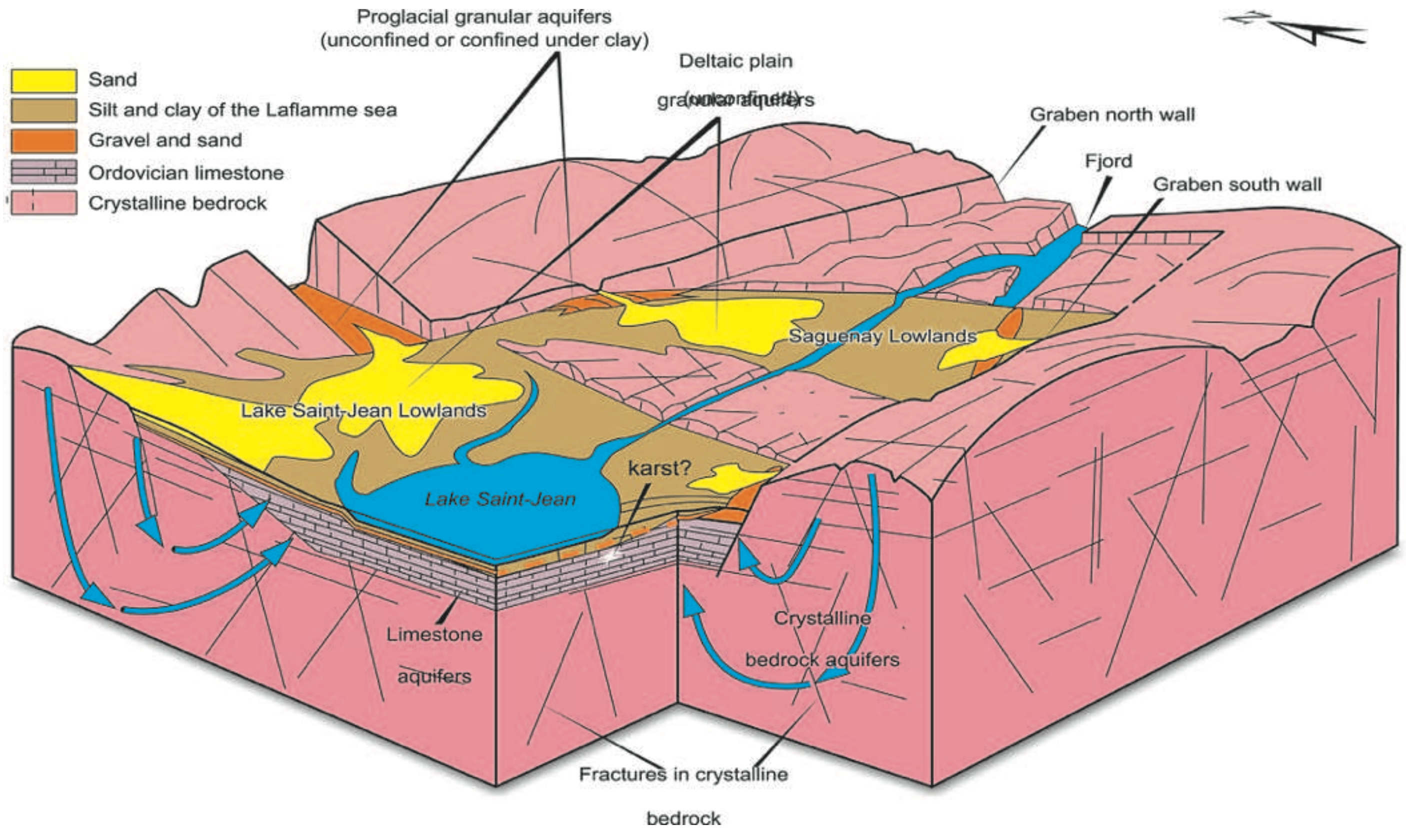


Figure 11.4 Schematic block diagram of aquifer types identified in the Saguenay-Lac-Saint-Jean region (modified from Rouleau et al., 2011).

Saguenay lowlands, near the east-west oriented northern and southern graben faults. In glaciofluvial deposits such as eskers and kames, fine particles have been washed out in many places during the sedimentation process, resulting in permeable granular aquifers. Extensive glaciofluvial sand and gravel deposits are present in some areas, such as the Larder Lake esker in northern Ontario, and the Berry-Saint-Mathieu esker near Amos, Quebec. Fine particle washing has also taken place locally in other glacial deposits, such as moraines, producing complex aquifer systems. These granular units are either unconfined, or confined by extensive units of silt or clay deposited at the bottom of glacial lakes or seas.

A second type of Quaternary granular aquifer is comprised of post-glacial deposits such as large outwash plains and deltaic systems, particularly along Shield margins. In the SLSJ region (Figure 11.4), rivers discharging from both sides of the graben into the invading Laflamme Sea after the last glaciation have deposited granular sediments in their deltas or deltaic plains. These deposits constitute relatively productive unconfined aquifers. The Saint-Honoré aquifer, described by Tremblay (2005), and Tremblay and Rouleau (2004), constitutes an example of a paleodeltaic aquifer that has been put in place by a river flowing to the south and discharging into the Laflamme Sea.

Water wells in these types of Quaternary aquifers provide an important municipal drinking water supply because of their high yield. Most of the rural communities in the SLSJ region, for instance, are pumping groundwater from these granular aquifers for their municipal water distribution system. Also, these permeable granular deposits facilitate groundwater recharge, increasing groundwater flux within underlying bedrock aquifers.

11.4. CURRENT KNOWLEDGE ON GROUNDWATER IN THE CANADIAN SHIELD

11.4.1 Hydrology and climate

Total annual precipitation (P) over the Canadian Shield decreases from about 1400 mm in the south (Proulx et al., 1987) to about 400 mm at the northern tip of the Ungava peninsula (Lapointe, 1977). The percentage of total precipitation falling as snow varies from about 25% in the south to more than 50% in the northern part of Quebec (Gagnon and Ferland, 1967).

Evapotranspiration (ET) also decreases with latitude (van Everdingen, 1987), even more notably than precipitation. As a result, the ratio of runoff (Q) to precipitation, i.e., the runoff coefficient (Q/P), is often higher to the north. As an example, Q/P is estimated at 80% in the Nastapoka and the Grande-Baleine Rivers, both discharging into Hudson Bay near Kuujjuarapik (Hydro-Québec, 1993). Q/P is around 65% in the southern part of the Canadian Shield (Ferland, 1969; Proulx et al., 1987), and about 50 to 60% at the southern limit of Quebec (Simard and Des Rosiers, 1979).

Analysis of stream baseflow, in relation to factors such as precipitation, geology and topography, provides a first assessment of groundwater resources in areas with a temperate or cold climate (Gustafson and Krásný, 1994). This is particularly valuable in a region with a low population density such as the northern half of the Canadian Shield, since baseflow is often the only hydrogeological data available there.

Water budget calculations with an emphasis on the groundwater component have been carried out by Singer and Cheng (2002) on watersheds of five major rivers discharging into Hudson Bay and James Bay (Severn, Winisk, Attawapiskat, Albany and Moose Rivers, Figure 11.5), as well as the Ontario part of the Upper Ottawa River. The bedrock geology of these watersheds is composed mostly of Precambrian basement, with sedimentary rocks of the Phanerozoic Hudson Bay Platform on the downstream part of those northern flowing rivers. The bedrock is covered in large part by a generally thin layer of Quaternary deposits, which can, however, exceed 100 m in thickness in some bedrock valleys of the Canadian Shield (Dredge and Cowan, 1989). These unconsolidated deposits can be more than 200 m thick in places over the Hudson Bay Lowlands. The long term mean annual precipitation in that region varies from 471.4 to 796.6 mm, and Singer and Chen (2002) have estimated that the long-term mean annual groundwater recharge ranges from 33.6 to 44.0 mm.

The northern half of the Canadian Shield is covered more or less continuously by permanently frozen ground (the permafrost). The presence of a perennial or seasonal frozen layer reduces water infiltration and groundwater recharge considerably, both in surficial deposits and in the bedrock (van Everdingen, 1987). The reduction of groundwater recharge in permafrost terrains is reflected by a one order of magnitude decrease in stream baseflow (expressed in $m^3/s/km$) with increasing latitude, from about 5×10^{-3} in the southern part of discontinuous permafrost, to about 5×10^{-4}, and approaches zero in continuous permafrost areas (Lapointe, 1977; van Everdingen, 1987).

Groundwater flow regimes during past climatic conditions, from the period of the continental Laurentide ice-sheet cover of the Wisconsinian glaciation (120 ka) to present, have been investigated by numerical modelling. This modelling is supported by isotopic and hydrogeochemical data, for the northern part of North America, including

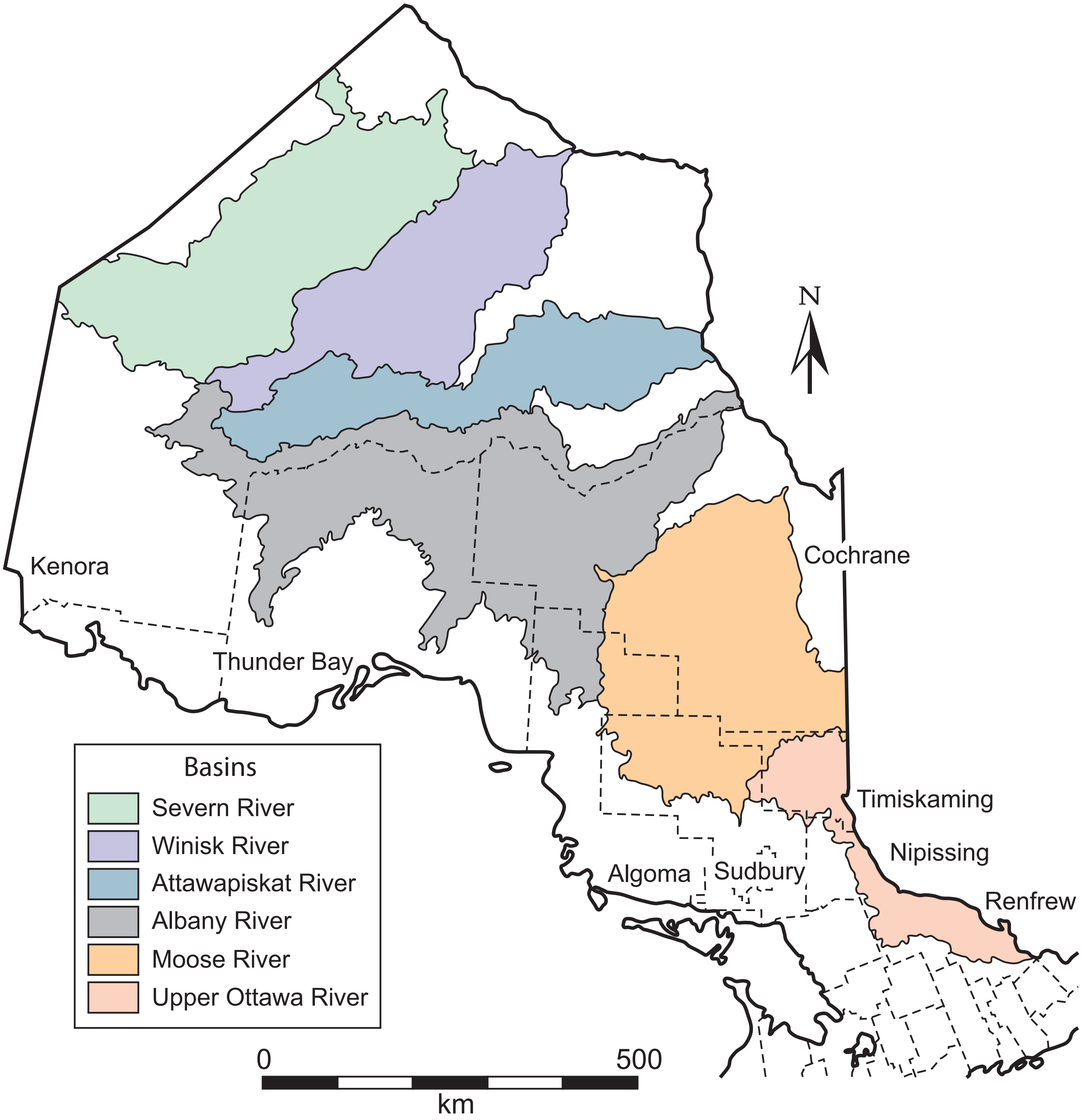


Figure 11.5 Map of northern Ontario watersheds draining into Hudson Bay, James Bay and Upper Ottawa River (From Singer and Cheng, 2002).

the entire Precambrian Shield region. The results suggest that most infiltration of subglacial meltwater occurs during ice sheet progression. Furthermore, during ice sheet regression, groundwater mainly exfiltrates on the surface, in both the subglacial and periglacial environments (Person et al., 2007; Lemieux et al, 2008).

11.4.2 Groundwater geochemistry

11.4.2.1 Overburden groundwater geochemistry

Overburden groundwaters on the Shield are generally dilute (TDS< 300 mg/L), Ca-HCO_3-type waters because overburden materials are generally comprised of low-solubility silicate minerals (quartz and feldspars) with trace to minor amounts of carbonates. Exceptions occur such as at Whiteshell where brackish overburden Ca-Mg-HCO_3-SO_4-type groundwaters have TDS concentrations up to 9,000 mg/L due to dissolution of more soluble minerals such as gypsum present in the clay-rich overburden (Gascoyne, 2004). Overburden groundwaters in the Hudson Bay drainage system of northern Ontario are also typically of the Ca-HCO_3 type with TDS concentrations generally less than 400 mg/L (Singer and Cheng, 2002).

11.4.2.2 Bedrock groundwater geochemistry

Testing at the AECL research sites provided the opportunity to analyze groundwater chemistry from near surface to as deep as about 1,000 metres. Groundwater samples from Shield mines have been collected from depths up to about 2,000 m. In recharge areas, groundwaters in the upper 200–300 m of the bedrock are typically fresh with TDS values of up to about 500 mg/L. TDS values reflect dissolution of silicate minerals and reactions with carbonate minerals present in the overburden or on fracture surfaces in the bedrock. There is also a gradual downward trend from Ca-HCO_3- toward Na-HCO_3-type water in the upper bedrock due to the exchange of Ca for Na sorbed onto clay minerals in the fractures. At depths of about 200–300 m, mixing between recent meteoric recharge and an older glacial meltwater component that infiltrated up to 20 kyr ago may be evident from the stable isotopic composition of the water (Bottomley et al., 1984, 1990; Clark et al., 2000). However, because both sources are relatively fresh, mixing of these two components does not typically result in a major increase in TDS. In contrast to recharge areas, regional groundwater discharge zones may be brackish Na-Cl-type water due to the upward flow of more saline groundwaters from depth along major fracture or fault zones (Gascoyne, 2004). High-Cl and high-TDS groundwater have also been observed in shallow wells drilled into the Precambrian bedrock in Quebec (Simard and Des Rosiers, 1979), particularly around Lake Saint-Jean (Walter et al., 2006).

Hypersaline brines are ubiquitous at depths greater than about 1,000 m in the Canadian Shield. These brines are of the (Ca-Na)-Cl type with TDS values up to 300 g/L (Frape et al., 1984b; Bottomley et al., 1994) and are clearly unfit for human consumption, livestock watering or irrigation. In Ontario, Quebec and the Northwest Territories these ancient brines appear to have penetrated the Shield by downward infiltration of early Paleozoic seawater that had been concentrated beyond halite saturation by evaporation (Bottomley et al., 1999, 2002). Exceptions to this mechanism may be seen at certain sites on the Shield near the contact with basinal sediments, such as the Whiteshell area, where formation waters may have been driven laterally into the Precambrian basement rocks in the past (Gascoyne, 2004). However, these saline waters have TDS values of less than about 100 g/L and are predominantly of the (Na-Ca)-Cl type. Because of their high density and the generally low regional hydraulic gradient in the Shield, hypersaline brines have not been observed as naturally discharging to the surface at present. They do, however, discharge into deep mines via fractures, faults and flowing boreholes, requiring pumping to surface for disposal (e.g., Benlahcen, 1996). Less dense brackish to saline bedrock groundwaters may discharge to surface under favourable hydrogeological conditions such as at the Whiteshell area (Gascoyne, 2004) and the enigmatic saline “moose licks” near Thunder Bay, Ontario (Frape et al., 1984a).

The transition zone between the hypersaline Shield brine at depth and the upper zone of fresh groundwater will vary to some degree between sites on the Shield depending on local hydrogeological conditions. In mining areas, where hydraulic depressurization promotes the downward flow of fresh water and its mixing with brine, the boundary between the two is likely to be rather gradational. The boundary may be sharper in undisturbed areas due to the significant density contrast between the two water masses, although some mixing will always be present due to diffusion. However, because the frequency of open fractures decreases with depth, the zone of active groundwater circulation in the Shield is typically limited to depths of less than about 400 m: below this, the probability that a borehole will encounter a fracture zone capable of yielding a sufficient water supply of potable quality rapidly diminishes.

Table 11.2 lists selected representative chemical analyses for groundwaters from several of the AECL research areas and selected Shield mines along with the predominant rock type at each site (Bottomley et al., 1984, 1990, 1999; Cramer and Smellie, 1994; Benlahcen, 1996; Boutin, 2001; Benlahcen, 2003; Gascoyne, 2004; Also shown are ″reference″ Shield groundwater chemical compositions based on average concentrations from hydrogeochemical datasets for AECL research areas and mine waters at Sudbury, Thompson, and Yellowknife (McMurry, 2004). Reference groundwater CS-50 in Table 11.2 is the average of chemical analyses for groundwater samples collected at these sites from the depth range of 0 to 100 m (average 50 m), while reference groundwater CS-750 is the average of chemical analyses for groundwater samples collected from the depth range of 500 to 1,000 m (average 750 m). It should be noted, however, that the range in concentration for certain parameters in both reference groundwaters may be very large. For example, the range in sulphate concentrations in samples used for CS-50 is about two and a half orders of magnitude (McMurry, 2004). Nevertheless, it can be concluded from Table 11.2 that the probability of encountering potable groundwater in the upper 100 m of the bedrock is very good but below a depth of 500 m the water is unlikely to be suitable for human consumption. The Cigar Lake groundwater analysis (Table 11.2) reveals that very good water quality can still be present at depth in the Shield under certain favourable hydrogeochemical conditions. At Cigar Lake, bedrock is comprised of the Proterozoic Athabasca Basin sandstone which consists largely of chemically resistant quartz, resulting in very low concentrations of total dissolved solids even at depths of 400 m. Notwithstanding these uncertainties, Figure 11.6 shows schematically how the major ion chemistry of groundwater typically changes in the Shield with increasing depth. It is important to note, however, that the chemical compositions shown, and the actual depths of the boundaries between the different compositional types, are controlled largely by site-specific dynamics of mixing between fresh meteoric recharge, glacial meltwater and deep Shield brine components.

11.4.3 Isotopes in groundwater

The recharge origin and age of groundwaters found within the Canadian Shield range from very local freshwater sources and seasonal recharge to high-salinity brines recharged up to hundreds of millions of years ago. The former are mostly associated with the clastic surficial aquifers of glacial outwash sands and gravels found throughout the Shield. They are also found in the

TABLE 11.2 REPRESENTATIVE CHEMICAL ANALYSES OF SHIELD BEDROCK GROUNDWATERS FROM AECL RESEARCH AREAS AND SELECTED MINE SITES. REFERENCE "AVERAGE" COMPOSITIONS FOR SHALLOW AND DEEP SHIELD GROUNDWATERS ARE ALSO SHOWN

LOCATION AND DEPTH	CA	MG	NA	K	HCO^3	SO^4	CL	PH
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	
Mine Niobec, Saguenay, Que.[1] (Carbonatite intrusion, Grenville)								
NiAB10, 210m	1000	370	3900	70	37	754.8	9700	6.7
NiAB30, 300m	1900	410	8500	360	46.4	120.4	19800	6.6
Mine Joe Mann, Chibougamau, Que.[2] (Archean greenstone belt)								
JM417, 128m	142	52	8	5.6	207	345	6.8	7.5
JM18100, 546m	82	20	82	2	122	117	410	7.5
Mine Bouchard-Hébert (Mobrun), Abitibi, Que.[3] (Archean greenstone belt)								
BH-2, 300m	111	20	125	3.3	92[a]	394	56	7.6
BH-7, 550m	590	31	150	1.4	38 [a]	1614	39.6	7.3
Chalk River, Ont.[4] (Grenville gneiss)								
CR13, 86m	17.0	2.8	36	0.4	158	8.0	1.0	8.5
CR13, 341m	35.1	2.4	209	1.1	50.1	53.8	325	7.9
Perth, Ont.[5] (Grenville gneiss)								
TW3, 32m	64	19	12	5.4	270	39	5.0	8.1
East Bull Lake, Ont.[6] (Archean gabbro-anorthosite)								
P1, 32–53m	1.9	0.1	53	0.4	139	6.7	0.6	9.1
EBL2, 111–126m	3.0	1.0	66	2.4	172	3.4	6.8	10.1
Whiteshell, Man.[7] (Archean granite)								
WD2-72-5, 65m	28.0	5.5	59.0	2.6	255	11.7	1.6	7.3
WB2-20-12, 725m	10540	34.2	4360	14.3	20	835	27900	8.6
Thompson T3 mine, Man.[8] (Proterozoic gneiss)								
B93035, 1067m	13195	408	7932	349	17	307	36849	6.4
Cigar Lake mine, Sask.[9] (Proterozoic Athabasca sandstone)								
B139, 439–443m	3.7	2.1	2.7	1.1	34.1	3.3	0.2	6.5
Yellowknife Con mine, N.W.T.[10] (Archean metagabbro)								
B8906, 1067m	194	75	995	7.8	256	113	388	6.9
B7126, 1616m	73789	198	30670	278	28	247	174582	6.9
"Reference" groundwater[11]								
CS-50 (0–100m)	40	11	75	3	235	50	40	7.9
CS-750 (500–1000m)	4110	60	3080	22	30	560	11925	8.0

[a] Total alkalinity (mg/L of $CaCO_3$)

[1] Benlahcen, 1996; [2] Boutin, 2001; [3] Benlahcen, 2003; [4] Bottomley et al., 1984; [5] Bottomley (unpublished data); [6] Bottomley et al., 1990; [7] Gascoyne, 2004; [8] Bottomley et al., 2003; [9] Cramer and Smellie, 1994; [10] Bottomley et al., 1999; [11] McMurry, 2004.

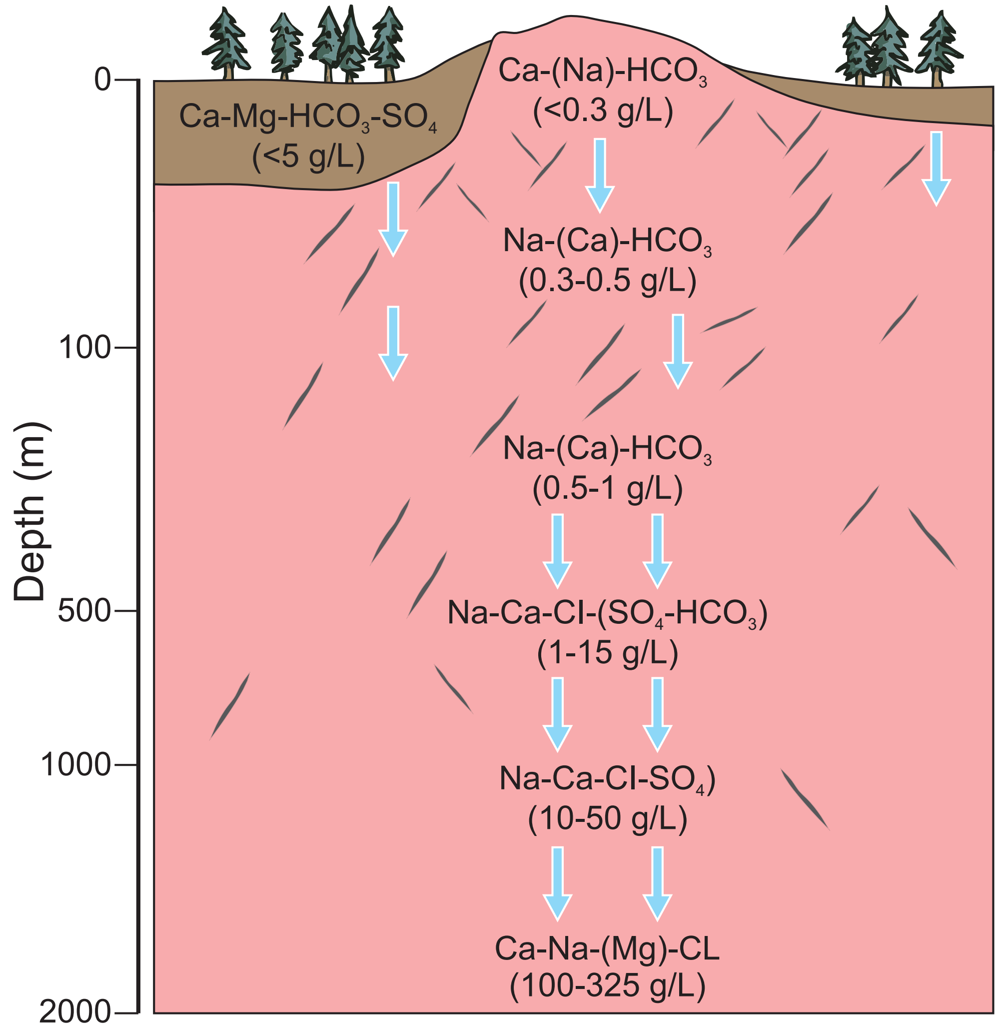


Figure 11.6 Schematic diagram showing typical hydrogeochemical variations with depth in the Shield (modified after Gascoyne, 2004).

shallow fractured bedrock. The brines, by contrast, are of scientific interest with little bearing on water resources; they do represent an end-member in a continuum of ages and origins. Research on the origin of groundwaters in the Canadian Shield is largely based on the use of naturally occurring stable isotope tracers. The δ^{18}O and δD signature of most groundwaters is established during precipitation and recharge. Here, the temperature-driven process of rain-out acts to enrich the rainfall in warmer climates with the heavy isotopes, ^{18}O and D. Lower-temperature precipitation in higher latitude, higher altitude and more continental regions then become more depleted in these isotopes. The correlation between temperature and the mean annual δ^{18}O in precipitation for central Canada can be approximated by $\delta^{18}O = 0.5\ T_{annual} - 15‰$ (based on Fritz et al., 1987).

Figure 11.7 provides the distribution of δ^{18}O in Canadian Shield groundwaters, showing gradients toward the higher latitudes and toward the continental interior. Groundwater data used in the construction of this diagram contains measurable tritium, signifying that groundwater is part of the active meteorological system. Tritium, ^{3}H or T, is a short-lived radioisotope of hydrogen, H. It is produced in the stratosphere by cosmic ray impacts on N and is transferred to the troposphere where it enters the hydrological cycle. Natural concentrations in precipitation over the Canadian Shield range from about 15 to 25 TU (1 TU or tritium unit represents a concentration of T per 10^{18} H in water). T was also produced during the era of atmospheric testing of hydrogen bombs, from 1952 culminating in the 1963 “bomb peak” in precipitation where this anthropogenic source reached over 4,000 TU in the northern hemisphere. While of little radiological hazard, the tritium peak in groundwater provides a time horizon for dating.

The recharge origin and age of groundwaters in the surficial aquifers have been mostly studied at sites near the southern margin of the Canadian

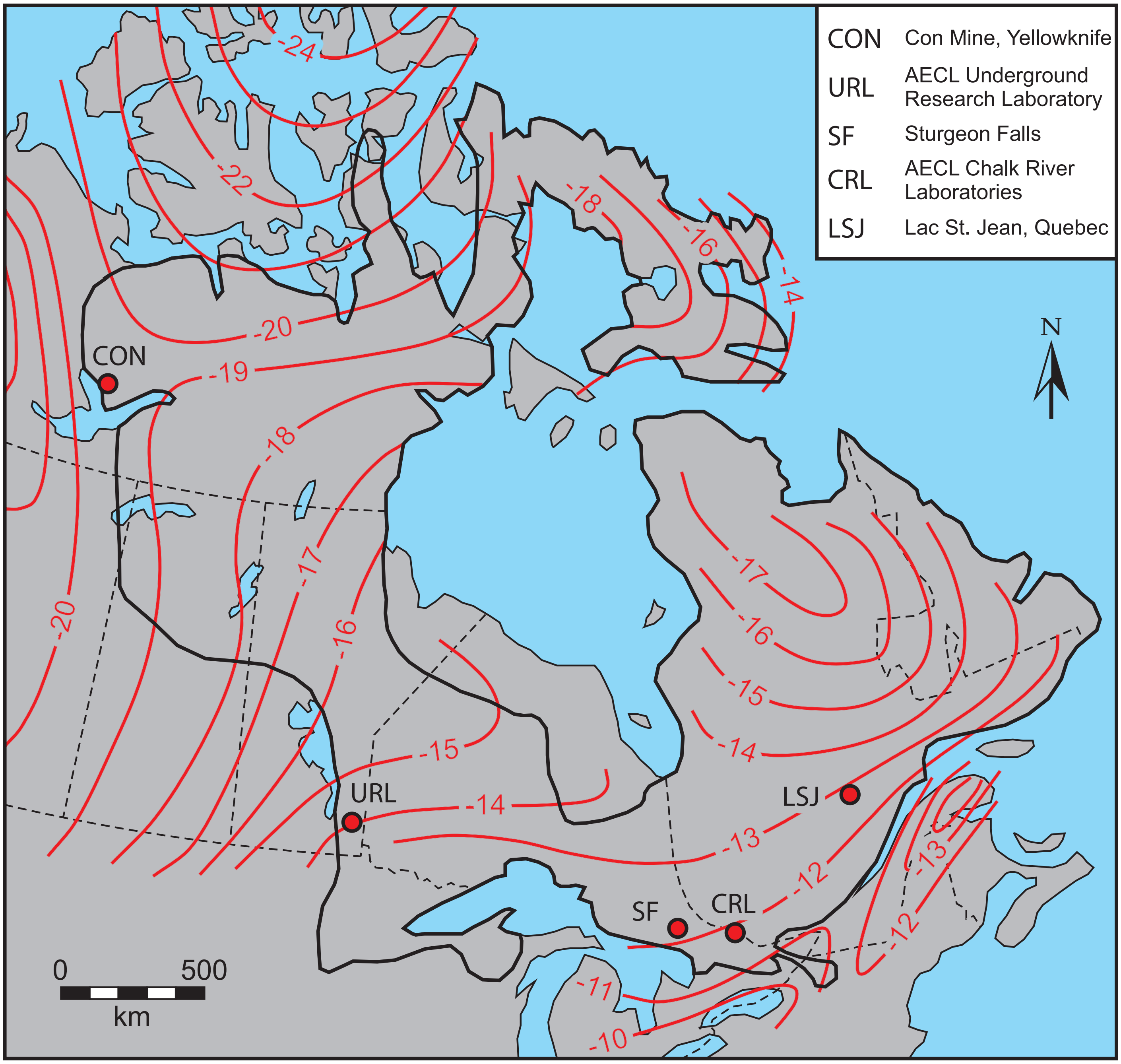


Figure 11.7 Stable isotope content ($\delta^{18}O$) of groundwater in the Canadian Shield. Isopleths (‰) based on data for tritium-bearing groundwaters that are considered to represent modern recharge (modified from a countrywide diagram in Clark and Fritz, 1997).

Shield. The shallow nature of these aquifers and tendency toward higher permeability due to the crystalline bedrock origin of the glacial material favours active recharge of precipitation although older groundwaters can be preserved. Most such groundwaters have isotope signatures that demonstrate local recharge, and most are tritium-bearing. Tritium-free groundwaters may be preserved under conditions of low natural gradients in deeper parts of surficial aquifers.

11.4.3.1 Isotopes in groundwater from surficial aquifers

The Sturgeon Falls aquifer near North Bay Ontario, studied by Robertson and Cherry (1989) and Renaud et al. (2005), comprises some

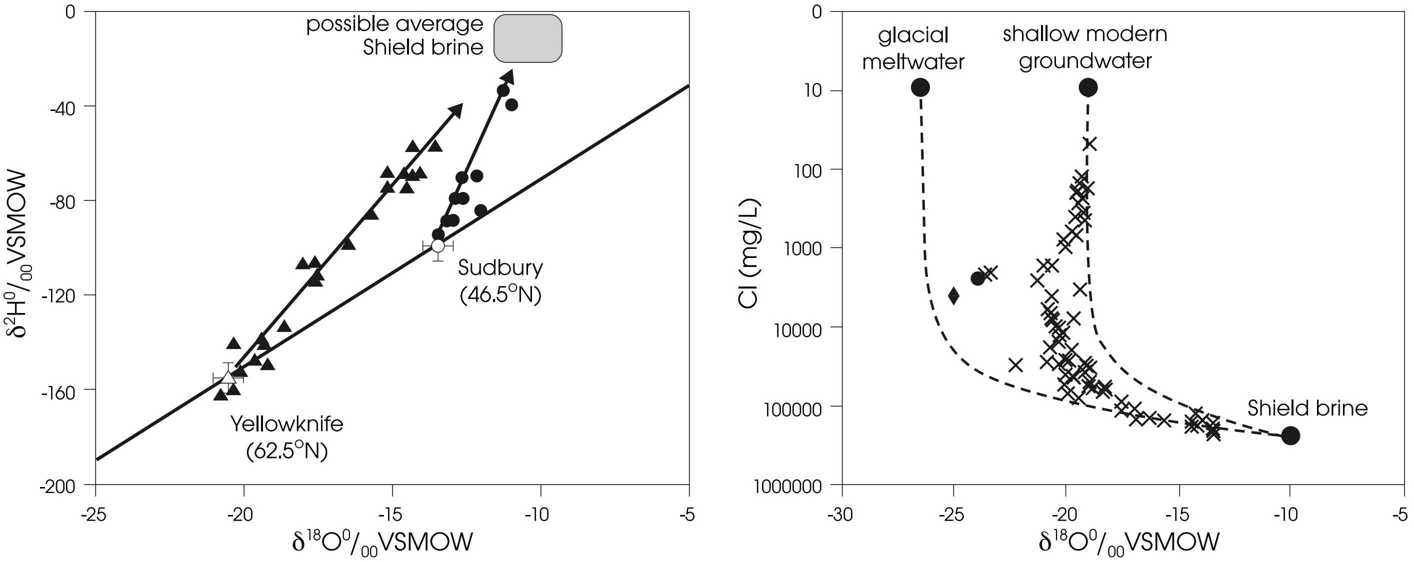


Figure 11.8 Isotope signature for Shield groundwaters. Left: $\delta^{18}O$ - δD diagram for Canadian Shield brines (closed symbols) with Ca-Cl salinities reaching 300 g/L. Sudbury (south) data from Frape and Fritz (1982), Yellowknife data from Frape et al. (1984b) and Clark et al. (2000). The characteristic strong deuterium enrichment over local meteoric waters (open symbols) is due to exchange reactions during hydration of primary silicate minerals. Right: glacial meltwaters in the Canadian Shield at Yellowknife (Clark et al., 2000), mixing with meteoric groundwaters in the shallow subsurface and with Shield brines up to 1600 m depth

23m of glaciolacustrine silty sand with hydraulic conductivity, $K = 2 \times 10^{-4}$ cm/s to 3×10^{-5} cm/s, underlain by 6 m of clayey silt and a basal sand aquifer with $K = 6 \times 10^{-3}$ cm/s. Water table contours demonstrate recharge by direct infiltration and downward movement. The thermonuclear tritium peak is preserved in these shallow groundwaters and constrains their age to the past 50 years. By contrast, the groundwaters in the underlying higher-permeability aquifer are tritium-free and so recharged prior to 1957. They also have a $\delta^{18}O$ signature of –11.5‰, which is about 1‰ depleted from the shallow, tritiated groundwaters, signifying a more regional recharge origin at a higher elevation. This example demonstrates that even within a local clastic sediment package on the Shield, groundwaters of differing age exist with local to regional recharge origin.

During deglaciation, some 8,000 to 12,000 years ago, peripheral regions of the ice-covered Shield were bounded by large glacial lakes and inland seas. As isostatic rebound reclaimed these areas of the Shield, fields of sand dunes developed by aeolian transport of the emerging landscape, and are particularly well developed along the eastern Lake Winnipeg region, the Ottawa River valley and in the Lake Saint-Jean region of Quebec. Eventually stabilized by vegetation, these fossil sand dunes now host actively circulating groundwater resources. Groundwater recharge and circulation in one such aquifer near the AECL Chalk River Laboratories (CRL) has been studied by Alverado et al. (2002). Infiltration is rapid into these fine sands and interstratified sand and silt sediments, with little to no surface runoff. The high permeability of this well-sorted material cannot sustain a high water table, and so the unsaturated zone can exceed 10 m in thickness. Groundwater flow rates on the order of 0.3 to 0.5 m/day have been measured by tritium-^{3}He dating (Noack, 1995). Discharge into a wetland along the aquifer boundary is typical of the Canadian Shield, where the considerably lower hydraulic conductivity of bedrock precludes regional drainage from surficial aquifers.

11.4.3.2 Isotopes in groundwater from crystalline aquifers

A few studies of groundwaters in the crystalline bedrock of the Canadian Shield have used environmental isotopes to identify recharge origin as well as mean circulation times. Commercial mines have provided valuable insights into the occurrence and movement of groundwater within the Canadian Shield. The access provided by drifts and exploration boreholes allows not only high-quality samples for isotope and geochemical investigations, but a visual presentation of fracture and fault architecture. Research over the past decades has revealed that below a lens of recently recharged fresh water lie high TDS brines with Ca-Cl salinities approaching 300 g/L (Frape et al., 1984b). Extensive interaction with silicates has altered the isotope signature of these brines, giving them a characteristic enrichment in D (Figure 11.8; left diagram).

The Con Mine in Yellowknife is an example of where over 25 years of studies have deconvolved a complex system of mixing between three different groundwaters (Clark et al., 2000), which seems typical of Shield groundwaters elsewhere. The deep subsurface (500 m to 1600 m) hosts an ancient brine ($\delta^{18}O$ value of approximately –10‰) that infiltrated millions of years ago (based on ^{129}I measurements; Bottomley et al., 2002) from an overlying marine evaporite basin (Bottomley et al., 1994). Open faults and fractures connected to the surface have allowed modern low-salinity groundwaters ($\delta^{18}O$ value of –19‰) to circulate within the upper 100 to 200 m of bedrock, although depressurization from mining now allows penetration of tritium-bearing meteoric waters down to a depth of some 1,600 m. Interestingly, the intermediate depths between the brines and fresh meteoric waters host a glacial meltwater component identified by a trend toward a glacial $\delta^{18}O$ value of about –28‰ (Figure 11.8; right diagram). Modelling shows that the high hydraulic gradient below the margin of the retreating Laurentide ice sheet circulates water to a much greater depth (hundreds of metres through fracture rock with ~1% porosity) than the 100 to 200 m depth of Holocene precipitation. The low-salinity groundwaters at the Con Mine plot very close to the local meteoric water line constructed from monthly precipitation data collected over a multi-year period. This suggests that recharge through the fractured surface of the crystalline bedrock is direct and unaffected by partial evaporation.

The Sudbury Basin provides an additional perspective on the recharge of groundwater in the Canadian Shield. Frape and Fritz (1982) found that the ubiquitous Shield brines have a common isotopic signature, generated by equilibration with the crystalline host rock at moderate to low temperature (Frape et al., 1984b). Groundwater from a range of depths shows dilution along mixing lines defined by the isotopic composition of local meteoric waters and the common brine, with clear regional distinctions. For example, even within the Sudbury Basin, the trend for groundwater from the northern mining camps is more depleted than that for the southern rim mines. This demonstrates the occurrence of local groundwater penetrating to depths of several hundred metres under the influence of the steep vertical gradients generated by mining activities.

AECL constructed the 450 m deep Underground Research Laboratory (URL) near Pinawa, on the southern Manitoba-Ontario border to investigate groundwater dynamics within the Canadian Shield. Research was undertaken on groundwater sampled from both surface-spudded and subsurface boreholes down to 1000 m (Gascoyne, 2004).

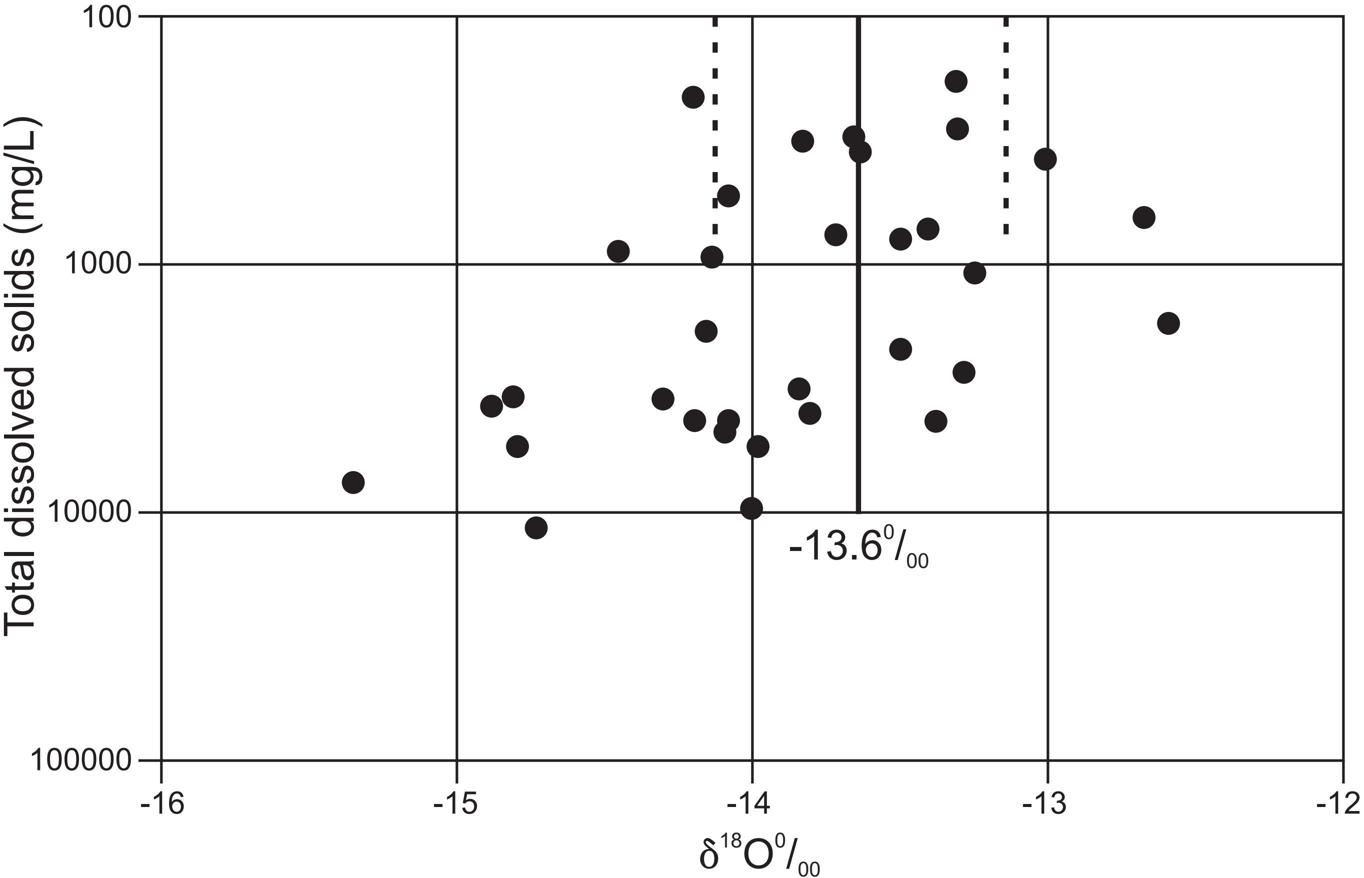


Figure 11.9 $\delta^{18}O$ composition of shallow Canadian Shield groundwaters around Saguenay-Lac St. Jean, Quebec, and trends with increasing solute concentration (modified from Walter et al., 2006). Low-salinity groundwaters are used to provide an estimate for the mean annual $\delta^{18}O$ of local meteoric waters (–13.6 ±0.49‰). Higher-salinity groundwaters show a depletion trend attributed to a glacial meltwater signal resident in the subsurface since the late Pleistocene.

They found that shallow groundwater in the upper 200 m fracture network is dilute (300 mg/L) Ca-Na-HCO_3 waters. Their $\delta^{18}O$ value of –13.5‰ is consistent with modern waters for that geographic region (Figure 11.7) and the groundwater contained modern tritium levels. Like the Con Mine setting, Gascoyne (2004) found that groundwater between 200 and 400 m in the Pinawa URL contained a glacial meltwater component with lighter $\delta^{18}O$ values. Groundwaters at greater than 500 m depth have a Ca-Cl geochemical facies and carry the signature deuterium enrichment found in Shield brines.

Not all Shield groundwater data comes from mines: other studies have used domestic wells. In the region of Lake Saint-Jean in Quebec, Walter et al. (2006) characterized the isotope geochemistry of groundwater in the upper 100 m of the crystalline Grenville province with geochemical facies varying between Na-(Ca)-HCO_3 and Na-Ca-Cl. The Cl– facies is attributed to leaching from marine clay pore waters preserved following deposition from the early Holocene Laflamme Sea. The mean isotope value for the low-salinity groundwaters (TDS < 1000 mg/L) is –13.8 ±0.49‰ (Figure 11.9). This value is close to that anticipated for this geographic region from Figure 11.7, with minor depletion perhaps reflecting recharge in the elevated topography surrounding the Lake Saint-Jean Basin. Higher-salinity groundwaters in these crystalline rocks, by contrast, show a depletion trend to values below –15‰. This depletion trend is attributed to a glacial meltwater component incorporated during deglaciation at about 12 ka before present. Walter et al. (2006) found that most groundwaters recharge with little to no evaporation.

11.4.3.3 Summary on isotopes studies

The growing number of isotope studies of groundwater in the Canadian Shield is developing an improving picture of their recharge origin and mechanisms. Surficial aquifers are composed of glacially derived sands and gravels in eskers, outwash fans and dunes. Most are phreatic, and stable isotopes show that they host groundwater recharged by local, direct infiltration with little to no evaporative loss. Tritium levels indicate active circulation with residence times on the order of decades. Such aquifers can be sensitive to inter-annual variability in precipitation and, of course, to land-use impacts on both recharge and water quality.

The crystalline basement outcrops over much of the Canadian Shield, present a fractured and faulted carapace that offers locally good aquifer potential. Discontinuities extending to hundreds of metres in depth allow active circulation of low-salinity meteoric waters. Stable isotopes show such groundwater originates through direct recharge at higher elevations within the local catchments. However, active circulation is restricted typically to 100 to 200 metres depth due to the subdued topography available as the hydraulic drive. No thermal springs (which would indicate circulation to depths of a kilometre or more as observed in the Cordillera) have been identified in the Shield.

Shield groundwater below about 100 m is found to include a remnant glacial meltwater component recharged beneath the retreating margin of the Laurentide ice sheet at the end of the Pleistocene period, and evident from a characteristic depletion in both ^{18}O and D. This ubiquitous meltwater lens has been preserved during the Holocene by the diminished hydraulic gradients present beneath the Shield's subdued topography.

The deepest permeable discontinuities within the Canadian Shield host Ca-Cl brines with salinities up to 300 g/L. Stable isotopes and geochemical constraints suggest an origin in some regions by infiltration of highly evaporated Paleozoic marine brine. Other brines may have evolved through leaching of salinity intrinsic to the rocks themselves. In all cases, extensive rock-water interaction and the ingrowth of radiogenic isotopes indicate that the Shield brines are of geological age.

11.4.4 Groundwater and mining

Mining constitutes the most important human activity in many areas of the Precambrian Shield. Groundwater plays an important role in many aspects of that industry, from the mineral exploration stage to mine closure.

11.4.4.1 Groundwater as a mineral exploration tool

Groundwater geochemistry surveys conducted for mineral exploration (Lalonde and Chouinard, 1983) have identified zones of potential sources of metal such as Cu, Pb, Zn, Ni, Co, Mn, Ag, in a number of regions in the Canadian Shield in Quebec (Lalonde et al., 1980; Lalonde and Pelletier, 1983; Pelletier, 1986; Kirouac, 1987). Hydrogeochemistry has also been proposed as an exploration tool for gold (Fréchette, 1986) and uranium mineralization (Otis, 1988). Considering the flow regime (e.g., recharge or discharge) at the sampling points, however, would improve considerably the usefulness of such studies.

11.4.4.2 Groundwater withdrawal for mining

The quantity of groundwater extracted for mine dewatering is relatively little (Charron, 1967) considering the large quantity of drifts and other excavations, all of which constitute groundwater drains often installed down to a depth of a few thousands metres. Fault zones, on the other hand, often yield large quantities of water into mines. This localized high water flow is favoured by those mine sites in the Shield which are often located under lakes and near major structural discontinuities. The hydrogeological functions of structural discontinuities become more important where these structures are in contact with a surface water body or a permeable surficial deposit. Gneissic rocks and greenstone belts are often cut by shear zones parallel to the foliation (Benson et al., 1974), which could make them very permeable down to a depth of about 600 m (Raven and Gale, 1986).

Local hydrogeological data, particularly from mine sites, is available only in the most populated areas of the Precambrian Shield: these are located in the Grenville Province and in the southern part of the Superior geological Provinces. Even in these populated areas, however, little use is made of groundwater, partly due to surface water abundance. Most of the water wells in the bedrock are used for individual household or for small communities.

Rouleau et al. (1999) compiled groundwater withdrawal data for the year 1993 in the Quebec part of the Abitibi geological Subprovince (Table 11.3). This area is part of the Abitibi Plains ecoregion, a subdivision of the Boreal Shield Ecozone (Environment Canada, 2005) that presents the highest number of mining sites of all Canada's ecoregions.(NRCan, 2003). In this territory, which covers about 90,000 km^2 of the Shield in Quebec, total groundwater withdrawn from the bedrock at the 35 mines amounts to about 57,000 m^3/day. This is roughly equivalent to the groundwater withdrawn by the 150,000 inhabitants of this mining region for all other usages, including drinking water, pisciculture and other industries. Moreover, the groundwater withdrawal not related to mining is mostly from granular Quaternary deposits overlying the bedrock, whereas mine dewatering takes place mostly within the bedrock.

11.4.4.3 Coupling of hydrogeological and geomechanical processes

Excavation in a rock mass disturbs the geomechanical stress field, which in turn affects the hydrogeological properties (Rouleau et al., 1999a). However, field data on rock mass permeability around excavations suggest that other processes, such as groundwater degassing and dissolution-precipitation along fracture planes, may also affect the hydrogeological properties of a rock mass around drained excavations (Benlahcen et al., 2001; Benlahcen, 2003).

Groundwater drainage in mines often produces an important drawdown cone. The presence of air in this enlarged unsaturated volume of rock enhances a number of geochemical reactions affecting the groundwater. In a rock mass with a high content in sulphide minerals, such reactions often result in an increase in the acidity and in sulphate concentration in the infiltrating groundwater (Benlahcen, 1996; Rouleau et al., 1995; Benlahcen et al., 1999).

11.4.4.4 Contamination from mine tailings

Tailings and waste rock associated with mining are likely the largest potential sources of contamination

TABLE 11.3 GROUNDWATER WITHDRAWAL IN THE QUEBEC ABITIBI REGION IN 1993 (FROM ROULEAU ET AL., 1999)

PURPOSE	WITHDRAWAL (M^3/YEAR)
Mine dewatering (ca. 35 mine sites)	57,000
Drinking water distribution system	28,000
Pisciculture	16,000
Others: bottled water, private wells, other industries, etc.	6,000
TOTAL	**107,000**

for Shield groundwater. In particular, base metal and gold mines across the Shield, and uranium mines in the Elliot Lake area of Ontario and northern Saskatchewan, have subaerially disposed massive volumes of these materials. Where they contain significant amounts of residual sulphides and arsenides, oxidation of these minerals frequently results in acid mine generation and the leaching of toxic metals, such as arsenic, nickel, uranium and radium-226, into surface waters and groundwaters (Morin et al., 1982). Bussière (2007) describes a number of innovative methods being developed and field-tested to reduce environmental risks associated with tailings storage: these include densified tailings, environmental desulphurization, various cover materials (Germain et al., 2004), and co-disposal of tailings and waste rock. Even if many aspects need to be optimized, these approaches can be considered today as interesting alternatives to conventional tailings management.

Toxic materials have been disposed of in underground mine workings, posing a significant risk to the environment because of their high solubility and mobility in groundwater flow systems. For example, about 237,000 tonnes of arsenic trioxide dust was disposed in the now abandoned Giant Mine in Yellowknife, Northwest Territories, and is now leaching into infiltrating groundwater resulting in arsenic concentrations as high as 4 g/L (Clark and Raven, 2004).

11.4.5 Sparse data on well yield, hydraulic properties

Although intact crystalline rock has a very low hydraulic conductivity (typically less than 10^{-9} m/s), fractured bedrock may be up to 5 orders of magnitude more conductive (Raven et al., 1987; Gascoyne, 2004). Fortunately, the Canadian Shield is typically fractured to depths of 300 to 400 m so the probability of a borehole encountering a sufficient groundwater supply for domestic water well is often very good.

In his regional study of groundwater resources within a strip of territory about 25 to 50 km wide on the northern side of the St. Lawrence River, between Montreal and Quebec City, McCormack (1983) identified about 180 water wells supplying a distribution system (or an industry). Twenty of these wells were drilled in the Precambrian bedrock (Grenville Province); the other wells were pumping water either from overlying sedimentary units of the St. Lawrence Lowlands, or from granular surficial deposits. McCormack found that water wells in the Precambrian bedrock generally yield less than 3 m^3/hr and are used for small communities with less than 500 people. Water wells with the highest yields in the bedrock are generally located in areas overlain by a significant layer of permeable sand or gravel, insuring a good groundwater recharge.

Singer and Cheng (2002) compiled a number of water well parameters for Northern Ontario using data obtained from Ontario's Water Well Information System (WWIS, Mantha, 1988). They distinguished data for wells in the Precambrian Shield (10,022 wells), in the Paleozoic sedimentary

TABLE 11.4 COMPILATION OF ROCK MAS HYDRAULIC CONDUCTIVITY VALUES REPORTED IN THE LITERATURE FOR THE CANADIAN SHIELD (FROM LEMIEUX ET AL., 2008B)

DEPTH	MEDIUM	HYDRAULIC CONDUCTIVITY K (M/YEAR)	POROSITY	REFERENCES[a]
Shallow (<500 m)	Matrix	10^{-5} - 10^{0}		3, 4
	Fracture	10^{-3} - 10^{3}	0.001 - 0.042	2, 3, 4
	Bulk	10^{-1} - 10^{2}	0.027	1, 5, 6, 7, 8
Deep (>500 m)	Matrix	10^{-6} - 10^{-4}		4
	Fracture	10^{0} - 10^{4}		4
	Bulk	10^{-2}		1

[a] The references are as follows: 1 is Raven et al. (1987), 2 is Raven (1986), 3 is Farvolden et al. (1988), 4 is Stevenson et al. (1996), 5 is Frost and Everitt (1997), 6 is Kuchling et al. (2000), 7 is Raven and Gale (1986), and 8 is Frost (1997).

rock cover (1,944 wells), and in the overburden (2,737 wells). A cumulative plot of the specific capacity of these wells on a logarithmic probability paper (Figure 11.10) shows approximately a straight line for each of these hydrogeological units, suggesting a log-normal distribution of the data. In this case, the 50% probability level corresponds to the geometric mean and to the most probable specific capacity value for a given hydrogeological unit. The geometric mean of specific capacity is 5.0 L/min/m (0.3 $m^3/h/m$) for the overburden wells, 2.5 L/min/m (0.15 $m^3/h/m$) for the wells completed in the Paleozoic rocks, and 1.9 L/min/m (0.114 $m^3/h/m$) for the wells completed in the Precambrian rocks. This geometric mean value of specific capacity for the wells completed in the Precambrian rocks is lower than all of the mean values given in Table 11.1 for Quebec; this is likely due in part to the fact that the geometric mean is generally lower than the arithmetic mean.

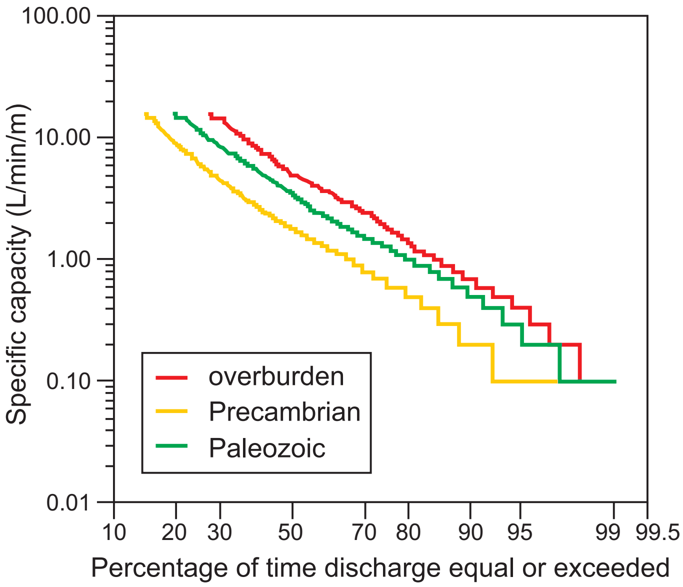


Figure 11.10 Specific capacity of wells completed in Precambrian, Paleozoic, and Quaternary formations in Northern Ontario (from Singer and Cheng, 2002).

Most of the detailed studies on the hydrogeology and the hydraulic properties of the bedrock in the Canadian Shield are related to the geological storage of radioactive nuclear wastes deep within crystalline rocks. These studies were mainly conducted in the Chalk River and Atikokan areas in Ontario, and at the Underground Research Laboratory (URL) near Pinawa, Manitoba. Lemieux et al. (2008b) presented results of a compilation of the hydraulic property values measured in the Canadian Shield and reported in the literature. Most of the values reported were derived from studies related to nuclear waste disposal. The objective of these studies was to examine the suitability of rocks of low permeability to isolate radionuclides for a sufficiently long time so as not to pose a threat to human health should a release occur from an engineered repository located at depth. Therefore, plutons and batholiths (intrusive bodies) which are less fractured than the other rocks of the Shield were primarily investigated. The values presented in Table 11.4 are thus biased by low hydraulic conductivity values.

11.5 CASE STUDIES AND SPECIFIC ISSUES

11.5.1 Groundwater vulnerability

Overburden aquifers on the Shield are often covered by relatively thin, fine-grained, low-permeability materials and so are, therefore, susceptible to contamination from the same point and non-point sources of potential contamination that threaten the quality of overburden groundwater in other hydrogeological regions in Canada. Bedrock groundwater on the Shield is also highly susceptible to contamination because protective overburden deposits are frequently thin or absent. Fracturing in the rock is capable of rapidly transporting near-surface contaminants to depths typically penetrated by water wells.

11.5.2 Contamination from natural sources

In certain settings granitic Shield rocks may also be a significant natural source of uranium and radium contamination for bedrock wells (Gascoyne, 1989). Betcher et al. (1988) reported that about 60% of the bedrock wells that they sampled in southeastern Manitoba had U concentrations in excess of the Canadian Drinking Water Guideline concentration of 20 µg/L, with maximum concentrations of about 2000 µg/L. They attributed this to the oxidation of reduced uranium that is often present in fracture minerals in this area. A number of Ontario and Quebec communities located on the Precambrian Shield have also shown elevated uranium concentrations in drinking water obtained from groundwater sources (Health Canada, 2006). Examples are water wells near the cities of Tweed and Dryden in Ontario, as well as a few wells in the Quebec regions of Laurentides, Outaouais, and Abitibi-Temiscamingue. Other radioactive elements, such as radium-226 and radium-228 have also shown concentrations exceeding 1.0 Bq/L, in some of these wells, particularly in the community of Kitigan Zibi in the Outaouais region. There appeared to be little correlation between the uranium and radium exceedance.

In the Abitibi region of Quebec, a few water wells in the bedrock show arsenic levels slightly exceeding the recommended limit of 0.025 mg/L (Poissant, 1997). In the Lake Saint-Jean area, fluoride has been observed exceeding the recommended limit of 1.5 mg/L in a number of wells (Simard and Des Rosiers, 1979; Walter et al., 2006, 2011). Less commonly, mafic Shield rocks may be a source of metal contamination for wells. About 50% of the wells sampled in the East Bull Lake gabbro-anorthosite pluton contained chromium concentrations above the guideline value of 50 µg/L. This is likely due to the weathering of Cr-bearing minerals such as pyroxenes, olivine and chromite present in the host gabbro (Raven et al., 1987).

11.5.3 Man-made contamination

As mentioned above, groundwater contamination from mine tailings is an important issue in mining camps located in the Canadian Shield. Other frequent sources of contamination include individual septic systems, municipal waste disposal sites, industrial waste sites related to metallurgical and forest industries, leakage of petroleum products from reservoirs, and infiltration of deicing agents used at airports.

11.5.4 Comparisons with other Shield areas in the world

Precambrian Shield is found in all of the continents of the World (Derry, 1980; Eriksson et al., 2004), under a wide variety of climatic and socio-economic conditions. The importance of groundwater in the Shield areas, as well as the type of interference with human activities varies accordingly: in some areas this groundwater constitutes the sole source of drinking water (Larsson, 1984), in other places, groundwater problems are related to tunnelling or mine excavations, to radioactive waste disposal, or to the extraction of geothermal energy (Gustafson et Krásný, 1994). In other parts of the World, exploration efforts are often required for source water supply in the Precambrian Shield and other bedrock basement regions, making use of a variety of approaches including lineament analysis (Magowe and Carr, 1999; Moore et al., 2002), structural geology and geophysical prospecting (Banks and Robins, 2002; Lipponen, 2006). Similar efforts should provide valuable information on the available groundwater resources in the Canadian Shield.

11.6. CONCLUSIONS

The Canadian Shield covers roughly half of Canada surface area and is constituted of fractured crystalline bedrock, Precambrian in age. The lithologies comprise belts of stratified or banded rocks, that have been metamorphosed and deformed to various degrees, as well as bodies of intrusive and highly metamorphosed rocks. These highly deformed units are overlain locally and unconformably by remnants of stratigraphic units deposited during a number of distinct episodes of sea invasion in the Proterozoic and Paleozoic eras.

These rock types are typically of low porosity, but the presence of discontinuities and fractures, such as joints, dykes, shear and fracture zones, allows for groundwater flow to take place locally, at different scales and down to a depth of a few kilometres. Groundwater is also present in granular aquifers, Quaternary in age, constituted of glaciofluvial deposits, put in place at the end of the last glaciations, and post-glacial deposits (large outwash plains and deltaic systems, particularly along Shield margins).

Hydrogeological data is available at few sites over the Shield region. These include a number of mine locations, as well as research sites for nuclear waste disposal. A general decrease in rock mass permeability with depth has been observed at many sites, as well as an increase in TDS within the groundwater. Mining constitutes the most important human activity in many areas of the Canadian Shield. Groundwater plays an important role in many aspects of that industry, from the mineral exploration stage to mine closure. Groundwater quality is also affected at several sites by tailings and waste rock associated with mining.

In recharge areas on the Shield, groundwater in the upper hundreds of metres in the bedrock is typically fresh with TDS values of up to about 500 mg/L. A gradual downward trend is observed from Ca-HCO_3 toward Na-HCO_3. Hypersaline brines are ubiquitous at depths greater than about 1000 m in the Canadian Shield. These brines are of the (Ca-Na)-Cl type with TDS values up to 300 g/L and are clearly unfit for most uses, particularly human consumption.

Discontinuities that extend to hundreds of metres in depth in the crystalline basement allow active circulation of low-salinity meteoric waters. Stable isotopes show that at higher elevations within the local catchments, groundwater originates through direct recharge. Shield groundwater below about 100 m is found to include a remnant glacial meltwater component recharged beneath the retreating margin of the Laurentide ice sheet at the end of the Pleistocene period, and evident from a characteristic depletion in both ^{18}O and D. Stable isotopes and geochemical constraints suggest that brines present at greater depths originate in some regions by infiltration of highly evaporated Paleozoic marine brine. Others may have evolved through leaching of salinity intrinsic to the rocks themselves. In all cases, extensive rock-water interaction and the ingrowth of radiogenic isotopes indicate that the Shield brines are of geological age.

CHAPTER 12

SOUTHERN ONTARIO HYDROGEOLOGICAL REGION

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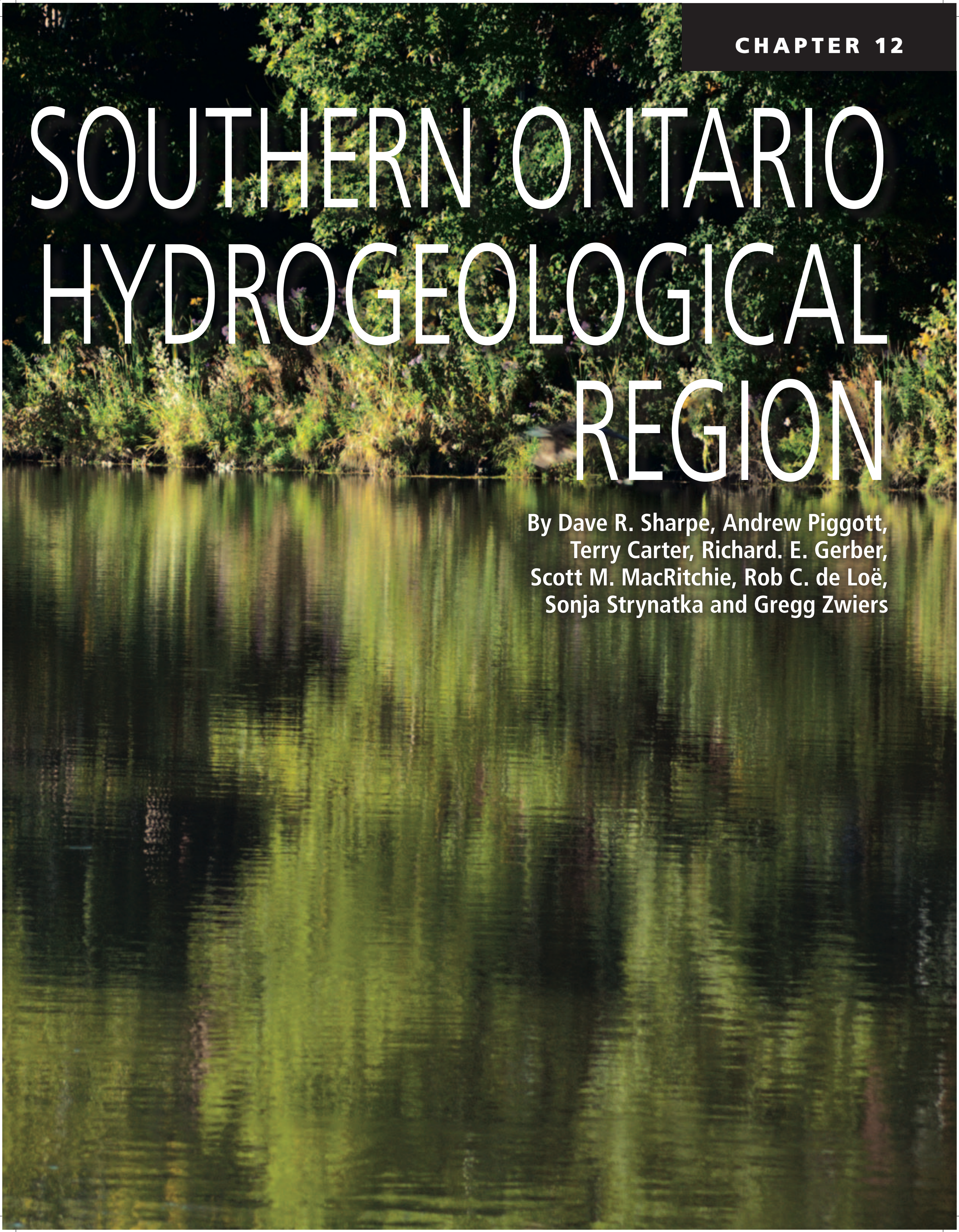

12.1 INTRODUCTION

Groundwater is vitally important to the quality of life enjoyed by the residents of southern Ontario and to the health of its economy and ecosystems. Groundwater is a significant source of water supply for agriculture, industry, and municipal and rural users. As a source groundwater is often more cost-effective than surface water. It is generally cheaper, needs minimum treatment, requires less costly pipelines, has uniform temperature, and has better water quality.

The goal of this chapter is to add to public understanding of groundwater resources in southern Ontario (e.g., Council of Canadian Academies, 2009). Water supply and quality issues are of increasing concern to Ontario's residents and there is growing awareness that lakes, rivers and streams are inextricably linked to groundwater systems. Driving this awareness are concerns about the long-term impact of climate change and the Walkerton tragedy in 2000 which put the spotlight on the issue of safety, security and sustainability of our water supply (see Box 12-1). Recent calls for action have come from the International Joint Commission (1999; which has jurisdiction over the Great Lakes basin) to protect water in the Great Lakes and to map groundwater in a systematic manner. As well, Ontario's Auditor General (2006) and its Environmental Commissioner (1997; 2000) have clearly identified the increasing needs and conflicts in water demand from urban, industrial and agricultural users, and the susceptibility of aquatic ecosystems to the impact of human activities in southern Ontario. These public concerns must be linked to groundwater science and considered in the management of our water resources.

How important is groundwater in southern Ontario (e.g., Cohen, 2006)? Current groundwater use in Ontario shows that a quarter of Ontario's residents, representing half a million households, are reliant on groundwater. About 1.3 million people use groundwater from private wells and 1.9 million from municipal supplies. Much groundwater use, other than drinking water supply, is for agriculture. For example, in agricultural counties of southwest Ontario, such as Middlesex and Elgin, about 25% of all groundwater use is domestic and municipal while agricultural use is closer to 30%. In those areas with significant sand and gravel operations, however, industrial use may be up to 35%.

About one-half of total streamflow in southern Ontario is estimated to be baseflow due to groundwater discharge. Surface aquatic habitats such as springs, streams, wetlands and many lakes depend on groundwater. The volume of groundwater discharge plays an important role in maintaining the depth of surface waters, or the "living space" used by aquatic organisms. With a constant temperature of 7°C to 9°C in southern Ontario, groundwater discharge maintains the conditions for cold-water fish such as brook trout. Groundwater sustains soil moisture along stream banks where healthy vegetation contributes to stream-bank stability. Groundwater can sustain food production, spawning areas, and connections along the channel and allow fish to access refuge areas during low-flow periods.

The analysis begins by looking at the climate and physical settings which provide the background necessary for understanding southern Ontario's groundwater resources. An examination of the hydrogeological framework which provides the geological overview for the water cycle and how it varies across different terrain conditions follows. The next section on groundwater resources

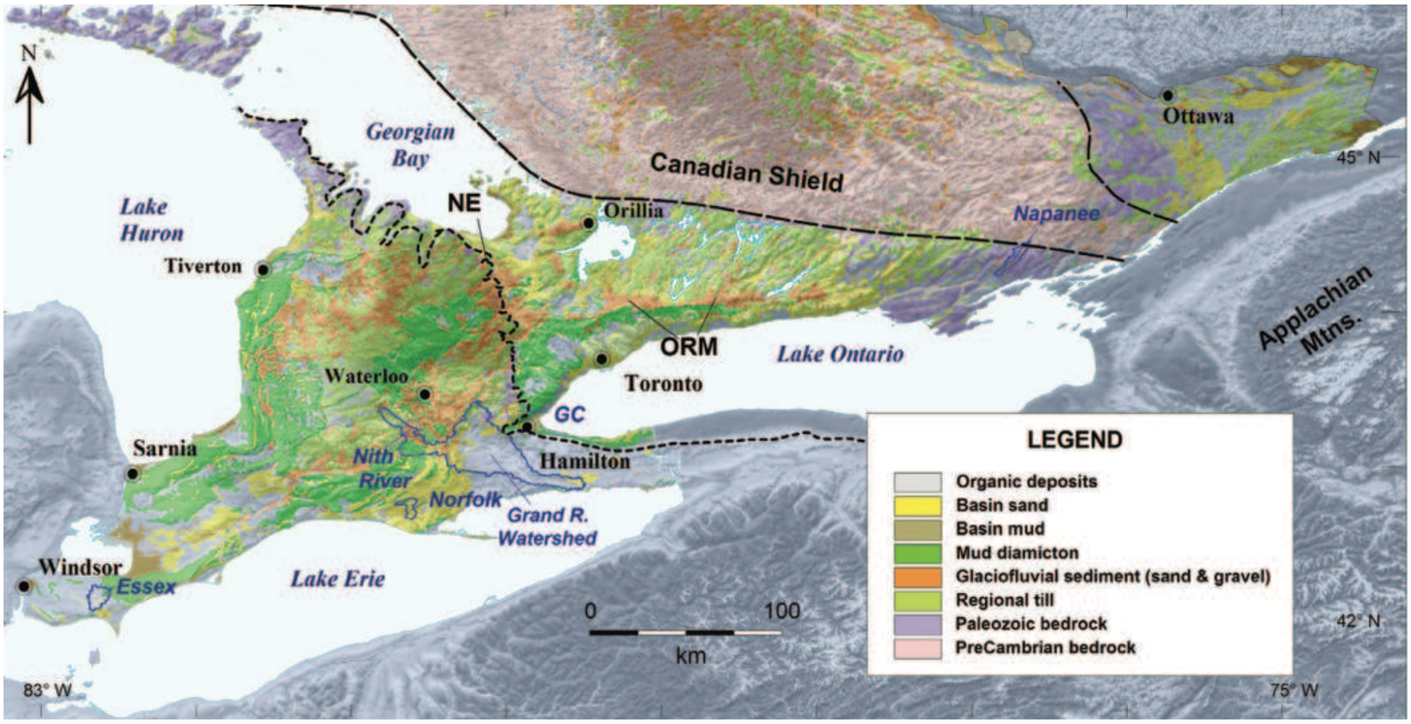

Figure 12.1 Geology guides the flow of groundwater.
The surface geology of southern Ontario, and adjacent areas such as the Canadian Shield, is draped on an elevation model to illustrate regional physiography. The generalized geology shows five main sediment types (sand, mud, diamicton or till, gravel and organic) plus the Paleozoic and Precambrian bedrock. It also illustrates that key hydrogeological terrains (blue outlines), to be discussed below, can be represented by the sediment types in which they are located. The Norfolk hydrogeological area is defined by sand; Essex by clay; Grey by till (east of Tiverton); Wellington by gravel (north portion of Grand river watershed); and Napanee by Paleozoic rock. Grindstone Creek (GC) and Nith River (NR) watersheds are also illustrated. NE= Niagara Escarpment; ORM= Oak Ridges Moraine. Tiverton is the site of a deep geological repository discussed later. Manitoulin Island is located in northern Lake Huron. Walkerton is located halfway between Waterloo and Tiverton.

offers a brief snapshot on groundwater availability and resource issues. Seven vignettes are interspersed throughout the text with a more detailed look at specific groundwater terrains and issues including 1. the Walkerton tragedy; 2. Norfolk sand plain, a sediment aquifer case study; 3. the Essex clay plain/ interface aquifer case study; 4. Napanee limestone plain aquifer case study; 5. fluoride and water quality; 6 the ecological significance of groundwater; and 7. Grand River watershed water budget (Figure 12.1).

12.1.1 Setting

Southern Ontario includes the sedimentary basins between Ottawa and Georgian Bay, bound in the south by the Great Lakes Huron, Erie and Ontario, and by the St. Lawrence River (Figure 12.1).

Southern Ontario covers an area of about 72,000 square kilometres, including Manitoulin Island, bounded by the Canadian Shield to the north and east, and by the Great Lakes to the south and west (Figure 12.1). The underlying bedrock is composed of Paleozoic marine sedimentary rocks deposited from the Cambrian through late Devonian time (~500 to 350 million years ago) and preserved in deep sedimentary basins. Hydrocarbon reservoirs are also present in the deeper parts of these sedimentary basins. Covering bedrock is unconsolidated sediment, mainly glacial, ranging up to 200 metres thick.

Southern Ontario has gentle topography, fertile well-drained soils, a warm growing season, and abundant rainfall, making it ideally suited to supporting extensive agriculture and woodlands.

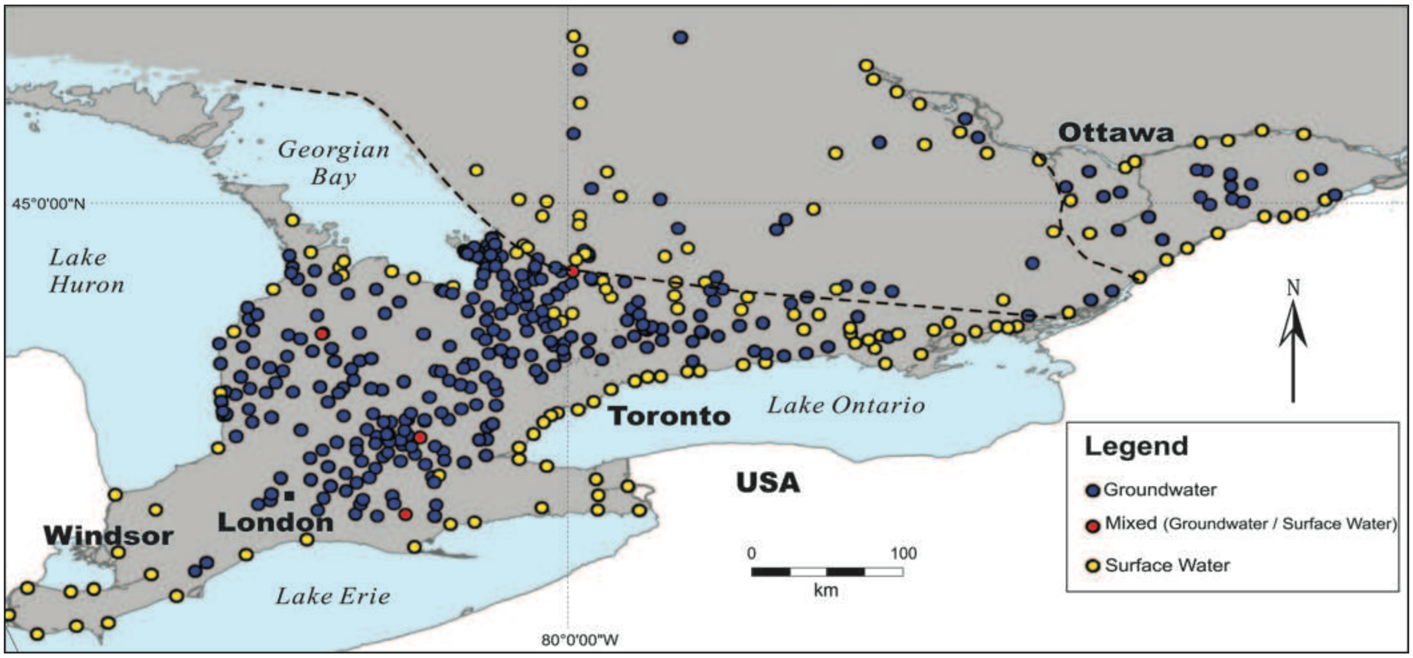

Figure 12.2 Do you use groundwater or surface water?
Municipal groundwater supply[1] is very prominent away from large, lake-based supplies. Water from Lake Ontario is used across much of the Greater Toronto Area despite the costs of treating this water and pumping it uphill to areas where groundwater is available. Map data was provided by the Source Protection Programs Branch, Ontario Ministry of Environment. London (black square) uses surface water from Lakes Erie and Huron (see also Ministry of the Environment, 2011).

The region is one of Canada's most important industrial hubs with a high population density: both factors affect land use and surface hydrology. Despite the proximity of abundant Great Lakes surface water, groundwater is a pivotal resource for agricultural and potable water use in inland areas, with about 90% of rural areas in southern Ontario and some 200 municipalities using groundwater as their primary water source (Figure 12.2).

12.1.2 Climate

Southern Ontario has a humid continental climate with warm to hot summers, cold winters, and reasonably uniform precipitation throughout the year (Brown et al., 1980). The Great Lakes modify the climate of the region, moderating temperatures inland from the Lakes and producing lake effect precipitation in areas east of Lake Huron and Georgian Bay (Figure 12.3). Average annual temperature varies (Figure 12.4) from 3.9°C in the north to 9.4°C in the south with a regional average of 6.1°C. Average monthly temperatures at Petawawa, west of Ottawa, vary from –12.9°C in January to 19.1°C in July. Temperatures at Windsor vary from –4.5°C in January to 22.7°C in July. Average annual precipitation also varies across the region (Figure 12.3), from 790 mm near Toronto to 1,200 mm in Bruce County, east of Lake Huron, with a regional average of 960 mm. Average monthly precipitation at Toronto varies from 43 mm in February to 80 mm in August. Precipitation at Paisley, near Lake Huron where lake effect precipitation is pronounced, varies from 70 mm in April to 150 mm in December.

12.1.3 Physiography

Topography and the types of soils and sediments at the surface are factors which determine how groundwater flows. Southern Ontario is part of

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[1] Map data provided by the Source Protection Programs Branch, Ontario Ministry of Environment, who provide guidance for the safe operation and security of municipal water supply systems.

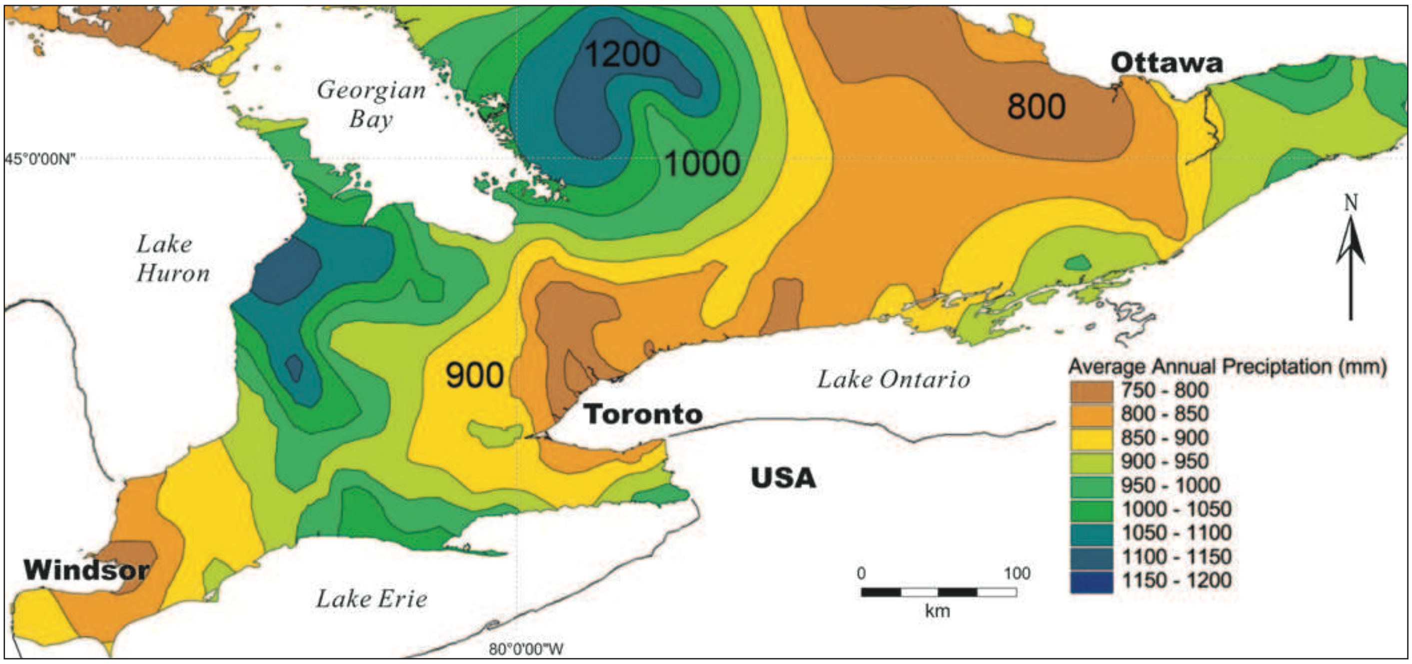

Figure 12.3 Precipitation nourishes streams and the groundwater system.
There is variation of average annual precipitation across southern Ontario. Data Source is Meteorological Service of Canada—Ontario Region; Internal Data Courtesy of National Climate Data and Information Archive.

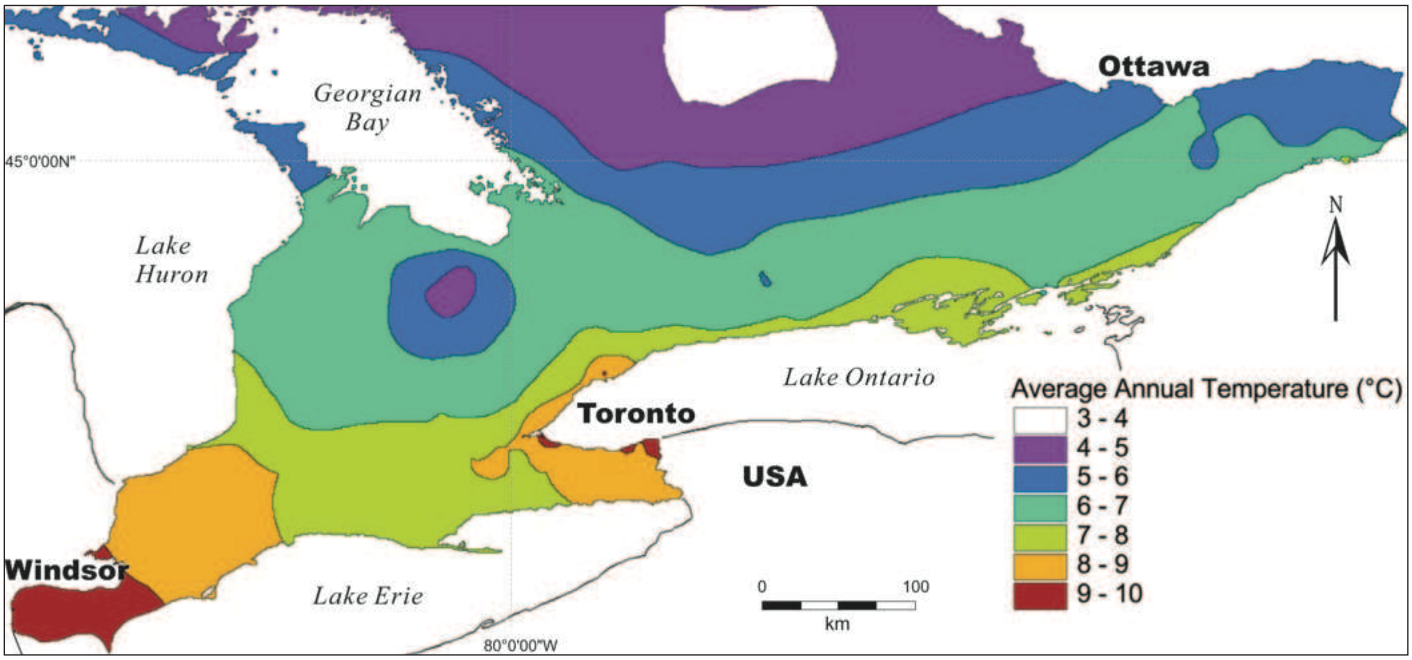

Figure 12.4 Temperature influences evaporation and transpiration, and hence the hydrologic cycle.
There is variation of average annual temperature across southern Ontario, particularly from southwest to northeast. Data Source is the Meteorological Service of Canada—Ontario Region; Internal Data Courtesy of National Climate Data and Information Archive.

the Great Lakes/St. Lawrence watershed that drains the lowlands between the Canadian Shield to the north and the Appalachian uplands to the south (Figure 12.1). This watershed is distinguished by low-relief bedrock topography interrupted by buried valleys and prominent escarpments. Southern Ontario's most significant high-relief feature is the Niagara Escarpment, a 725-kilometre-long, 100-metre-high bluff that extends from Niagara Falls to Tobermory at the tip of the Bruce Peninsula and to Manitoulin and Cockburn Islands, which separate Georgian Bay and northern Lake Huron. At its highest point, the Escarpment reaches about 500 masl and slopes gently southwest on inclined rock strata. The escarpment has been eroded over geological time which has led to enhanced fractures and cavities of the soluble escarpment cap rocks. More recently the escarpment has been eroded primarily by glaciation.

Southern Ontario's landscape is very much the result of the advance and retreat of the massive, kilometres-deep ice sheets that completely covered it until more than 10,000 years ago. Glaciers and their meltwater shaped the landscape largely by erosional and depositional processes during the Quaternary period. This 2-million-year era was a period of dramatic climate change with repeated cool episodes of glacial advance/retreat and intervening warm, inter-glacial periods. It was characterized by the accumulation of up to 200 m thick glacial, glacial-lake, glacial-river, and non-glacial deposits (Barnett, 1992).

Moraines, landforms containing undulating slopes formed as the ice melted and receded during the last ice age, are another important topographic feature found throughout southern Ontario. The Oak Ridges Moraine (ORM) is the largest and most significant rising up to 300 metres above Lake Ontario to form a series of mounds and ridges and a ~160 km long drainage divide between Lake Ontario and Georgian Bay (Figure 12.1). More typically moraines, and other common ice age landforms such as drumlins and eskers, provide lower-relief terrain and are 10–25 metres high. The ice age also left many prominent surface valleys with relief of 25–50 metres, largely developed as meltwater channels. Low-relief terrain, such as clay plains and sandy outwash deposits, have been incised by modern rivers to depths ranging from 10 to 25 metres as the land continues to rise following the melting of the thick ice sheets.

The varied and complex glacial deposits resulted in equally complex local groundwater flow patterns which can vary within 100s or 1000s of metres. Changes in the landscape wrought by the glaciers are still happening. Although the weight of thick glacial ice compressed the land, it is still rebounding at the rate of a few cms per century, which over time slowly disrupts drainage patterns. The load of the ice and the discharge of its meltwater during the glacial period also affected the flow of water deep below the land surface and changed the chemistry of this water.

12.1.4 Geology

Ancient (Paleozoic) marine sedimentary rocks of the Michigan and Appalachian Basins are the dominant geological feature of southern Ontario and exert a controlling influence on groundwater storage and regional flow directions (Figure 12.5). The basins are separated by a northeast-trending basement ridge known as the Algonquin Arch (to the northeast) and by the Findlay Arch (to the southwest). The Findlay Arch, in turn, is separated by a structural depression known as the Chatham Sag. These arches likely formed during basin subsidence, and together with the basins, control groundwater flow directions. Strata dip gently at 3.5 to 12 m/km westward into the Michigan Basin north of the Algonquin and Findlay Arches, and southward into the Appalachian Basin on the arches' south side (Figure 12.5). Bedrock strata along the crest of the Algonquin Arch have a regional southwest dip of 3 to 6 m/km into the Chatham Sag (Armstrong and Carter, 2010).

East of the Niagara Escarpment, bedrock strata younger than Ordovician age have been eroded away exposing subcropping Paleozoic bedrock consisting of sandstone, siltstone, shale and carbonate rocks of the Ordovician (~488 to 444 million years ago) and late Cambrian age (~500 to 488 million years ago). West of the Niagara Escarpment, carbonate and evaporite rocks are prominent in Silurian age (444 to 416 million years ago) formations that extend from Lake Erie to Georgian Bay and Lake Huron. Younger carbonate and shale rocks of Devonian age (416 to 359 million years ago) occur to the southwest near Sarnia, and extend eastward to the Niagara River. In general, strata in the Appalachian Basin are more clast-rich in composition, while those in the Michigan Basin are more carbonate-rich. Thick evaporite and halite (salt) beds also occur within the Michigan Basin.

Paleozoic bedrock has variable porosity and permeability depending on grain size, lithology, sorting, depositional setting, lateral facies changes, fracturing, and post-depositional weathering and alteration. In general these bedrock tiers form a thick stratified succession of aquitards with a few thin, confined aquifers (underground water-bearing units) and erosional breaks; flow directions are controlled by regional dip of the strata (Figure 12.6). The dominant control on the occurrence and movement of water in these rocks, and in particular the carbonate and evaporite rocks, is their proximity to the present-day erosion surface and/or paleo-erosion surfaces represented by unconformities in the deep subsurface bedrock (Carter and Castillo, 2006). Chemical dissolution of carbonate and evaporite rocks at these unconformities has created major regional aquifers in the subsurface, at the present-day surface, and in areas of thin sediment cover (Brunton et al., 2008; see Figure 12.12). Where these same rocks have not been exposed to surface weathering and dissolution they form aquitards and even aquicludes (no water flow). The best example of this phenomenon is the Salina Group. The beds of halite, anhydrite, dolostone, limestone and shales in the deep subsurface that form the Salina Group have no effective permeability, and form aquicludes where thick beds of halite are still present. In the near-surface, the halite and anhydrite dissolve in the presence of fresh groundwater and meteoric water, and the rock is reduced to a karstic rubble of rock fragments with greatly enhanced porosity and permeability. Recognition of these surface karst terrains (see Figure 12.12) and subsurface karst intervals (Armstrong and Carter, 2010) is critical to understanding the movement of water in Paleozoic bedrock and development of accurate models of water movement in bedrock.

Southwestern Ontario is tectonically stable. Faults are widely spaced, with a maximum vertical displacement of ~100 metres on steeply dipping normal faults (Armstrong and Carter, 2010). Modelling of fracture systems by Sanford et al. (1985) indicates the greatest density of fracturing and faulting is along the crest of the Algonquin and Findlay Arches and in the Chatham Sag. Paleozoic rocks in the Ottawa area, have been affected by block faulting (Late Mesozoic) along the Ottawa-Bonnechere graben (tectonic zone). Faulting is most severe near the Ottawa River with vertical displacement of up to 1,000 metres on steeply dipping normal faults (Williams, 1991). Such faults received large amounts of fresh glacial meltwater which was forced deep into the bedrock (>100 m in depth) by thick glacial ice during glaciation, pushing brackish and saline water deeper into the basin. The glaciers eroded the bedrock

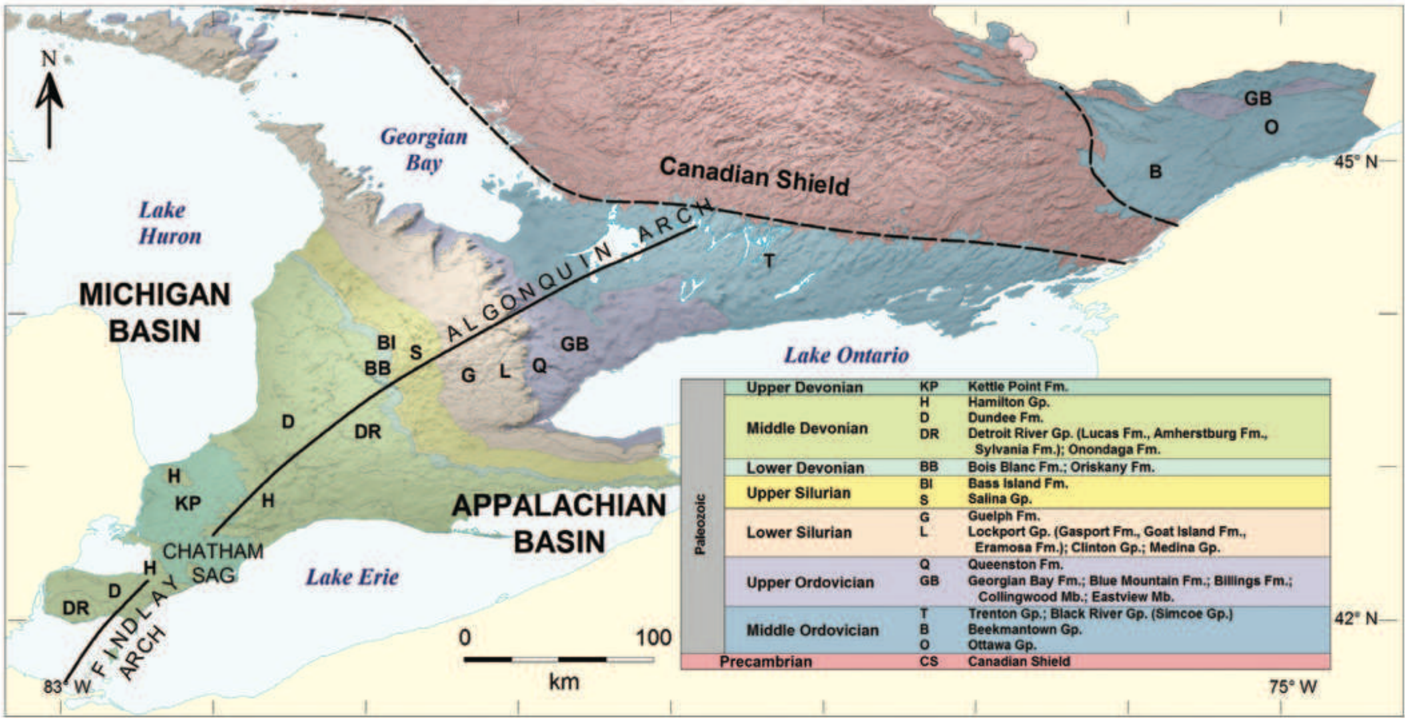

Figure 12.5 Geology and topography of the bedrock surface.
Geological setting and bedrock strata of southern Ontario[2] control groundwater flow at larger scales than does surface topography. Bedrock strata form barriers to downward movement of fresh water except where these rocks have been fractured, weathered or affected by karst. Bedrock strata may control the location of bedrock valleys due to differential erosion (see Figure 12.9). The map illustrates major structural elements (arches and basins), major formations (marked by letters) and major age groups (marked by colours) on an elevation model. Arch locations varied at different points in geologic time. It is important to note that the time-stratigraphic correlation of the Silurian is undergoing revision (Cramer et al., 2010) and the term "Amabel" has been abandoned and replaced by Lockport. The oldest rocks (Canadian Shield), in the north and east, are overlain by successively younger ancient marine rocks from northeast to southwest. The Niagara Escarpment occurs at the eastern margin of where hard carbonate rocks overlie soft, more erodible shale rocks (see Figure 12.9). Cambrian strata are not shown on this map, but are exposed on the eastern flanks of the Frontenac Arch of the Canadian Shield (narrow area east of Lake Ontario).

and partially covered the landscape with glacial sediment, which again altered groundwater flow patterns within the basin. In recent times, without glacial loads and pressures, fresh water typically reaches shallower depths (<100m) below ground surface (Figure 12.6).

Bedrock is covered by thin unconsolidated clastic sediments of glacial or recent origin in most of southern Ontario (Figure 12.1): its thickness ranges from zero to >200 metres, but is usually tens of metres thick. Sediment cover is thinnest near escarpments and along river valleys. The thickest sediment occurs along buried bedrock valleys, such as the Laurentian valley connecting Georgian Bay and Lake Ontario (Figure 12.9), and below major moraines such as the Oak Ridges Moraine. Thick sediment also fills or partially fills former meltwater channels important to regional groundwater flow. The variety of sediment types affects groundwater infiltration toward bedrock, and includes sand, clay, till uplands and sand and gravel channels that dissect uplands.

12.1.5 Key groundwater information sources

12.1.5.1 Province-wide reports

Understanding of regional groundwater systems and their related settings in southern Ontario comes from past geologic and hydrogeologic frameworks (e.g., Scott, 1967; Sibul et al., 1977; Turner, 1977; 1978; Barnett, 1992; Farvolden and Cherry, 1988;

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[2] Geology from Armstrong and Dodge (2007).

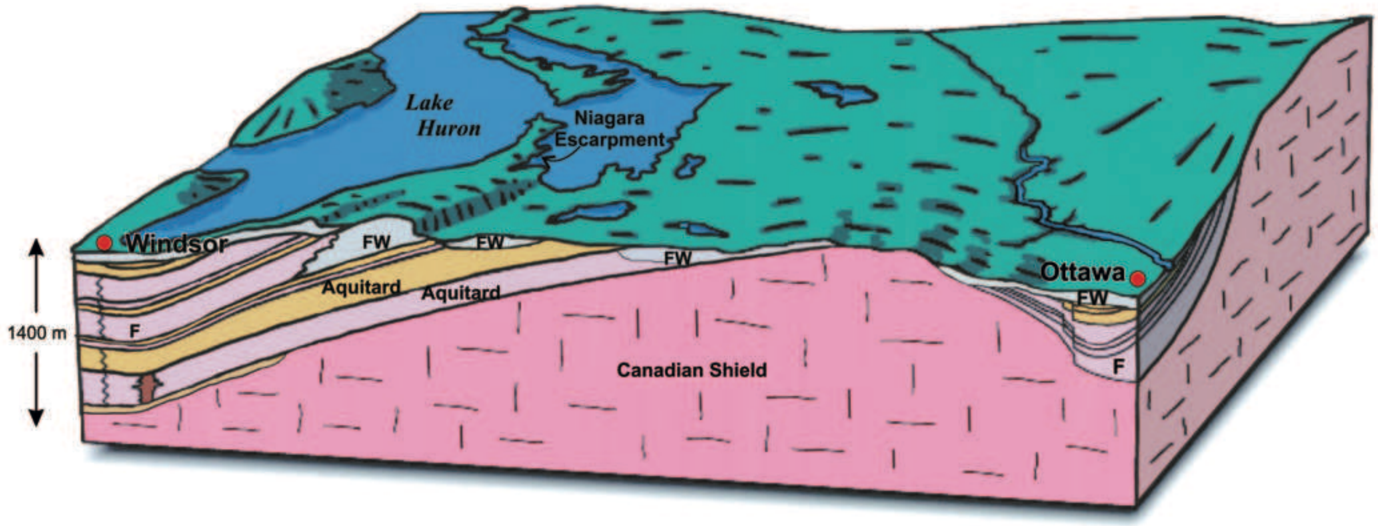

Figure 12.6 Geology below the surface and groundwater flow.
This geological cross section extends from Windsor to the corner of southeastern Ontario. It shows generalized bedrock lithology (purple—carbonate rocks, orange—shaley rocks) with a ~10–100 m thick sediment zone near the surface (light grey). The thicker grey zone indicates enhanced recharge and deeper flux of fresh water in karst and reefal shallow carbonate bedrock along the Niagara Escarpment area to depths beyond 100 m. Bedrock units identified as aquifers are only viable in the top 100–250 m below surface; deeper water becomes brackish to very salty. Note faults (F) in the Ottawa valley basin sequence. Geology is from Armstrong and Dodge (2007) and Sanford and Arnott (2010).

Novakowski and Lapcevic,1988; Johnston et al., 1992; Karrow, 1989; Singer et al., 1997; Eyles, 2002), and, from synoptic reports such as "Groundwater in Ontario" by MacRitchie et al., 1994 and "The Hydrogeology of Southern Ontario" by Singer et al., 2003; from a series of municipal groundwater studies (e.g., Oxford County, 2003) that preceded the serious water problems at Walkerton; and from Source Protection watershed assessment reports which followed the Clean Water legislation.

The MacRitchie report highlights major groundwater sources, quality, and management across Ontario. It identifies several major aquifers within the region (the Alliston, Oak Ridges and Waterloo moraine aquifers in sediment, the Lockport-Guelph and Detroit River Group carbonate aquifers, and the Nepean sandstone aquifer in eastern Ontario, for example).

The Singer report describes the occurrence, distribution, quantity and quality of groundwater on a regional scale in southern Ontario, based on more than 215,000 water well records. The report combined this data with physiography, geology and hydrogeological information to create synoptic maps of key parameters and regional relationships. Groundwater was analyzed according to major geological formations, and the occurrence of wells drilled in bedrock and/or in sediment. The wells were assigned as water sources, specifically as 18 bedrock aquifers and 164 sediment aquifers, including a number of well-known aquifer systems. New geological insights, in particular the recognition of a regional interface or contact zone aquifer system at the point of contact between bedrock and the unconsolidated sediments, has led to the realization that sediment and bedrock waters in the near surface are mixed and cannot easily be classified as strictly bedrock or sediment aquifers. Groundwater quality may form a continuum between bedrock and sediment settings.

Of particular note in Singer's report, data from 33 stream gauges indicated highest groundwater discharge during spring, with an ensuing decline until fall precipitation. This data was also used to estimate a long-term mean groundwater recharge of between ~83–285 mm per year, depending on soil and slope conditions. Groundwater quality, tested in over 1,000 samples and from well records, is generally very good across the region with some natural and man-made water quality issues. Anthropogenic effects have led to many problems in shallow aquifers which are poorly protected from near-surface contamination sources. The main concerns for groundwater quality and management are waste and sewage disposal, agricultural activities, and road salt application.

12.1.5.2 Municipal groundwater studies and Source Protection assessment reports

From 1999 to 2005, groundwater studies were produced for each Ontario municipality which utilized a groundwater supply for drinking water (see conservation authority or municipality websites). These studies examined groundwater resources at local and regional levels to identify potential risks. The studies included delineation of wellhead protection areas for municipal wells, mapping of groundwater recharge and discharge areas, and identification of sensitive groundwater areas. The resulting groundwater management plan was designed to manage activities which would reduce the risk of contaminating drinking water supply for each municipality.

The Clean Water Act (Province of Ontario, 2006) provides a framework for the development and implementation of local, watershed-based Drinking Water Source Protection plans. The Act also implements the Drinking Water Source Protection recommendations made by Justice Dennis O'Connor in Part II of the Walkerton Inquiry Report. The Act came into effect in July, 2007, along with the first five associated regulations (O'Connor, 2002).

To comply with the Act, municipalities and conservation authorities have conducted technical studies to delineate those areas around municipal drinking water sources (groundwater supplies) which are most vulnerable to contamination and overuse (Ministry of the Environment, 2004). Within vulnerable areas, the studies have identified historical, existing and possible future land uses that are, or could pose, a threat to municipal water sources. The resulting Assessment Report provides the scientific foundation to develop a Source Protection Plan for each region (Figure 12.7); such plans aim to eliminate significant threats and prevent new ones from developing.

Source Water Protection is focused on municipal water supplies, but rural residents also require groundwater advice and protection. Some 90% of southern Ontario's rural residents rely on groundwater and use ~750,000 private wells; ~20,000 new wells are drilled each year. There are an estimated 100,000 abandoned wells, and because these wells are not serviced, they may pose a contamination threat as they offer a preferential flowpath from surface land uses to the aquifer system.

While Ontario regulations require that all residential well owners keep their well accessible at all times for cleaning, treatment, repair and inspection, many homeowners compromise the integrity, reliability and safety of their wells, and possibly those of their neighbour's through poor practices. Indeed, a high percentage of wells in southern Ontario suffer from poor location, construction and maintenance. A recent survey of over 1,500 private well owners in Ontario, conducted by the Water Policy and Governance Group, found that many well owners do not understand how to protect their water supplies through testing and inspection (Kreutzwiser et al., 2010). The

Figure 12.7 How is Ontario safeguarding groundwater following Walkerton?
Ontario is subdivided into a number of Source Water Protection Areas and Regions. Each area must prepare an assessment report and a Source Water Protection Plan (see Ministry of the Environment SWP website http://www.ene.gov.on.ca/environment/en/subject/protection). Source Protection Areas are grouped into Source Protection Regions led by a Source Protection Committee responsible for guiding the required technical studies, setting standards, and developing planning policies to protect drinking water supplies within each region.

Well Aware program (http://www.wellaware.ca/) provides a full range of practical information on safe practices in well construction, maintenance, decommissioning, and protection of groundwater to ensure that wells are in safe running order.

12.1.5.3 Groundwater monitoring, databases, and mapping

The Ontario Ministry of the Environment (MOE) operates the Provincial Groundwater Monitoring Network (PGMN) in partnership with 10 municipalities and all 36 Conservation Authorities (e.g., Ministry of the Environment, 2007). As of 2012, the PGMN consisted of 435 groundwater monitoring wells located in southern Ontario. These wells were selected to provide scientific information on groundwater quality and levels in the area. Water samples from the wells are collected annually and analyzed for a variety of chemicals. Groundwater levels and chemistry collected by the PGMN can be accessed on the MOE website http://www.ene.gov.on.ca/environment/en/resources/collection/data_downloads/index.htm#PGMN.

Groundwater quality is also monitored at selected municipal drinking water systems under the Ontario Drinking Water Surveillance Program, which provides information on the quality of raw (untreated) water and treated drinking water. The raw water quality data can be used to assess ambient environmental conditions, and complements information collected by the Provincial Groundwater Monitoring Network.

Two databases are the principal sources of basic information on the occurrence of groundwater and subsurface geology in southern Ontario. The Water Well Information System, maintained by the Ontario Ministry of Environment, contains over 600,000 records, including basic data on well location, sediment or rock type, water quality, quantity and static level, pumping rates and well construction. The Ontario Petroleum Data System, a relational database, is maintained by the Petroleum Resources Centre of the Ontario Ministry of Natural Resources. These records provide geological, drilling and engineering information on over 26,000 petroleum wells drilled in Ontario since the 1800s. Stored data includes well location, status, depths, geological formation tops, well construction, oil/gas/water intervals, logging and cored intervals, and drill samples. Water interval data includes depth, elevation, static level, water type and geological formation; the basic well data is available free of charge from www.ogsrlibrary.com, but oil/gas/water and geological data access is restricted to Library members. Water well data from across southern Ontario is publicly available for viewing at http://ontariogroundwater.com/.

Maps, reports and digital data on the surficial and bedrock geology of Ontario can be found on the Geology Ontario website available at http://www.geologyontario.mndm.gov.on.ca/. This website provides access to geoscience information from the Ontario Geological Survey, with its 1,000s of reports and 1,000s of maps which include digital field data, geophysical surveys and geochemical analyses for the region.

The Ontario Geological Survey has a program of aquifer mapping to characterize the geology and geochemistry of groundwater in southern Ontario. This includes 3D mapping of aquifers in sediments and bedrocks, mapping of karst and bedrock aquifers of the Niagara Escarpment (e.g., Bajc and Shirota, J. 2007; Brunton, 2009; Brunton and Brintnell, 2011), and characterization and mapping of the geochemistry of natural groundwater. Geochemical results from over 900 water wells (Hamilton, 2011) represent the largest and most complete regional database of ambient groundwater chemistry for southwestern Ontario, in addition to complementing data available from PGMN. The Geological Survey of Canada also has regional hydrogeological information available on its websites.

12.1.5.4 Accessible groundwater information

With growing public awareness and concerns about groundwater, information is in increasing demand from many of the above-mentioned government agencies. To meet this demand and to accommodate users' preference for web accessible information, a national Groundwater Information Network (http://gw-info.net) has presented a web-based system for mapping and analyzing water-well and monitoring data. This website enables users to find, view (in 3D), analyze, download and model their well and water resource data online. Decision-making requirements regarding groundwater resources are therby enhanced. It is hoped that this online groundwater resource centre, a cross-country collaboration of water agencies, will advance web-based groundwater data technology and improve knowledge of watersheds.

12.2 HYDROGEOLOGICAL FRAMEWORK

This section examines water movement through the landscape and seeks answers to several basic questions: What factors control the movement of water in southern Ontario once it reaches the surface or enters underground pathways? What are the important water-bearing (aquifers) and water-controlling (aquitards) formations? Where are these aquifers located and how can we assess them to improve knowledge of groundwater and related surface water flow? and, finally, is the quality of groundwater and surface discharge affected by southern Ontario's rock and/or sediment types through which the water flows?

Water-bearing formations must be assessed with respect to their elevation within the landscape and their soil or rock properties. Topography provides the gradient which drives water flow. Geology, through internal rock or sediment properties, controls how flow occurs through sediment or rock. A descriptive framework, therefore, begins with geology and topography. Next, we need to look at how water enters the subsurface (groundwater recharge), how it flows through the subsurface (hydrogeologic properties), and where it leaves the subsurface (groundwater discharge).

12.2.1 Bedrock topography and overlying sediment thickness

Variations in bedrock topography and overlying sediment thickness affect groundwater flow. These factors, along with the composition of bedrock and sediment units, affect the quality of water in the flow system. Bedrock irregularities occur where softer rock (e.g., shale, evaporite) was preferentially eroded, while harder rock (e.g., limestone) resisted erosion, leaving escarpments and troughs on the landscape. Sediment thickness and bedrock topography maps are consequently prime prospecting tools in the search for new aquifer water supplies in southern Ontario's thick sediment or shallow bedrock (Figure 12.8). These maps are also useful for identifying depth to the important contact zone aquifers.

The geographic distribution of southern Ontario's most important aquifers has been mapped by combining bedrock elevation and sediment thickness data, modified by water well usage in each of these main strata, bedrock and sediment (Figure 12.8b, c). Shallow bedrock and the contact zone between bedrock and sediment (contact zone aquifer) are targeted for groundwater in many areas except where sediment is thick, such as bedrock valleys and areas of stratified moraines. Thick sediment areas are the best areas for high-yield wells in unconsolidated sediment. The importance of bedrock aquifers may be qualified insofar that many wells drilled into bedrock obtain fresh potable water from overlying sediments. This contact zone aquifer has been identified as a discrete and separate bedrock aquifer in previous studies (e.g., Singer et al., 2003), but it is, in fact, a connected, complex, semi-confined or unconfined aquifer system of regional extent occurring at the contact between the Paleozoic bedrock and overlying sediments. A special case of a contact aquifer occurs where bedrock and sediment meet in a sediment-filled bedrock valley.

12.2.1.1 Laurentian buried valley

Buried bedrock valleys have been known in southern Ontario since the 1880s when geologist J.W. Spencer (1881; 1890) suggested that an ancient Laurentian river network might have helped form the Great Lakes. The Laurentian valley, 20 km by 80 km with sediments ~100–200 m thick, is located beneath the urban region west of Toronto and has considerable groundwater resource potential (Figure 12.9). Owing to the expense of collecting data from such depths, we have a poor idea of the form, geometry and nature of these buried valleys (Russell et al., 2007). Many municipalities across southern Ontario need to increase water supplies from groundwater, yet they lack the knowledge and tools to assess potential aquifers in buried valleys (Russell et al., 2007). Existing maps based on water well records show only general trends for prospecting (Figure 12.9). To improve mapping and to assess sustainable groundwater use require an enhanced geological framework provided by high-quality subsurface data.

A modern prospecting tool, the seismic survey, gathers reflected subsurface sound waves to provide amazing new cross–sections of buried strata down to bedrock (Figure 12.10). The Nobleton profile reveals a 1.5 km wide portion of the Laurentian bedrock valley overlain by a layered sequence of strata. A borehole, drilled into the bedrock along the profile to a depth of 192 m, yielded a continuous sediment core, downhole physical properties, and samples for particle size, water content, and sediment structure, all of which helped develop models of valley formation. This high-quality data provides a completely new picture of the

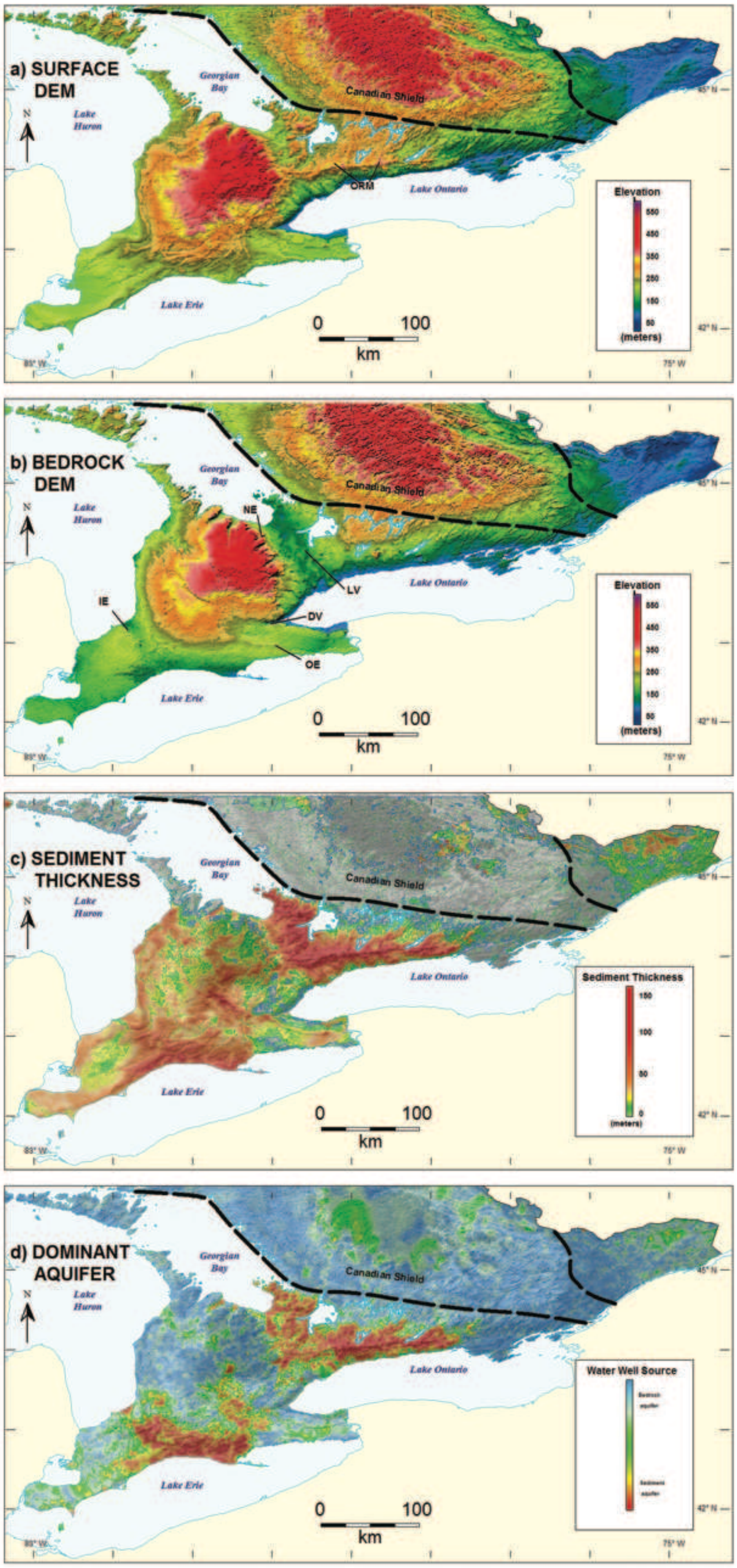

Figure 12.8 Slope and rocks determine how water moves through the landscape.
a) surface topography provides a gradient for surface runoff and groundwater flow to streams, ponds and lakes: the red areas represent high elevation and the blue areas low; b) shows the bedrock topography, with major escarpments: NE= Niagara, OE=Onondaga, IE=Ipperwash and valleys; LV=Laurentian, DV=Dundas; c) shows sediment thickness. Note that thick sediment occurs below major escarpments and in stratified moraines (e.g., Oak Ridges Moraine); d) shows dominant aquifers in sediment or bedrock based on the numbers of wells completed in each setting; these two regional aquifer settings are discussed in more detail later. In summary, groundwater tends to flow away from the topographic high near the Niagara Escarpment and to become stored in areas of thick sediment and along the contact between sediment and rock, and in areas where bedrock valleys occur (from Hinton et al., 2007). Note variation in colour bars.

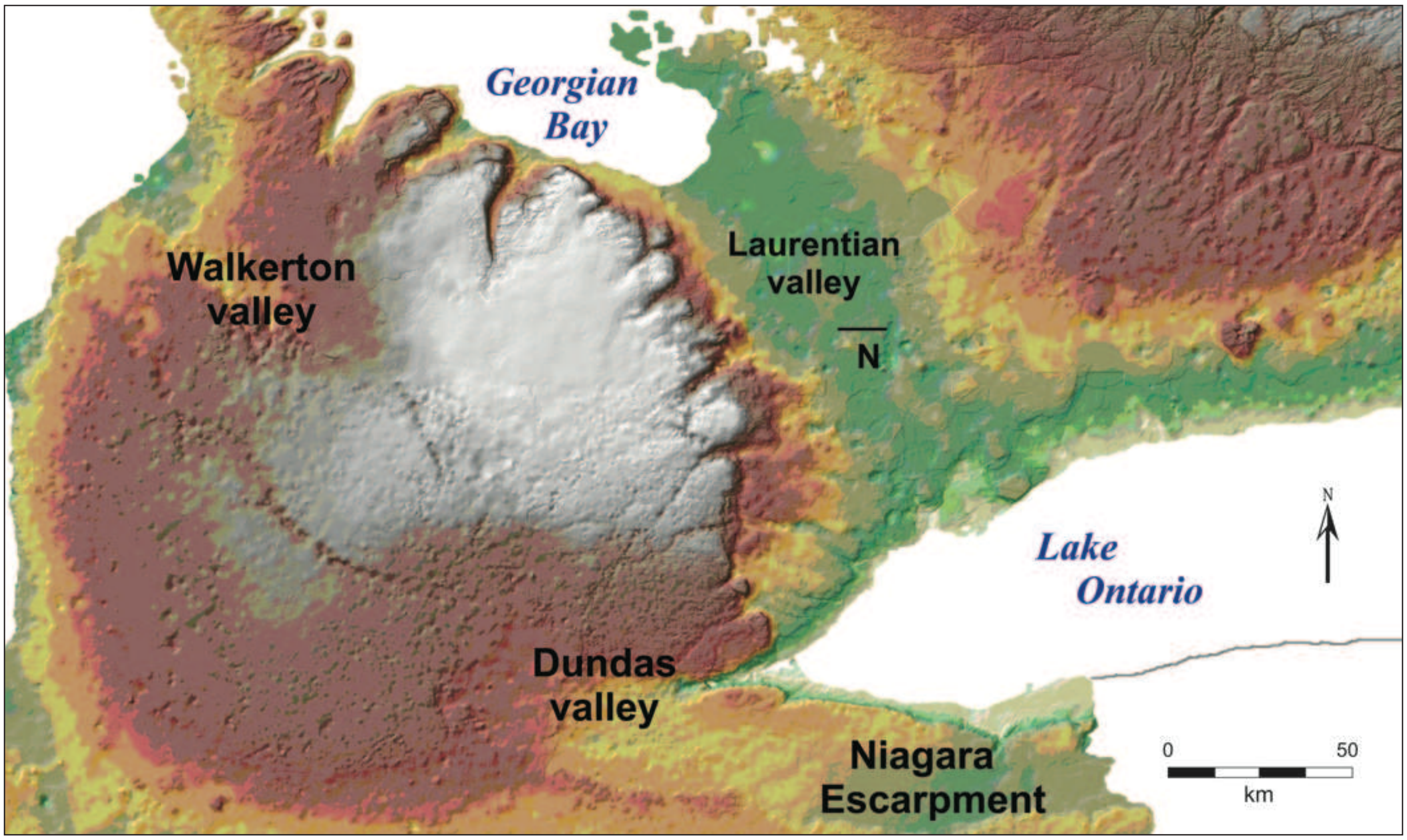

Figure 12.9 Where soft rocks meet hard rocks.
This bedrock topography map (from Gao et al., 2006) shows hard carbonate cap rocks of the Niagara Escarpment that resisted erosion, while the softer shale rock in the Laurentian (buried) valley to the east was heavily eroded to form a deep (~200 m) depression. The map also indicates the general location of other buried valleys, such as the Dundas valley and the Walkerton valley, as determined from water well records. Some bedrock valleys correspond to the subcrop location of easily eroded bedrock formations. For example, Walkerton Valley corresponds to the location of the evaporite rocks of the underlying Salina Group. N marks the location of the Nobleton subsurface seismic profile.

subsurface, context for water-level monitoring, and guidance for understanding groundwater flow patterns.

The movement of water in bedrock valley aquifers depends on many factors including the complex geology of the valley infill. Gravelly valley infill favours flow, but it may not be continuous along the valley floor. The lack of deep borehole data and no seismic profile leads to uncertainty with respect to potential connecting segments for bedrock valley aquifers. Water level monitors can record aquifer connection along bedrock valleys. Hydrographs for deep test wells at three locations along a valley tributary to Laurentian bedrock valley (Figure 12.9) show that many of the seasonal fluctuations observed in the shallow groundwater flow system are also evident in the deep bedrock valley system. This indicates that surface water is hydraulically connected to deep groundwater levels. Long-term groundwater pumping tests, temperature fluctuations and groundwater chemistry may indicate aquifer connection along these valley sites if there is a similar water level response to the groundwater pumping.

Buried bedrock valleys may contain very productive aquifers and their potential impact and value warrants the expense and time required to carry out exploring for them. Analysis and interpretation are needed to improve both the hydrogeological understanding of buried valleys, like the Laurentian valley, and the regional exploration for buried-valley aquifers (Davies, et al., 2008a,b).

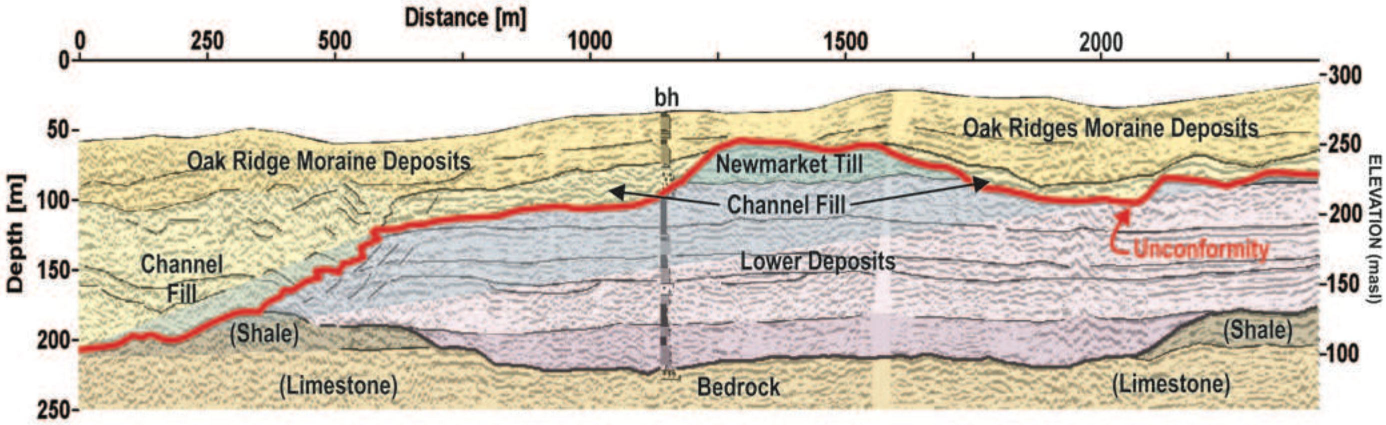

Figure 12.10 Sound waves map of a buried bedrock valley.
A section of the Nobleton west-east seismic profile depicts the Laurentian valley (bedrock channel) where it cuts through shale into limestone bedrock. A borehole core (bh, vertical line) records glacial sediments that fill Laurentian valley: aquifers (yellow) and aquitards (blue). This sequence is truncated by a younger, glacial channel erosion surface (red line), before glacial meltwater sediment filled the valley and built the Oak Ridges Moraine. This profile shows, for the first time, how groundwater strata are arranged below the Humber Valley watershed (west Toronto).

12.2.2 Hydrogeological settings

Four major hydrogeological settings describe groundwater systems in southern Ontario:

1. Sediment
2. Sediment-bedrock interface (i.e., contact zone)
3. Exposed or thin sediment-covered bedrock
4. Deep bedrock

Freshwater aquifers occur mainly in regional-scale, shallow or exposed carbonate bedrock, or in sediment complexes (mainly glacial sediments) with flow at local to intermediate scales. Exposed bedrock and thin sediment-covered bedrock occurs on Manitoulin Island, the Bruce Peninsula, the Niagara Escarpment, Lake Ontario shorelines, and along margins of the Canadian Shield (Figures 12.8; 12.11). Sediment aquifers are hydraulically linked to bedrock aquifers and help to capture water and recharge it to depth, particularly in porous sands, less so in clayey sediment areas. Important sediment aquifers occur below large major stratified moraines, as in the Oak Ridges and Waterloo moraines (Figure 12.1), and in sediment fills of buried bedrock valleys as described above. Stratified moraines have a number of key attributes that make them prolific water-yielding formations. Sediment aquifers are hydraulically linked to bedrock aquifers and help to capture water and recharge it to depth, particularly in porous sands, less so in clayey sediment areas.

Bedrock strata in southern Ontario consist of ancient layered sedimentary rocks of Paleozoic age (Figures 12.5, 12.6). Fractured bedrock is a unique hydrogeological setting because of its combination of relatively high hydraulic conductivity, or ease of flow, and relatively low storage capacity. Hydraulic properties (aquifer/ aquitard designation) might not necessarily agree with geologic strata as fractures may be present in some layers and not in others. As a result, changes in water quantity and quality can both be quite rapid (for example across formations) in fractured rock aquifers, as was the case at Walkerton. By contrast, sediment aquifers display lower conductivity but have a much higher ability to store and filter groundwater.

Deep bedrock settings, recorded by petroleum well records, do not produce or transmit much water. Most shale, evaporite and carbonate rocks can be considered to act as water-poor aquitards (Figure 12.6). Carbonate rocks and limestones of the Trenton Group and Black River Group, in

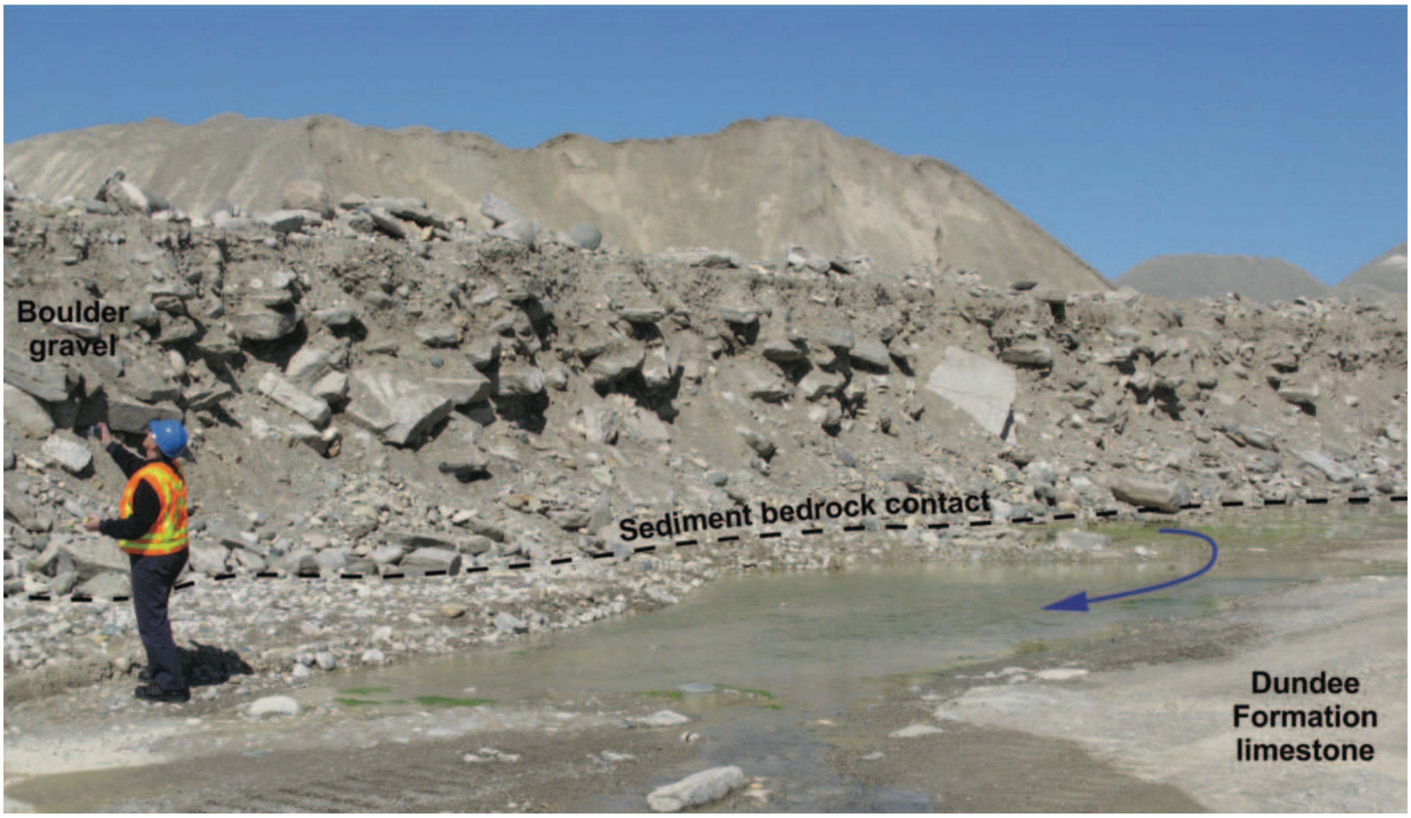

Figure 12.11 Groundwater flows from the interface or contact zone aquifer.
This Interface aquifer consists of boulder gravel directly overlying Dundee Formation limestone. Meteoric water has percolated downward through the highly permeable gravel to the upper surface of the nearly impermeable limestone, and is flowing toward the viewer on the slightly inclined bedrock surface. Note that sand and silt was removed from above the boulder gravel.

particular, form thick aquitards, with very low hydraulic conductivity or ease of flow. Thin aquifers of regional extent are confined within these bedrock formations; however, most of these aquifers contain non-potable formation water with very high salinities or high total dissolved solids; locally, they may contain reservoirs of crude oil or natural gas. In summary, potable water mainly occurs in thick glacial sediment, in exposed, karst-influenced carbonate bedrock, or in sediment-bedrock contact zone aquifers.

12.2.2.1 Sediment hydrogeological setting

Most of southern Ontario's major water-producing aquifers are found in sediment hydrogeological settings. Unconsolidated sediment (e.g., gravel to silt) provides enhanced infiltration of rainfall and snowmelt, and flow between sediment grains. Typical rates of flow, under a similar hydraulic gradient, range from ~1,000 to 0.0001 mm/day. Depending upon grain size and sorting, a sediment setting can have pore space that exceeds 40% to 50% of its total mass, resulting in a large groundwater storage capacity (Athy, 1930). Pore space flow also allows percolating water to take up the chemical character of the sediment as it flows toward the sediment-bedrock interface, or toward surface water bodies.

Variable sediment properties, thickness, type, and composition affect hydrological processes and the location of aquifers across southern Ontario (Figure 12.8). Thick sediment (50–200 m), for example, occurs in former meltwater channels and in valleys below escarpments (e.g., Niagara, Onondaga), and along the trend of buried valleys such as Laurentian valley. Thick glacial sediment, such as in moraines, has variable sediment type, geometry and internal structure; this usually results in complex aquifer systems with multiple layers (Sharpe et al., 2002). The higher groundwater infiltration, storage and flux associated with aquifers in sediment (Box 12-2) tends to yield good-quality water with low mineral content and few dissolved solids. Sediment aquifers, although smaller in size (tens of square kilometres) compared to bedrock aquifers (hundreds of square kilometres), are the source of most of southern Ontario's potable groundwater, and they are readily recharged from surface and atmospheric water that may mix with older glacial-age water (Husain et al., 2004) and/or deeper basin water.

12.2.2.2 Sediment setting case studies

The variable movement of water in unconsolidated sediments will be assessed by examining two representative sediment type case studies: i) the Norfolk sand plain (Box 12-3) and ii) the Essex clay plain (which also doubles as an interface aquifer; Box 12-4). Two other regional sediment types, till and gravel areas will be discussed for comparison. Sand, clay, till and gravel sediment areas combined, account for ~90% of the southern Ontario hydrogeological region (Figure 12.1); hence, these four sediment types summarize the shallow hydrological systems of most of the region.

Sand and gravel areas allow water to readily infiltrate, replenish and store groundwater in the accessible pore space between sediment grains. Less infiltration occurs in till, and very little occurs in clay, except by way of fractures, as is the case in most bedrock terrain. When saturated, both till and clay can store significant amounts of water, but these sediments do not transmit as readily as sand and gravel, and they discharge water more slowly. Differences in water level hydrographs between sediments and between sediment and bedrock are apparent. Each of the sediment case studies presented here is set in a low-relief location where topography provides modest yet differing gradients to water flow; the direction of flow is an important property as well but we will not discuss it until our Oak Ridges Moraine case study.

12.2.2.3 Sediment-bedrock interface hydrogeological setting

An important hybrid hydrogeological setting is found where sediment and bedrock meet. Water collecting at this interface forms a regional freshwater aquifer that underlies most parts of southern Ontario where sediment is thick (Figure 12.8).

Water and petroleum well records indicate that the top few metres of bedrock are often porous and permeable, regardless of rock type; this is caused by a combination of weathering and jointing, and in some places with sand and gravel at the interface. To some extent[3], all Paleozoic bedrock in southern Ontario exhibits regularly spaced vertical joints. These joints usually extend a few metres below the bedrock surface. The few metres of porous bedrock, together with the lowermost few metres of overlying sediment, form a "contact" or "interface" aquifer (Weaver et al., 1995; Husain et al., 1998, 2004; Carter, 2012). Below this porous bedrock, the unweathered and unfractured bedrock is several orders of magnitude less permeable than its overlying sediment, forming a barrier to

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[3] These joints are probably related to passive tectonic activity (Hancock and Engelder, 1989; Eyles et al., 1997) and formed in response to erosional unloading of younger sedimentary rocks or, more recently, to the melting and retreat of the one- to two-kilometre-thick continental ice sheets that covered southern Ontario at the end of the last ice age. Joints within the uppermost few metres of bedrock were also exposed to erosion and weathering during glaciation. Strata which contain evaporite minerals, in particular the Lucas Formation (Middle Devonian) and the Salina Group (Upper Silurian) may also have enhanced permeability at the sediment-bedrock contact due to dissolution of soluble evaporite minerals (e.g., salt, gypsum), forming a karst rubble.

downward percolation of fresh water. This contact aquifer (Figure 12.11) is part of a widespread sediment-rock system, and is the most regionally extensive freshwater aquifer in the southern Ontario hydrogeological region. Contact zone aquifers are also common in the Ottawa-St. Lawrence Lowlands (Cummings and Russell, 2007).

Flow direction in the contact aquifer is influenced by bedrock topography, and flow can follow buried bedrock valleys wherever the hydraulic gradient is sufficient. Regional flow directions inferred from bedrock topography indicate a flux from Niagara Escarpment highlands, south of Georgian Bay, toward topographic lows in lakes Erie, Huron and Ontario.

Reports of "bedrock" aquifer yield in water well records can be misleading as much of the potable water comes from sediment overlying the bedrock, rather than from the rock formation itself. About 58% of the so-called "bedrock" water wells in Essex region, for example, terminate within three metres of the bedrock surface (Strynatka et al., 2007), and draw water from the interface zone in a sand bed (Figure 12.13). The same is true for most areas of southern Ontario. The Essex clay plain (Box 12-4) is a good example of a contact zone aquifer as little aquifer potential exists deeper in the limestone bedrock or in the thick overlying clay sequence. This setting also illustrates the different hydrology of a clay plain as compared to a sand plain.

Water from the contact aquifer has a hybrid composition, reflecting the dual effects of travel through and residence time within both sediment and bedrock. Contact zone waters have lower mineral content, are less saline and hence more potable than water from confined deep bedrock aquifers. Conversely, contact zone waters are usually more mineralized than water from wells completed entirely within sediment, and they may have distinctive chemical characteristics, presumably reflecting the mineralogy of bedrock water with a longer residence time being drawn in.

Methane is also commonly found in contact aquifers, wherever the local bedrock is black organic-rich shale, notably in the Kettle Point Formation. This so-called "shale gas" is probably biogenic in origin, the result of the interaction of anaerobic microbes in the groundwater with organic material in the shale (Hamblin et al., 2008).

In areas dominated by carbonate bedrock, the joints at the bedrock surface may be solution-widened and extend to depths much greater than a few metres. In these areas the contact aquifer is connected to and transitional with the karst aquifer setting described below.

12.2.2.4 Exposed, thin sediment-covered bedrock hydrogeological setting

This setting is widespread, occurring where Paleozoic sedimentary rocks are exposed at the surface, or thinly covered by sediment (Figure 12.1), although paleo-karst features in areas of thick sediment cover are also possible. Rocks such as carbonate, sandstone and shale allow precipitation and snowmelt to readily run off to streams, or, to infiltrate fractures and joints. Carbonates, in particular, are very susceptible to erosion by acidic rainfall and groundwater. Infiltration into this setting contributes to regional groundwater recharge and storage, as ease of surface flow into rock openings allows penetration of fresh water to much greater depths than is usually observed (Hurley et al., 2008). This raises the importance of groundwater protection by constraining certain land uses in this setting. Recent and ongoing studies by the Ontario Geological Survey (Brunton et al., 2008;

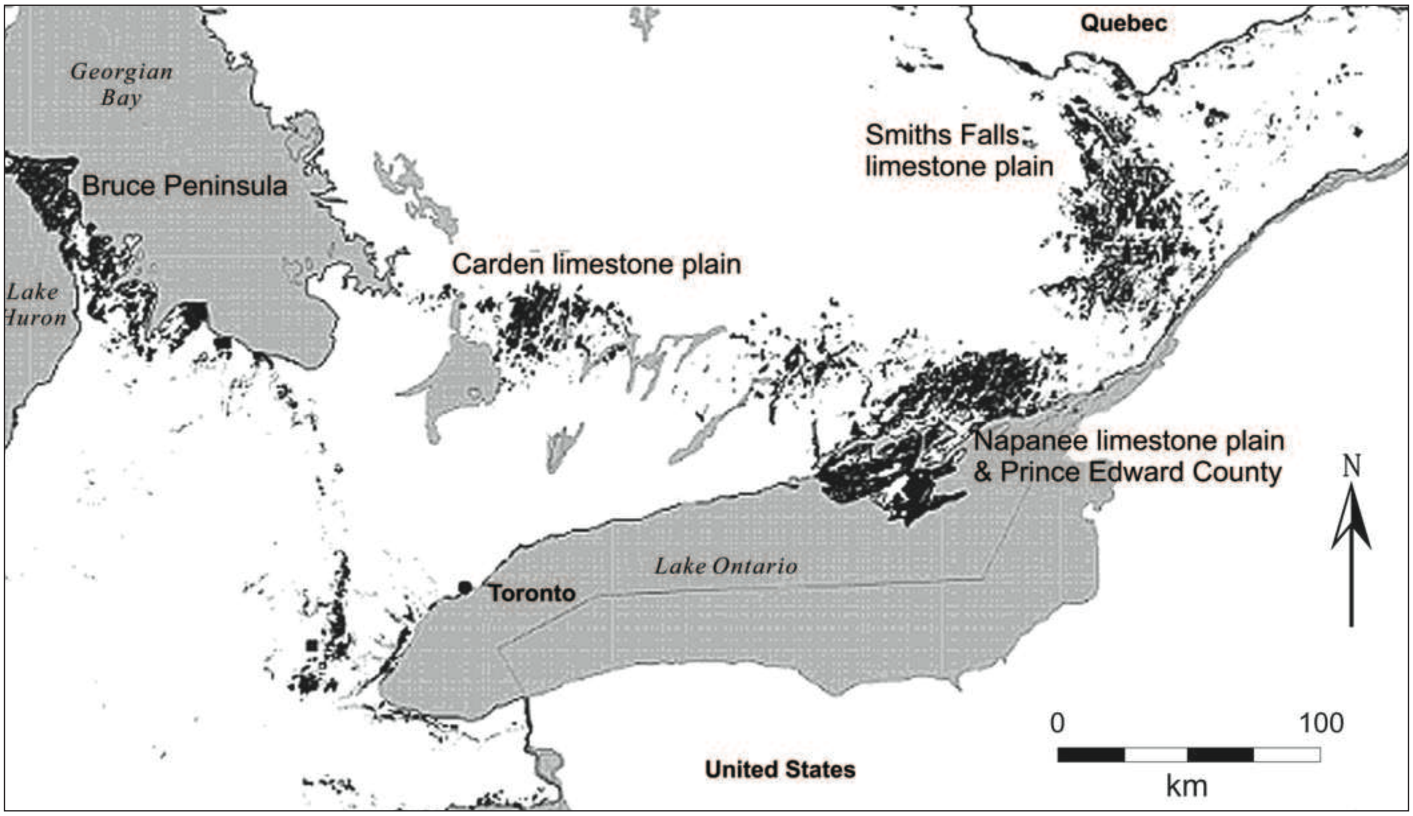


Figure 12.12 Cave-like karst openings allow more water to flow faster.
Carbonate rocks (limestone, dolostone) and evaporite rocks (anhydrite, gypsum, salt) are susceptible to dissolution by acidic surface water and groundwater resulting in solution-widened fractures and joints through which surface waters readily flow down to aquifers. These are called karst terrains and are widespread in southern Ontario (from Brunton et al., 2008).

Brunton, 2009; Brunton and Brintnell, 2011) have documented the importance of karst in controlling groundwater flow in exposed bedrock and the thin drift areas of southern Ontario.

Karst-influenced flow is of particular importance in the exposed bedrock setting (Figure 12.12) (e.g., Worthington, 2002). Karst is formed as a result of weathering and the chemical erosion of exposed or thinly covered carbonate bedrock by acidic surface and groundwater over thousands of years or more. This process enhances permeability, especially by solution-widening of joints or fractures in the upper tens of metres of exposed or thinly buried bedrock. The result is pipe-like groundwater flow both vertically and laterally. The greater connectivity between surface waters and groundwater aquifers makes these aquifers more susceptible to biological and chemical contamination from surface sources (e.g., Perrin et al., 2011). Water interval records from petroleum wells have reported fresh water at depths of up to 250 metres in karst-influenced bedrock.

Karst terrains in southern Ontario (Figure 12.12) display distinctive features including closed, surface depressions, well-developed underground drainage systems, and few surface streams. Other key features like sinkholes, sinking streams, caves and large springs may result from solution interaction with circulating groundwater and related streamflow. Larger, pipe-like, karst dissolution influences the amount, timing and distribution of groundwater recharge, as well as the depths and lengths of active groundwater flow systems. The Napanee limestone plain (Box 12-5) illustrates such water flow in the exposed, thin sediment-covered bedrock setting.

The Napanee karst-rock aquifer setting usually contains potable water, like that found in the Trenton Group limestones (Figure 12.5). The original saline formation water has been replaced by infiltrating fresh water of atmospheric or glacial meltwater origin. Almost all limestone units east of the Niagara Escarpment display good joint-fractures in outcrops with variable degrees of dissolution (Brunton et al., 2007). Larger groundwater flow that occurs in cave openings is common in Gull River Formation rocks and is controlled by proximity to the Paleozoic-Precambrian boundary (Figure 12.1), to rivers and swampy areas, and to margins of mini-escarpments between major rivers.

Other significant potable groundwater sources in karst carbonate bedrock, west of the Niagara Escarpment, are the Guelph-Lockport aquifer extending from Hamilton to the Bruce Peninsula, the Lucas Formation aquifer west of London (Figure 12.5), and the Detroit River Group (MacRitchie et al., 1994). The Lucas and Guelph-Lockport karstic aquifers are recharged at their outcrop edges with down-dip flow within the strata west of the Niagara Escarpment (Figures 12.5, 12.12). Down-dip penetration of fresh water is limited by the dense saline formation waters within the deep subsurface (Figure 12.13).

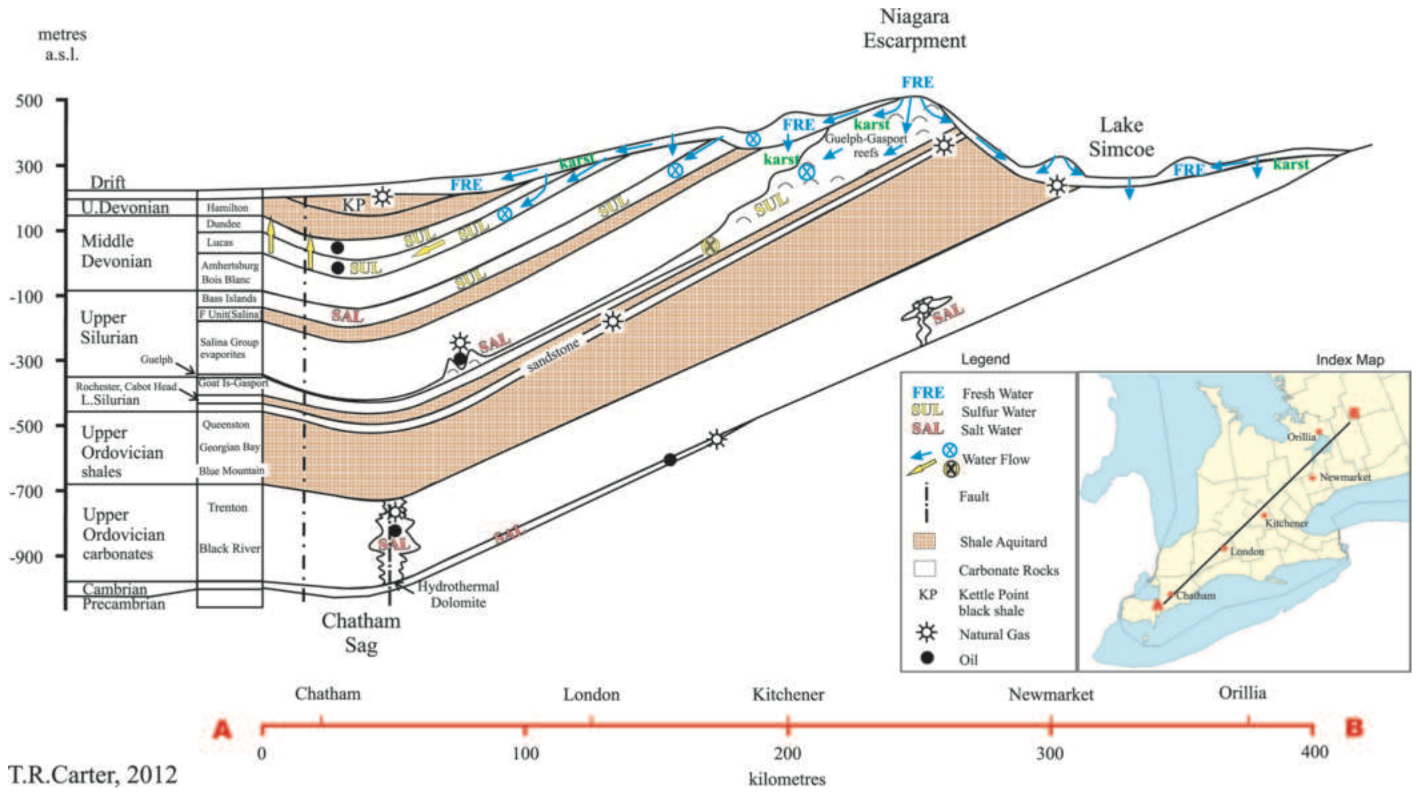
12.2.2.5 Deep bedrock hydrogeological setting

A system of thick regional aquitards and thin confined aquifers defines the deep Paleozoic bedrock setting of southern Ontario (Figure 12.13). Shale forms thick regional aquitards within the sequence; the thickest and most extensive of these are the Upper Ordovician Queenston, Georgian Bay and Blue Mountain formations (Figure 12.5) with combined thickness >300 m. The Salina Group evaporites with halite also form regional aquitards with combined thickness >230 metres. Most carbonate rocks may form aquitards as well, particularly in the thick limestones of the Trenton and Black River groups. Several regional aquifers, containing non-potable formation water of moderate to very high salinity, are confined between these aquitards. Potable water only occurs within these bedrock aquifers where porous bedrock formations outcrop at the surface or immediately beneath sediment in the contact aquifer zone (Figure 12.11).

Regional confined aquifers of saline water are found within the Middle Devonian Lucas and Dundee formations, the Upper Silurian Bass Islands Formation, in the Upper Silurian Guelph Formation, within fault-related hydrothermal dolomite zones in the Upper Ordovician limestones of the Trenton and in the Black River groups and in Cambrian sandstones (Figure 12.13). The deeper strata contain extremely high concentrations of total dissolved solids (140–390 g/L) dominated by sodium and calcium chlorides (Dollar et al., 1986; 1991). The Devonian and shallow Silurian strata contain brackish to saline waters (3–50 g/L TDS) of similar composition.

Sulphur water (dissolved H_2S) occurs regionally at intermediate depths in the Devonian and Silurian aquifers, and is usually found from a few metres beneath top of bedrock to ~500 metres depth. Sulphur water is also locally common in sediments overlying bedrock.

Groundwater chemistry changes with depth below surface; from fresh water, to brackish - saline sulphur water to deep saline water. This geochemical zonation was recently recognized in southern Ontario, and has been clearly documented at the proposed deep geological repository for low to intermediate level nuclear wastes at the Bruce



T.R.Carter, 2012

Figure 12.13 How does groundwater flow in a sedimentary basin?
A scaled geological cross section across southern Ontario showing regional southwesterly dip of bedrock formations and occurrence of water, oil, and natural gas in these layered rocks (Carter, 2012). Bedrock consists of marine strata: carbonate, sandstone, shale, siltstone, and evaporitic rocks, up to 1,400 m thick. Fresh water (blue-FRE) is confined to a relatively thin veneer (<250 m) of glacial sediment and very shallow bedrock. Saline water containing dissolved H_2S (sulphur water—SUL), shown in yellow, occurs at intermediate depths to ~ 500 m, and the deepest rocks contain saltwater with no dissolved H_2S (orange—SAL). Interpreted flow is downgradient from topographic highs and down regional dip of confining geological formations. Fresh water forms a three-dimensional flow system in upper part of confined aquifers (circles with × symbols), while saline water will remain confined in lower part due to its higher density. There is likely little or no actual movement of water in the deep subsurface strata. This sketch is based on petroleum well records and drill core and cuttings maintained by the Ontario Ministry of Natural Resources at its Oil, Gas and Salt Resources Library in London.

Nuclear power station at Tiverton (www.nwmo.ca/dgrsubmission).

The Nuclear Waste Management Organization is conducting detailed hydrogeological studies of Paleozoic bedrock at their proposed Deep Geologic Repository, for low- to intermediate-level radioactive waste at the Bruce nuclear station near Tiverton (Jensen et al., 2009; Gartner Lee Limited, 2008). Deep drilling indicates that there has been no penetration of fresh surface water below depths of ~250 metres. Flow model simulations indicate that groundwater velocities below a depth of 200 metres are extremely low or stagnant. Dissolved constituents move mainly by molecular diffusion. This very low-flow regime, and evidence from geochemical tracers, indicate that water in these rocks likely represents evaporated seawater that has resided in the bedrock for about 300 million years (e.g., Hobbs et al., 2008; Sykes et al., 2009; 2011, www.nwmo.ca/dgrsubmission). This new understanding will be used in support of site design investigations with a proposed waste repository to be situated 680 metres deep in the Cobourg Formation limestone (upper Ordovician).

Deep bedrock aquifers do not produce potable water because fresh recharge from recent precipitation does not readily percolate beyond shallow (1–200 m) depths depending on location (Figure 12.6). The deeper saline aquifers, however, have other important uses. Saline formation water is a nuisance by-product of crude oil and natural gas production. This "oil-field fluid" is safely disposed of by injecting it, using disposal wells, into deep bedrock aquifers, often the same formations from which it was produced. Some brines have compositions (e.g., high-calcium content) that make them of commercial value, and these are retrieved using special brine production wells. Deep saline aquifers may be targeted for possible future injection and permanent storage of carbon dioxide captured from large industrial point sources (Carter et al., 2007; Bachu and Adams, 2003).

Crude oil and natural gas are present in the Devonian, Silurian, Ordovician and Cambrian aquifers (Figure 12.13); economic accumulations occur in isolated reservoirs. Natural gas occurs in a continuous distribution in the Lower Silurian sandstones, escaping to the surface along the face of the Niagara Escarpment. Cumulative production to the end of 2006 was 86 million barrels of crude oil and 1.3 trillion cubic feet of natural gas (Lazorek and Carter, 2008).

12.2.2.6 Summary of hydrogeological settings

Most potable water is derived from sediment, exposed bedrock, or from sediment-bedrock (interface) aquifer geological settings. Water in deep aquifers is too saline for potable uses. The distribution and type of surface sediment determines the flux of water to the other three hydrogeological settings. Because the generalized geology of southern Ontario (Figure 12.1) shows wide variation in sediment type for the five main geologic areas or terrains (sand, clay, till, gravel and bedrock), case studies of this control on surface and groundwater were examined. Additional hydrogeological case studies (Norfolk sand, Essex clay and Napanee limestone plains) show hydrograph patterns and fluxes that reveal distinct hydrologic conditions for Grey County till uplands, and Wellington gravel valleys, landscapes that cover large areas (40%) of southern Ontario.

The five selected geological areas of Figure 12.1 characterize about 90% of the southern Ontario hydrogeological landscape. These areas vary approximately as follows: clay= 20%; sand= 20%; carbonate rock= 15%; sand and gravel= 5%; till uplands= 35%. As a result, we can generalize the main characteristics and hydrological behaviour of these sediment/ rock types (terrains) represented in the hydrograph trends for each illustrated case study (e.g., Boxes 12-3, 12-4, 12-5). Hence, clay plain behaviour in Windsor is comparable to clay plain hydrological behaviour near Ottawa. If we know how clay plains move water and how they differ from sand plains, till plains, gravel valleys and limestone plains, then we improve our regional understanding of surface water and groundwater movement in similar terrain types across southern Ontario (Figure 12.1).

Clay plains, for example, promote surface runoff to streams, inhibit groundwater recharge and, as a result, their watersheds experience low baseflow as groundwater discharge during dry seasons. Aquifers in clay plains reside at the sediment-bedrock interface. In contrast, gravel areas show no overland flow and induce considerable groundwater recharge: consequently, streams in those watersheds show large year-round discharge of cool groundwater to streams. Sand plains and till uplands show conditions between these two end member landscapes.

Other factors, such as sediment thickness, and/or the sequence and variation of sediment type, play a role in determining groundwater flow deeper below the surface within sediment setting.

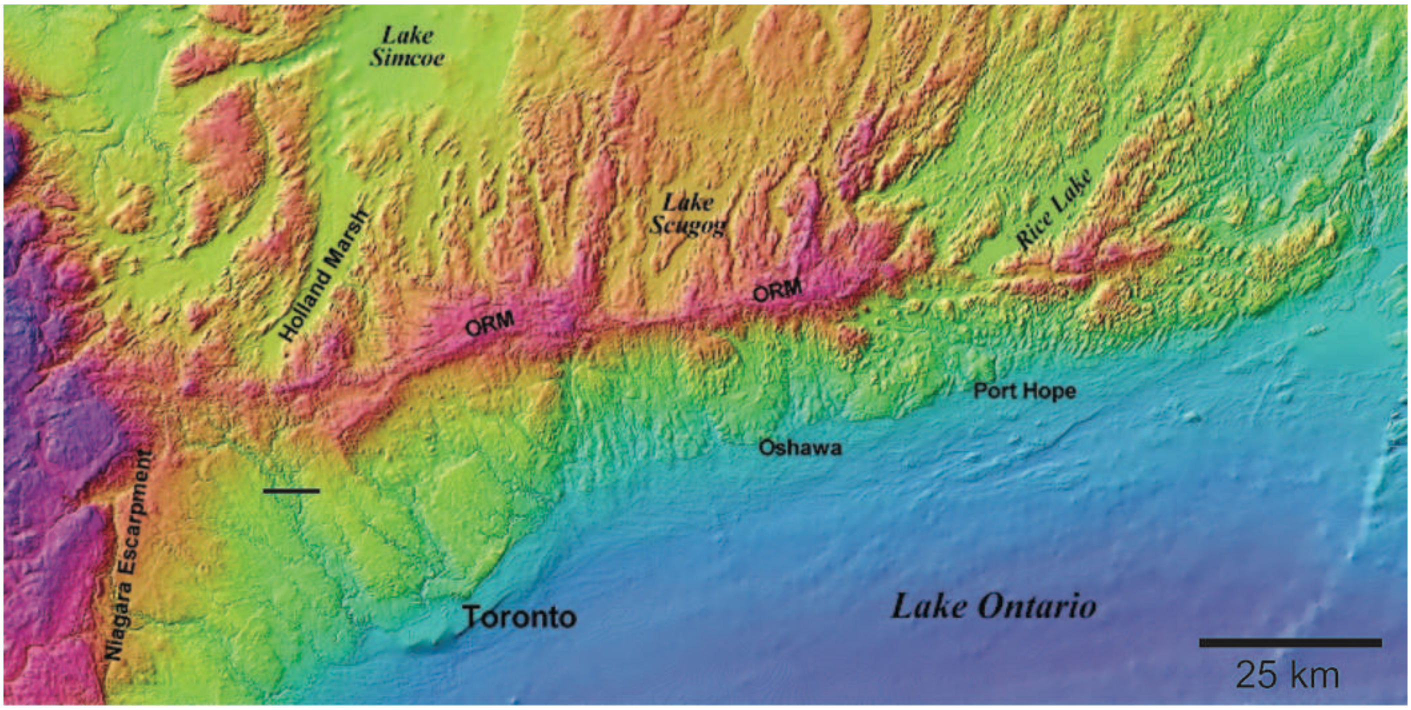


Figure 12.14 Oak Ridges Moraine surface topography is a window into the subsurface.
An elevation model shows blue in lower areas such as the shoreline of Lake Ontario (blue) to higher areas such as the ORM and Niagara Escarpment (purple). Surface channels such as the Holland Marsh extend beneath the ORM southward as shown on the seismic profile (see Figure 12.10). A 2.5 km seismic profile located near Nobleton (black bar) reveals subsurface geology south of the ORM, for example, the southern extension of the Holland Marsh channel and related channel aquifer sediments deposited on the channel floor. A 192 m deep borehole (east end of black bar) was cored from surface to the top of bedrock within a 1.5 km wide bedrock valley. Borehole details are shown on Figure 12.15.

12.2.3 Oak Ridges Moraine: Thick sediment case and the need for high-quality data

Our profile of the Oak Ridges Moraine, a thick sediment terrain, is based on high-quality subsurface information collected to address key groundwater issues associated with municipal water supply and land use planning (e.g., Gerber and Howard, 2002).

The Oak Ridges Moraine (ORM) is a prominent glacial landform located north of Lake Ontario within the Greater Toronto Area (Figure 12.14). It is a 5 to 20 km wide ridge of sandy hills extending from the Niagara Escarpment eastward beyond Rice Lake. These 50 to 100 m high hills rise more than 200 m above Lake Ontario. As a result, direct ground and surface water flows south to Lake Ontario and north to Lake Simcoe. The ORM occupies a significant and sensitive position in relation to the hydrology, hydrogeology and ecology of southern Ontario as it forms a major drainage divide and is the headwater for more than 40 streams, many with vibrant cold-water fisheries. As well, it is one of the most important aquifers in southern Ontario providing water supply to more than 200,000 people. Groundwater discharge from the ORM provides more than 50% of streamflow across the region.

Management of urban growth in the Greater Toronto Area requires an advanced understanding of groundwater flow systems within the ORM and across an area of 10,000 km^2. Key information includes a digital elevation model of the ground surface, geophysical probes, sediment cores and data from multi-level water monitoring devices in key strata. Such high-quality information leads to a sound 3D conceptual geological model (Figure 12.15a). Detailed geological mapping of the interior structure and complex sediment sequences in the

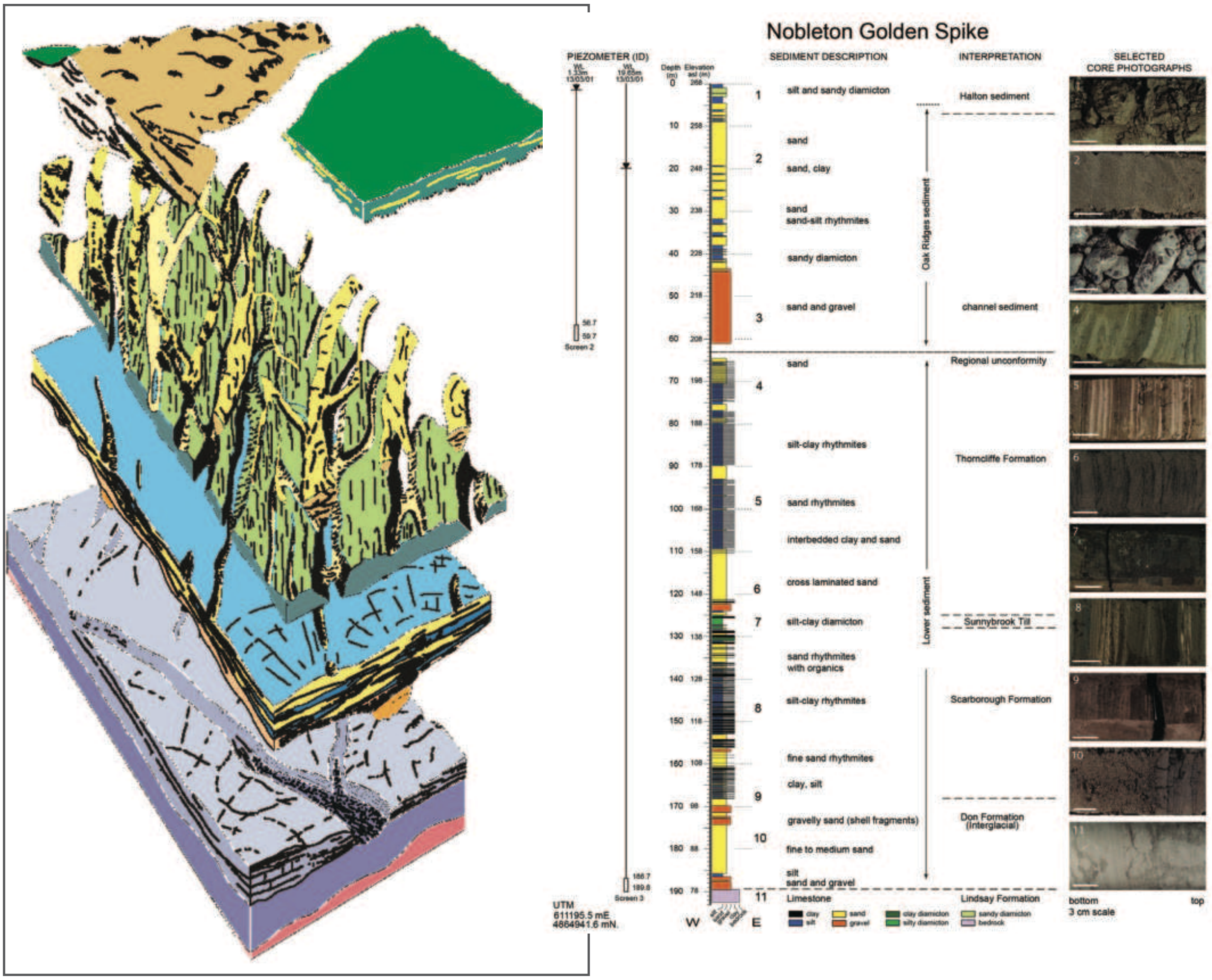


Figure 12.15 Oak Ridges Moraine 3D geological model and groundwater system.
The ORM 3D conceptual model consists of six main strata from oldest to youngest: i) bedrock, ii) lower sediments, iii) Newmarket Till, iv) channels Fill, v) ORM, and vi) Halton Till. These strata contain a number of stacked aquifers shown as yellow and oranges layers; blue-green layers transmit much less water. Layers in the model were observed on seismic profiles and confirmed by continuous sediment core drilled to bedrock. (b) shows a continuous sediment core with key photos of the main ORM strata (Knight et al., 2008). One can visualize the ORM 3D geological model by linking the elevation model (Figure 12.14 to detailed geological mapping (Sharpe et al., 1997) and then build a 3D hydrogeological framework across this 10,000 km^2 area (Logan et al., 2006).

ORM (Figure 12.15b) help identify the main geological elements controlling groundwater recharge, flow and discharge (Sharpe et al., 2007).

Regional groundwater flow occurs through a number of aquifers at different levels within the ORM model. Flow is driven by topographic gradients and is enhanced due to preferential flow in sand and gravel along connected channel networks. Channel sand also intersects sand sheets and deeper channels in the regionally extensive lower sediments. Lower sediments can be viewed at the Scarborough Bluffs on Lake Ontario and traced inland using seismic profiles and drill core results. These data dramatically improve confidence in the conceptual model and related numerical groundwater flow models (e.g., YPDT-CAMC and Earthfx Inc., 2006).

A critical feature of the ORM is its extensive

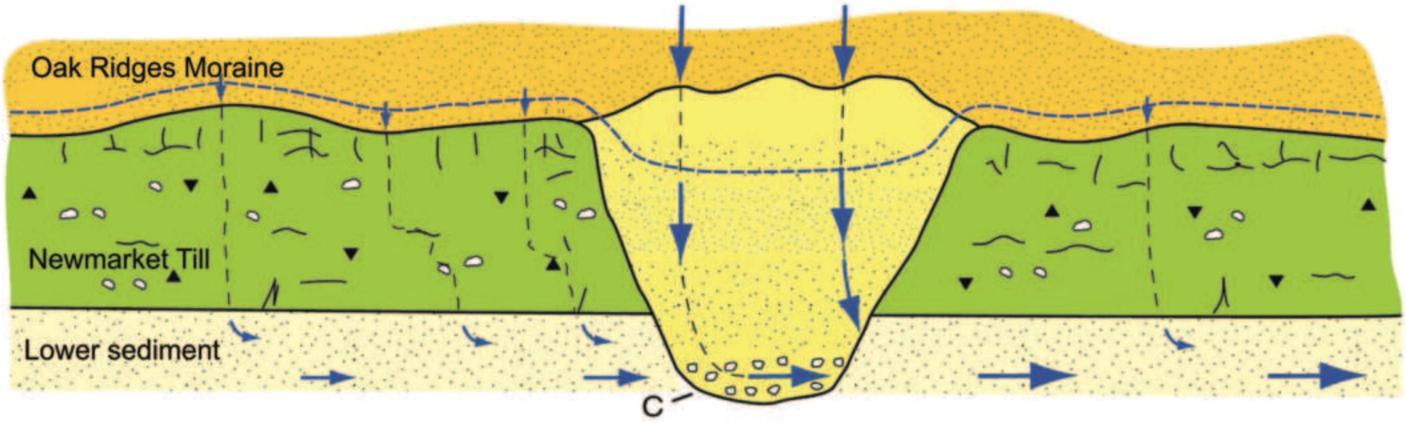


Figure 12.16 How does groundwater flow through channels or uplands under the Oak Ridges Moraine?
Water infiltrating the ORM may encounter Newmarket Till through which flow will be slow (small vertical arrows), or less likely, it may encounter channel sand (which breaches the Till) through which groundwater flow may be much faster (large vertical arrows) depending on permeability of the infill sediments and vertical hydraulic gradients. Flow along both the "slow" and "fast" routes is improved when there is drainage to lower water levels such as a river or lake (increasingly large arrows in the lower sediment aquifer unit). Note that the water table (dashed blue line) is lower over the channel breach.

network of north-south-trending valleys, such as the Holland Marsh, that underlie thick sandy hills (Figures. 12.15a). The size of valleys like the Holland Marsh, 1 to 5 km wide and more than 100 m deep, is about ten times larger than valleys eroded by modern rivers and about one hundred times larger than modern precipitation regimes could have created. These valleys were likely eroded when large glacial floods periodically released very large volumes of water stored under the glaciers. The valley network extends for 10 to 50 kilometres north of the ORM and south toward and beneath the ORM. North of the ORM, the valleys are visible utilizing digital elevation models. Many valleys are known to underlie the ORM, based on seismic research which shows these valleys to be 1 to 3 kilometres wide and greater than 100 m deep. In places, the valleys can be filled with a silt-sand-gravel sediment sequence, from surface to bedrock. Understanding the dimensions, depth and how these subsurface valleys or channels are filled is significant to understanding local, watershed and regional scales of groundwater flow.

These buried channel valleys may direct infiltrating water deeper into the subsurface. They may help to replenish deeper aquifers, depending on valley sediment fill and vertical hydraulic gradients (Figure 12.16), which can vary in direction and magnitude seasonally and with groundwater pumping. Deeper flow occurs where water flows readily through sandy channel sediments and the direction and magnitude of flow directs drainage downward. Over much of the ORM area, where shallow and deep aquifer systems are separated by the Newmarket Till, there are large water level differences between aquifers. The resistance to flow in the Newmarket Till limits downward flow and results in the higher water levels. Downward flow through the Newmarket Till to deeper aquifers is estimated to be less than 35 mm per year on a regional basis (Gerber and Howard, 1996; 2000; Gerber et al., 2009) in an area where climatic data indicate that 350 mm per year may be available for recharge. As a result, areas of channel erosion with higher-permeability infill sediments may be very important to regional groundwater flow and sustainable water supply. Where the Newmarket Till is breached by channel erosion and infilled with

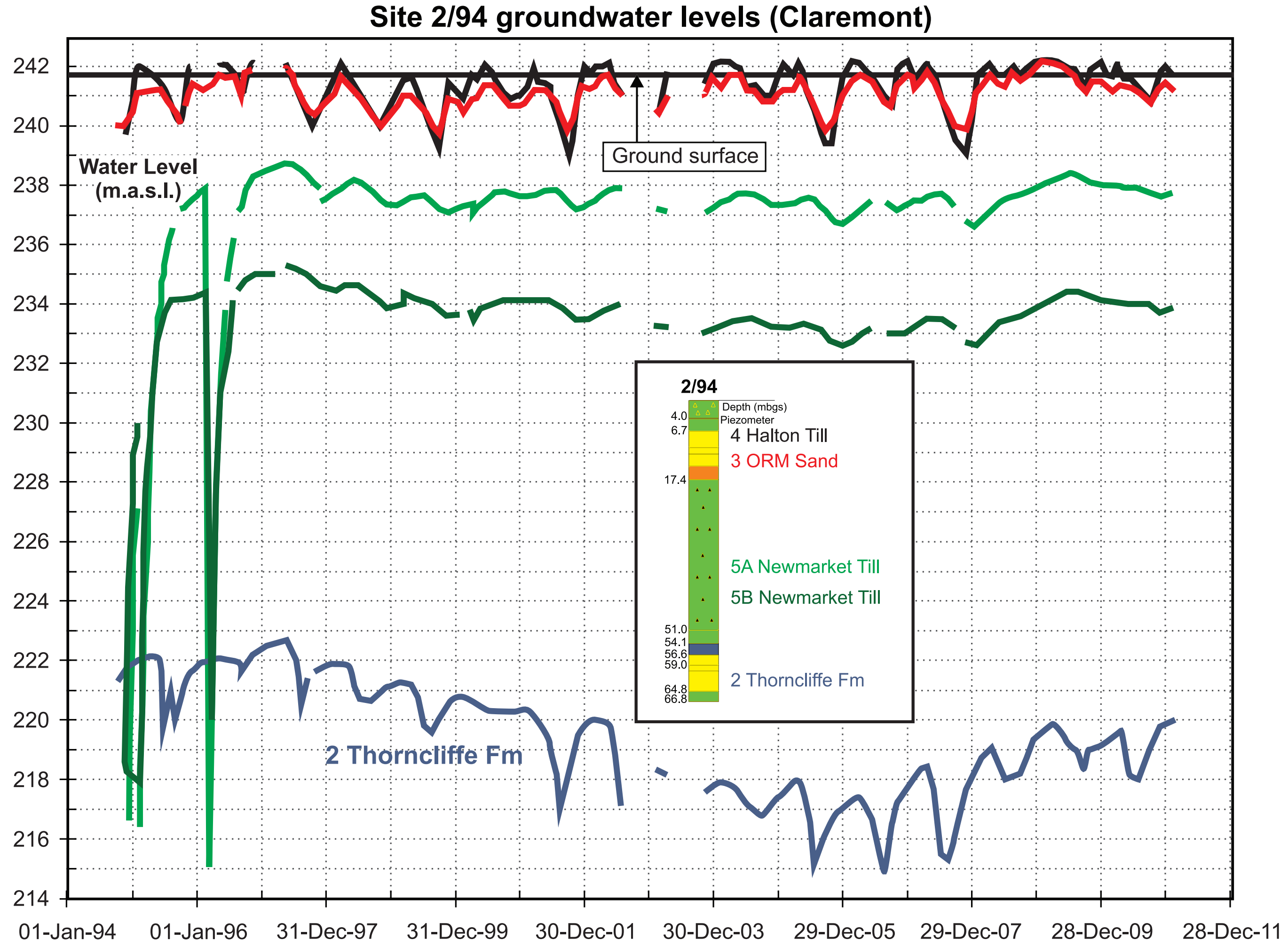


Figure 12.17 The pulse of the ORM plumbing system—different levels in different strata.

Water levels in the top two strata (Halton and ORM) at Site 2/94 (red and black lines), Claremont, are in direct hydraulic communication and indicate seasonal rhythms (2– 3 m), recharge and lateral groundwater flow from upgradient on the ORM. In contrast, water levels in lower strata (Newmarket Till, green lines, and Thorncliffe Fm, blue line) are 4 to 20 m lower than upper levels with a weaker annual rhythm, ~1 to 2m. These monitors indicate two components of the ORM groundwater flow system: one shallow with local recharge and discharge and the other deep with more widespread recharge and remote discharge further downgradient. Note that Thorncliffe levels show decline from ~1996 to ~2006 likely due to pumping (see general location on Figure 12.14).

sandy sediment, water level differences are less than in till-covered areas, due to less resistance to flow. This key finding makes it clear that in areas with sandy channels, it is particularly important to protect the quality and flux of water from land uses where this water is likely to recharge deep aquifers.

Groundwater levels are monitored at a number of locations across the ORM as part of the Provincial Groundwater Monitoring Network (PGMN). Key, longer-duration groundwater monitoring occurs at two sites situated south of the ORM. These are linked to the geological framework, which allows researchers to place monitors accurately, relate their water level trends to specific water-bearing units and better understand the flow of groundwater from recharge to discharge areas. One of the sites, monitor 2/94 (Figure 12.17), is situated where surface till overlies shallow ORM aquifer sand and a deeper aquifer.

This well-monitored site (Gerber and Howard, 2002) is situated on the south flank of ORM (Figure 12.14), where ORM aquifer sediment pinches out and is confined by overlying Halton Till (Figure 12.17). Water levels within the shallow ORM aquifer are near or above the ground elevation. Levels vary seasonally by up to 3 m and demonstrate good near-surface hydraulic connection. Annual fluctuations within a deeper aquifer are ~2 m, but they fluctuate in rhythm with near-surface hydrographs, and demonstrate some connection to and recharge from the shallow ORM aquifer. Lower fluctuations may be affected by groundwater discharge to nearby streams such as Duffins Creek, and by pumping, indicated by the ~10 year decline in trend (1996–2006) and seasonal level changes of ~4 to 5 m.

Detailed water budgets can be estimated for ORM watersheds (Gerber and Howard, 2002). These budgets sum all water flux into and out of the watershed, including creeks that drain southward into Lake Ontario from headwater areas situated along the ORM south flank. According to these water budgets, approximately 60% of the groundwater discharge emanates from the south flank of the ORM; about 75% of the groundwater discharge occurs from relatively shallow aquifer systems, while the remaining groundwater discharge occurs from deep aquifers in the southern parts of the watersheds. Most of the groundwater discharge is to rivers and creeks within the watersheds, with little groundwater discharge directly into Lake Ontario (Grannemann et al., 2000).

This brief description of the ORM highlights several key issues in assessing groundwater resources in southern Ontario. Understanding groundwater flow in areas of thick sediment requires high-quality data. Such data, in turn, enables detailed three-dimensional interpretation of hydrostratigraphic units and their interaction within the flow system (e.g., Sharpe et al., 2002). The identification of new hydrogeological features, such as buried channels in sediment and bedrock, has proven of economic significance in finding and protecting sources of water supply, waste disposal sites and directing land-use planning. Further, the use of improved geological models to advance groundwater science, methods, and collaboration has assisted in a number of developments in the ORM. For example, it has helped in setting out formal plans (e.g., 2001 Oak Ridges Moraine Conservation Act) to protect groundwater source areas. These models have also provided guidance in the development of the Clean Water Act and source water protection strategies. A coalition of municipally funded conservation authorities and local municipalities is building upon the groundwater science, education and outreach for the ORM. They hope to influence public awareness and local planning decisions related to groundwater systems and management (www.ypdt-camc.ca).

12.3 GROUNDWATER RESOURCES

How important is groundwater in southern Ontario and what issues arise to manage it well? Groundwater is critical to the quality of life of residents of southern Ontario and to the health of its economy and ecosystems. It is very cost-effective and forms a significant water supply for agriculture, industry, municipal and rural users.

Does land use affect the amount and quality of groundwater? How accessible is groundwater, and can it service and sustain current and increased use in the future, particularly with potential changes in climate? Increasingly, watershed managers are recognizing that groundwater and surface water, as the water cycle shows, is one connected resource.

12.3.1 Groundwater quantity and availability

There is considerable variation in timing of hydrological processes across southern Ontario, and these variations have a major impact on how groundwater moves. Mean annual temperature here varies by more than 5 °C. This variation affects rates of both evaporation from water bodies and transpiration water losses from plants (and, hence, reduced infiltration to the water table). Deviation in mean annual precipitation of ~500 mm means that annual runoff can vary from 190 to 590 mm, for an average of ~380 mm/year. As a result, assuming that there is no pumping from groundwater storage, overall streamflow water quantity changes throughout the year. It is important to note that about 40% of precipitation forms streamflow (total streamflow includes flow derived from overland runoff and from groundwater discharge), while the remaining 60% is returned to the atmosphere by evapotranspiration. Overall, ~45% of the total streamflow comes from shallow groundwater storage and discharge. This discharge is greater in areas with more permeable sediment and bedrock, lower in areas with less permeable material, such as is found in clay basins (e.g., Essex) and areas covered by thick till. Overall, variation in groundwater levels is less compared to that in streamflow levels.

12.3.1.1 Water availability in a typical setting—a Nith River watershed

Snow accumulation and melting and evapotranspiration (the combination of evaporation of water from the landscape and transpiration of water from plants) alter the availability of water throughout the year. Figure 12.18 illustrates average monthly precipitation and streamflow for a watershed of the Nith River located 30 km northwest of Kitchener and Waterloo. Both precipitation as rain and snow, and precipitation adjusted for snow accumulation and melting are depicted. The streamflow data is summarized as the total volume of streamflow during each month and per unit area of the watershed so that it can be compared to precipitation. Precipitation distribution is reasonably uniform; however, precipitation is slightly below average during January to March and slightly above average during August, September, and November. Snow accumulation and melting reduce water availability during November to February, when there is net accumulation of snow, and increase availability during March and April, when there is net melting of snow. Evapotranspiration modifies the relation between precipitation, adjusted for snow accumulation and melting, and streamflow, which closely matches precipitation during January and February when temperatures and plant activity are low. Streamflow becomes an increasingly small fraction of precipitation from March to a minimum in July and August as temperatures and plant activity increase, and, then, an increasingly large fraction from September to December when temperatures and plant activity decrease. Average annual precipitation and streamflow are 990 and 390 mm, respectively, and therefore 600 mm of precipitation is returned to the atmosphere by evapotranspiration or otherwise removed from the watershed.

Figures 12.19 and 12.20 illustrate the variation of average annual precipitation and streamflow across southern Ontario using data for 336 watersheds. Precipitation is largest immediately to the east of Lake Huron and Georgian Bay and generally decreases to the east. Streamflow follows the same trends but also reflects factors such as temperature and land cover, which influence evapotranspiration (e.g., Fernandes et al., 2007). In some cases, groundwater flow across watershed boundaries and human processes such as water use and diversion may also influence streamflow. The averages of precipitation and streamflow for the watersheds

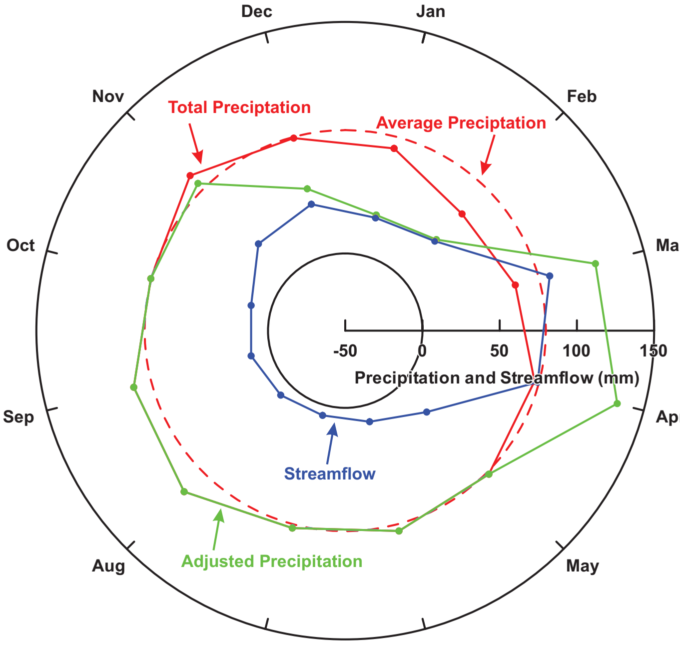


Figure 12.18 Is water available evenly throughout the year?
This graph illustrates the annual cycle of water availability for a watershed of the Nith River. Monthly average precipitation (red points and solid red line) is compared to the average for all months of the year (dashed red line). Precipitation, adjusted for snow accumulation and melting (green points and line), is compared to streamflow (blue points and line). Note that both precipitation and streamflow are high in the spring.

are 950 and 380 mm, respectively, and therefore evapotranspiration (approximated as precipitation minus streamflow) is roughly 570 mm on average.

Average annual groundwater recharge (the amount of water that enters groundwater flow systems from precipitation) varies across southern Ontario because of variations in precipitation, evapotranspiration, geology, and terrain (Figure 12.21). The highest levels occur in areas with coarse textured sediments such as sand and gravel in the shallow subsurface while the lowest levels occur in areas with fine-textured sediments such as clay.

A monitoring well in Wellington County near Acton sampling a gravel aquifer overlain by deposits of clay and silt illustrates a local water cycle, based on precipitation, streamflow, and groundwater level data (Figure 12.22). Precipitation data is adjusted for snow accumulation and melting. The streamflow data is from a watershed of the Eramosa River located approximately 15 km

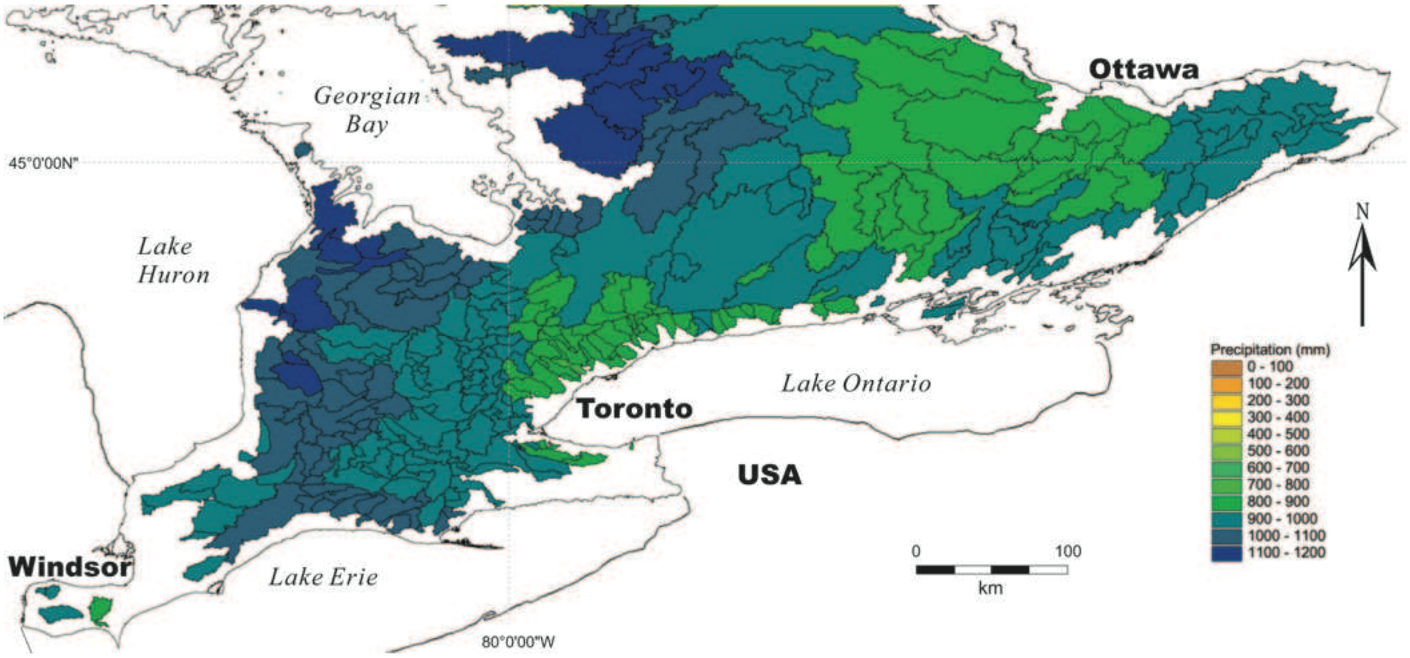


Figure 12.19 Precipitation drives the water cycle.
Average annual precipitation for 336 watersheds in southern Ontario varies from highs of 1,200 mm to lows of 800 mm. Note "lake-effect" in higher precipitation levels east of Lake Huron and Georgian Bay. Note: Precipitation, streamflow, and recharge are shown for a selection of 366 gauged watersheds. These watersheds do not provide complete coverage of southern Ontario and therefore precipitation (Figure 12.19), streamflow (Figure 12.20), and recharge (Figure 12.21) are not shown in some (white) areas.

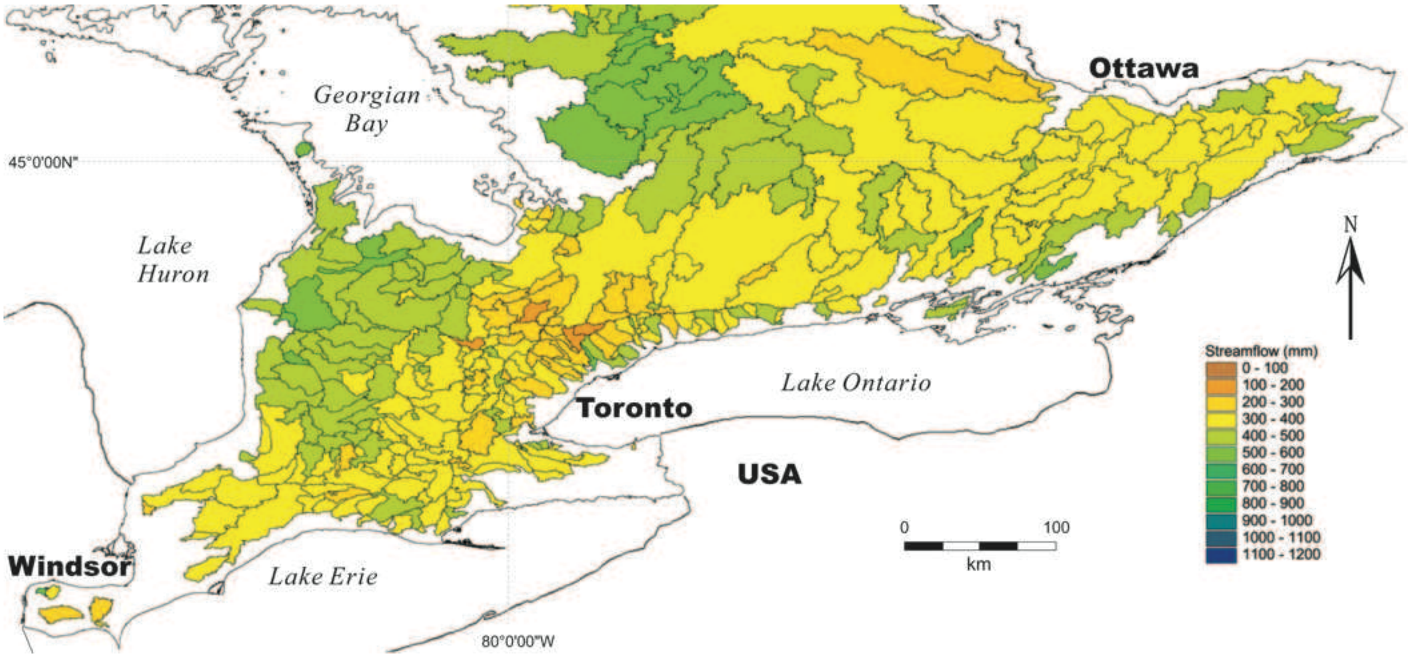


Figure 12.20 How much water flows in steams and where does it come from?
Average annual streamflow for 336 watersheds in southern Ontario varies from highs of 600 mm to lows of 200 mm.

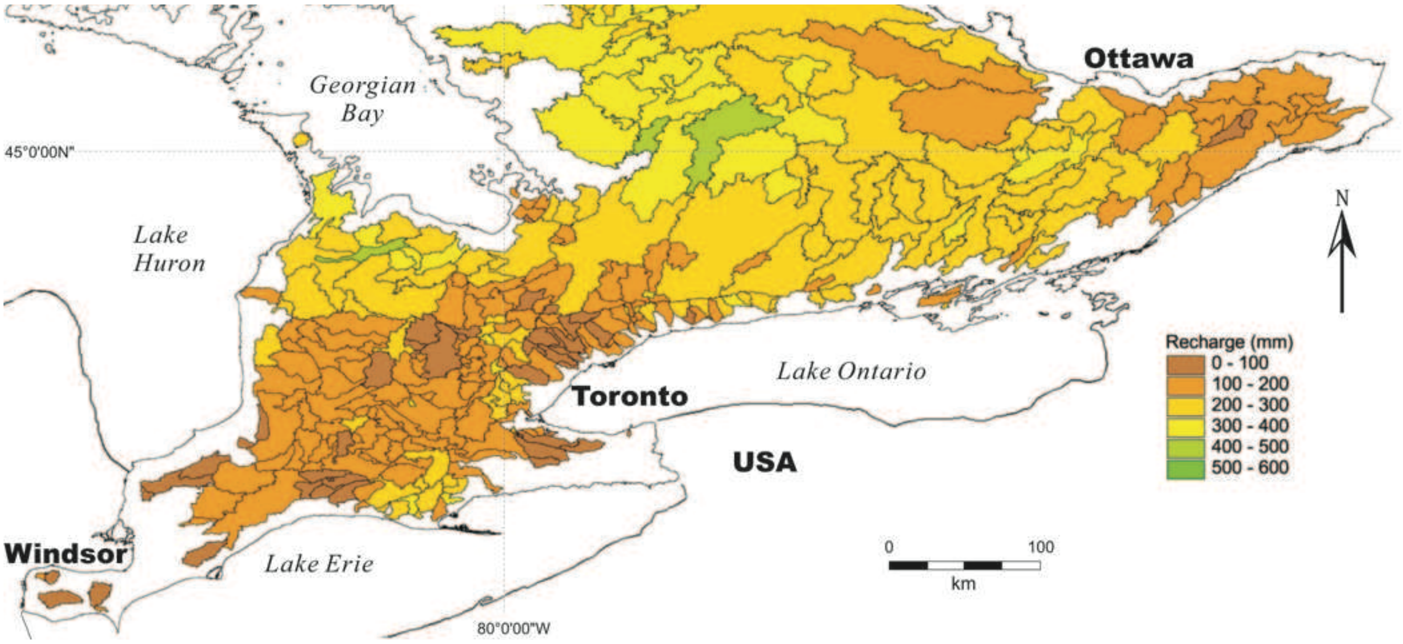


Figure 12.21 How much water goes into the ground?
Average annual groundwater recharge for 336 watersheds in southern Ontario varies from highs of 400 mm to lows of less than 100 mm.

northeast of Guelph. This data has been summarized as the total volume of streamflow during each day and per unit area of the watershed so that is can again be compared to precipitation.

The rapidly varying streamflow data consists of total streamflow, the actual flow in the river (m^3/d), while the slowly varying data is the baseflow component believed to be due to groundwater discharge to the river (Figure 12.22). The departure of streamflow from baseflow conditions reflects runoff across the ground surface and directly into the river following precipitation and snowmelting events.

Groundwater levels increase significantly following events in January to May and November

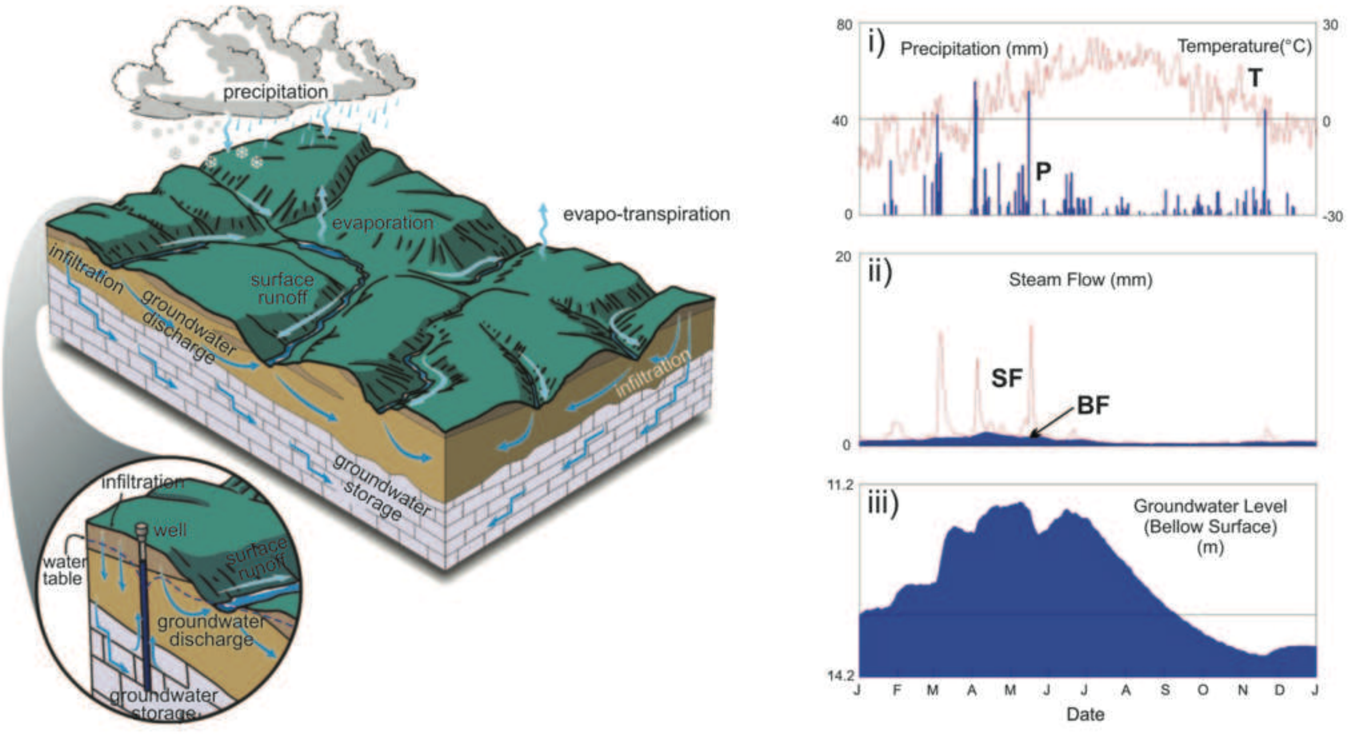


Figure 12.22 Streamflow and groundwater response to precipitation.
Streamflow (SF, ii) and groundwater level (iii) both respond to the larger precipitation events (i) that occurred in January to May and in November. Declining groundwater levels (iii, August to November) reflect groundwater discharge to surface water, which forms baseflow (BF) throughout the year (ii).

(Figure 12.22), which indicates that another portion of available water recharged the groundwater flow system. The decline in the levels following these events and during the summer and fall reflects the discharge of groundwater to the river, which is the source of baseflow. The ratio of baseflow to streamflow, in this case 59 percent, indicates the contribution of groundwater discharge to streamflow and the partitioning of precipitation into surface runoff and groundwater recharge.

12.3.1.2 Groundwater occurrence and regional aquifers

As we have seen in southern Ontario, groundwater occurs widely in sediment, bedrock and at their interface, particularly in ancient marine carbonate rocks. The exception is those locations with very thick sediment cover (e.g., near escarpments). We know this, in part, from the very abundance and even distribution of water wells in each of these settings (Figure 12.8) including the interface between sediment and bedrock. Indeed, a key feature of water use in southern Ontario is the fact that most rural homes have a well. Southern Ontario's main aquifers can be linked and defined by three key hydrogeological settings: i) exposed bedrock, ii) sediment-bedrock interface, and iii) thick sediment (Figure 12.8d). Groundwater within a deep bedrock hydrogeological setting is generally not used for water supply due to water quality issues and the cost of the deep drilling.

12.3.1.3 Groundwater recharge, flow, and discharge

Groundwater discharge is important from a human perspective. It maintains streamflow, and therefore surface and/or stream water quantity and quality, between precipitation and snowmelting events. It is also important from an ecological perspective because, for example, some aquatic species are highly dependent on water temperature, which is moderated by groundwater discharge during both the winter and summer.

There are several ways to estimate groundwater discharge. One is to calculate the baseflow component of streamflow using a mathematical process known as hydrograph separation. The resulting baseflow is the slowly varying component of streamflow (Figure 12.22) and is an estimate of groundwater discharge in many areas not affected by surface water body flow regulation devices (e.g. dams). Streamflow is monitored across southern Ontario and therefore it is possible to estimate groundwater discharge across the region in a reasonably seamless and consistent manner. To do this, it is convenient to first summarize streamflow and baseflow as baseflow index, which is defined as the long-term average of baseflow divided by the matching average of streamflow. Baseflow index is a number between zero and one where increasing values indicate increasing baseflow and groundwater discharge. If values of baseflow index are interpreted with geological mapping, then it is possible to derive an estimate of baseflow index for each geological unit across southern Ontario (Figure 12.23).

Figure 12.23 illustrates the results of this approach using 1:1,000,000 scale mapping of the surface geology (Figure 12.1). The estimated values of baseflow index vary from 0.15 for fine-textured sediments such as silt and clay (e.g., Essex), to 0.73 for coarse-textured sediments such as sand and gravel (e.g., Norfolk). Areas with the smallest values of baseflow index tend to be larger and more continuous than those areas with the largest values of baseflow index. On average, approximately 50 percent of streamflow is estimated to be due to groundwater discharge. Thus, roughly one-half of streamflow in southern Ontario has first flowed through the subsurface as groundwater, often for years to centuries and longer. Groundwater is a hidden resource that is difficult, costly, and time-consuming to investigate using methods such as those developed for the Oak Ridges Moraine. Methods such as separating baseflow from streamflow are simpler and economical, while providing useful information when used at appropriate scales.

As we have seen in the hydrographs provided in our case studies, climate, streamflow, and groundwater levels have a dynamic interaction in the hydrological cycle. Central hydrological processes, which are complex functions of geology, terrain, land and water use, include: partitioning precipitation between surface runoff and groundwater recharge, streamflow that combines surface runoff and groundwater discharge, and groundwater flow from recharge to discharge. Approximate estimates of groundwater discharge (baseflow) across the Great Lakes basin and across southern Ontario made use of geology (Neff et al., 2005; Piggott and Sharpe, 2007) to help assign streamflow components. Subsurface hydrology, groundwater, is expensive to study, yet it is inexpensive to study its relationship with discharge by measuring streamflow.

12.3.1.4 Climate stress

Groundwater, as an important component of the water cycle, responds to changing climate and is linked to water availability. The analysis of a temperature rise and precipitation fall can be tied directly to a decrease in groundwater discharge in a southern Ontario stream, and this means that simple climate and streamflow data may serve as an early warning for possible climate change impacts on sensitive watersheds. For example, precipitation change affects the volume of water

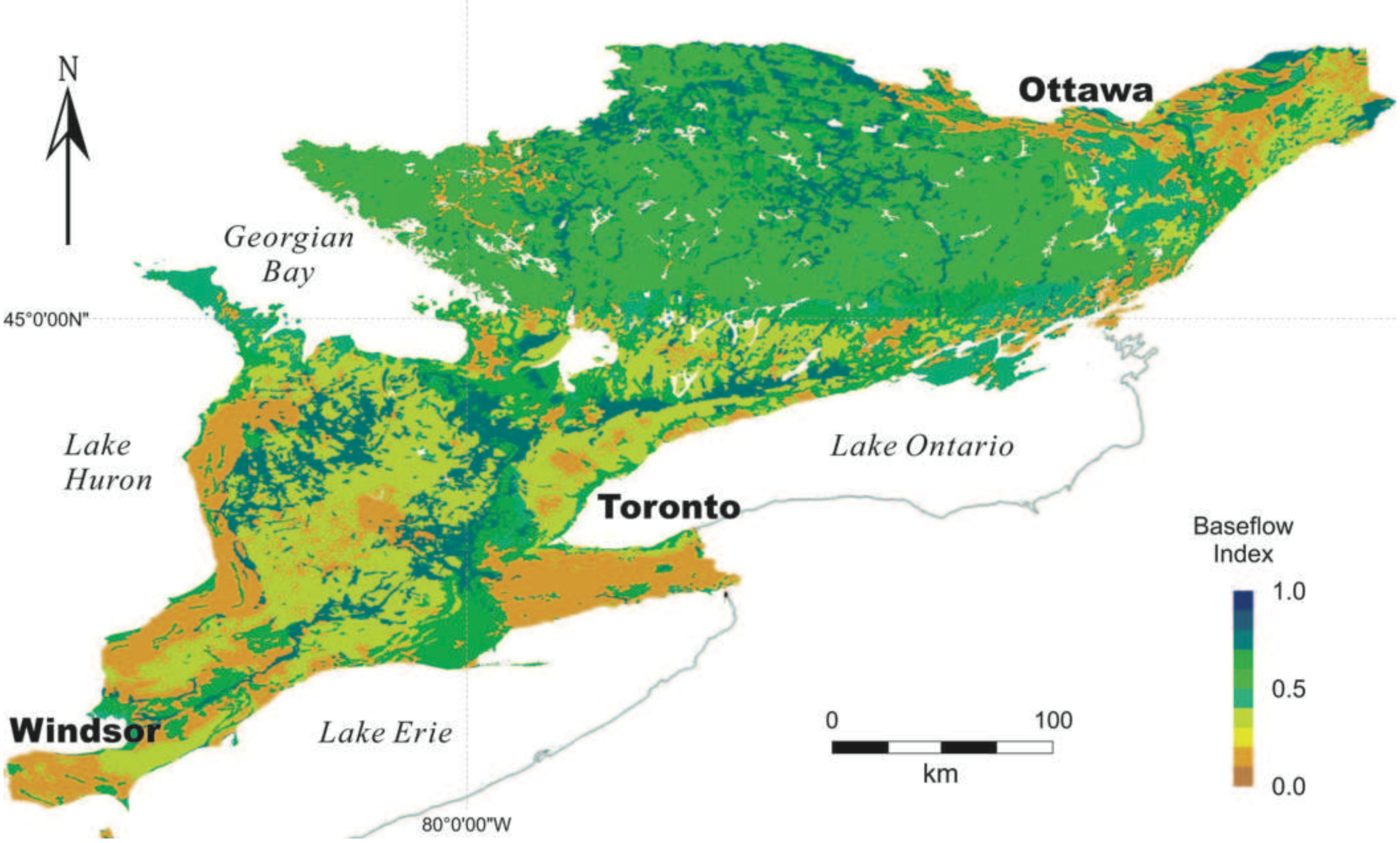


Figure 12.23 Can groundwater flow to streams be compared across the region?
High values of baseflow index (>0.5) relate to areas of permeable sediment and rock with sufficient groundwater storage such as glacial meltwater channels (blue tones), or morainic areas like the Oak Ridges Moraine north of Toronto. High values in Shield terrain relate to the number of lakes and wetlands that contribute stored water to streamflow.

available for groundwater recharge, flow and discharge. Temperature change will also affect snowmelt, accumulation, the timing of groundwater recharge, as well as recycling water to the atmosphere. The potential impacts of climate change on groundwater conditions in southern Ontario are varied and have recently been summarized by Environment Canada (2005; 2007) as changes in annual streamflow and water levels linked to geological and topographic setting.

Assessing impacts of climate change on groundwater is difficult because of limited data on subsurface hydrology, uncertain knowledge of the geology and flow systems, and projected variability of climate change trends at the provincial and watershed scales. This is further complicated by the fact that we also need to assess a range of factors such as stresses on groundwater resources caused by urban growth, increasing water use and intensified agriculture.

The diversity of groundwater discharge across southern Ontario implies that impacts of climate change will be similarly variable. Grindstone Creek (GC, Figure 12.1) for example, a waterway with a high baseflow index (high groundwater discharge), but a quick drop-off in baseflow during the year (from a lack of groundwater storage), illustrates the estimated impact of warmer and drier climate conditions. The low-flow conditions in Grindstone Creek resulted in loss of aquatic habitat and restricted migration of many species of fish to sustainable aquatic conditions. Some of the lost fish likely had survived under some stress for several years, but this watershed proved to be vulnerable to climatic stress. Even though Grindstone Creek had an above-average baseflow index, the lack of groundwater storage and the quick decline of both groundwater levels and discharge made the watershed susceptible to moderate drought conditions. This tangible example of climate impact is a signal to improve understanding of watershed flows, levels and timing in order to maintain and manage future groundwater/surface water resources. Ontario Ministry of Environment has prepared guidelines on how to conduct climate change assessments to assist in managing water resources within Ontario in a new publication "Sensitivity mapping and local watershed assessment for climate change detection and adaptation monitoring".

12.3.2 Groundwater quality

Both natural and human-induced changes in groundwater quality can affect the safe use of groundwater (Environment Canada and EPA, 2005). Groundwater can dissolve elements and compounds from the sediment and rock that it flows through. These natural constituents provide a baseline water quality for comparison with groundwater that may have picked up man-made chemicals.

Groundwater quality may also change due to natural chemical evolution along a flowpath, such as acidic rainfall which can dissolve calcium carbonate as it seeps into limestone rock, and more as it flows along the limestone fractures. Such trends may provide valuable insight into the dynamics of groundwater flow systems (e.g., tracers showing connection between aquifers or lack of connection in aquitards that reduce or deflect flow). Monitoring allows identification of changes in water quality. Natural groundwater may be of low quality for some uses (Rudolph et al., 1998; Goss et al., 1998); groundwater with a salt content, for example, would not be suitable as drinking water, but could be of acceptable quality for industrial uses. In addition, pollution from urban growth, industrial uses and agricultural activity may significantly degrade groundwater quality over portions of southern Ontario, diminishing safe use of groundwater and damaging aquatic environments.

12.3.2.1 Ontario drinking water objectives

Under Ontario's Safe Drinking Water Act, the Ontario Drinking Water Quality Standards are legally enforceable limits on constituents in drinking water. These standards are designed to protect public health by limiting the amount of specific constituents allowed in drinking water. Three different types of constituents, some of which may be contaminants, are covered briefly below: microbiological, chemical, and radiological.

Microbiological standards are for *E. coli*, fecal coliforms and total coliforms, and they should not be detectable in drinking water. Coliforms are those bacteria that come from human and animal waste. Operators at drinking water treatment plants are required to test regularly for coliform bacteria. Disinfection of drinking water by chlorination is designed to eliminate these harmful bacteria.

Chemical water quality standards for both inorganic and organic chemicals are expressed in milligrams per litre (mg/L), e.g., for lead as maximum concentrations allowed in drinking water. Some chemicals can cause health problems if, over a lifetime, they are consumed in drinking water at levels above limits. Mercury, for example, can cause kidney damage.

Radiological standards are for natural and artificial radionuclides, expressed as maximum allowable concentrations in becquerels per litre.

Radiological contaminants include natural radionuclides, such as radium 228 that result from the erosion of naturally occurring rocks and sediment, and radionuclides released anthropogenically, such as tritium released into water and vapour by nuclear power plants.

Ontario does not regulate cosmetic or aesthetic problems such as taste and odour in drinking water. Odour and taste, as well as colour and clarity, are considered to be aesthetic parameters, and not a risk to health.

Ontario's Drinking Water Quality Standards can be accessed at http://www.e-laws.gov.on.ca/html/regs/english/elaws_regs_030169_e.htm.

12.3.2.2 Groundwater quality monitoring and related studies

12.3.2.2.1 Provincial Groundwater Monitoring Network

In 2000, the Ontario Ministry of the Environment (MOE) began the Provincial Groundwater Monitoring Network (PGMN) in partnership with 10 municipalities and all 36 Conservation Authorities. As of 2012, the PGMN consisted of 474 groundwater monitoring wells located across the province. Of the 474 monitoring wells, 360 are routinely sampled for water quality. The PGMN helps to establish baseline groundwater conditions by monitoring groundwater levels and sampling groundwater to determine its chemistry. This information is used by the MOE, conservation authorities and municipalities responsible for managing groundwater.

Water quality results for sampled monitoring wells are compared to the Ontario Drinking Water Quality Standards (ODWQS). When a parameter is above the ODWQS, MOE sends a notice to local health unit and conservation authorities. A preliminary hydrogeological report helps determine why the parameter is above the ODWQS, and sets an agenda for pertinent parties to discuss the report findings and next steps.

Many measured parameters are believed to be naturally occurring and their sources are linked to the geological setting and natural groundwater conditions.

12.3.2.2.2 Water well records

Groundwater quality can be reviewed for several regions across southern Ontario using a few simple measures such as chemical composition, taste (saline), smell (sulphurous), appearance (iron-staining), as well as through readily available public water well records (Figure 12.24).

Because groundwater reflects and inherits the chemical composition of the sediment and rock units through which it percolates or through which it is drawn, its quality mirrors the geology of southern Ontario. Groundwater can be mapped for its aesthetic qualities such as taste, smell and turbidity. The Ontario Ministry of Environment developed such a map in 2007 (Ministry of the Environment, 2007) using water well records from across the region. The map shows areas of fresh and saline water, and areas affected by sulphur, gas, iron and high-mineral content (Figure 12.24), based on qualitative drillers assessments. Fresh well water appears to be most common in sediment aquifers and in the Canadian Shield. Sulphur gas is common and is most likely to be found in wells that penetrate bedrock in areas north of Lake Erie, south of the Shield margin, and in the Ottawa-St. Lawrence Valley.

12.3.2.2.3 Ambient chemical characterization of regional aquifers

Regional data across southern Ontario shows broad

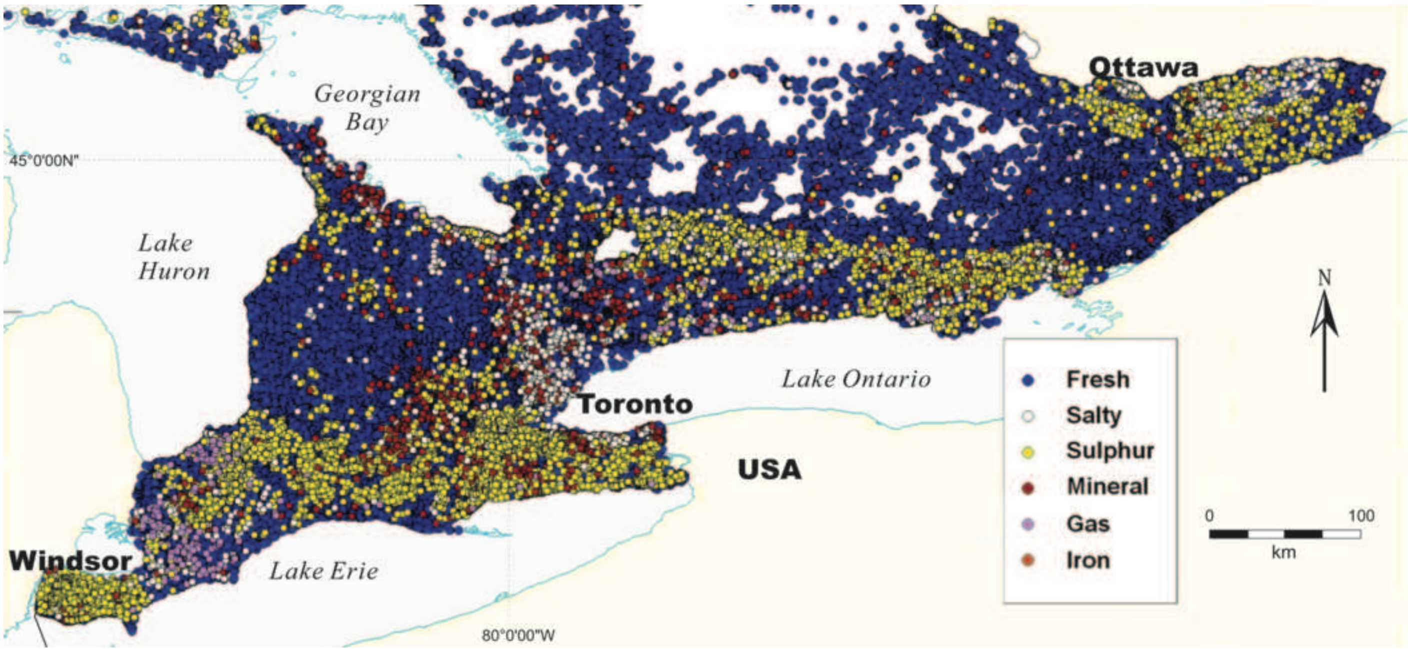


Figure 12.24 Aesthetic groundwater quality in wells across southern Ontario.
Fresh water was reported in ~85% of all wells: less-potable water was found in the other 15%. Each dot represents a group of wells with similar aesthetic water quality based on Ministry of Environment water well database.

areas with differing water chemistry measured in those groundwater wells located in sediment and in bedrock (e.g., Waterloo Hydrogeologic Inc, 2008). These patterns can be viewed within a regional framework of basin water chemistry (Figure 12.25). In general, calcium-bicarbonate-rich water is characteristic of surface infiltration or young groundwater where calcite, common to limestone terrain or limestone-rich sediment, is dissolved (Figure 12.25). Thus calcium-bicarbonate water appears in most areas with calcite-rich sediment or near-surface limestone bedrock. In some areas, water which is largely saline is associated with key formations such as the Salina Formation with its concentrations of halite (salt), or with local upwelling of deeper basin brines (which produce calcium-chloride-rich waters where freshwater mixing occurs). Sodium bicarbonate water occurs in several areas where sodium from saline waters has also mixed with infiltrating carbonate-rich water (e.g., from deep basins). There is also a reasonably close association between the water chemistry in sediment and in rock: this association varies only by geological locality, and may indicate good hydraulic connection between water percolating through sediment to mix with water resident in bedrock fractures. The association may also indicate that chemistry of well water in bedrock reflects more mixed water found in "contact zone" aquifers.

A regional cross section of the southern Ontario (Figure 12.13) sedimentary basin reveals water quality changes as water moves from surface to deeper into the subsurface through three defined zones:

1. **Shallow zone:** low-salinity surface water and young groundwater dissolves calcite to produce a calcium-bicarbonate water ($Ca\text{-}HCO_3$); $Mg\text{-}HCO_3$ can also occur in dolostone bedrock.
2. **Intermediate zone:** medium- to high-salinity water dissolves gypsum or anhydrite to yield a calcium sulphate water ($Ca\text{-}SO_4$), or dissolves halite (salt) to produce a Ca-Cl water.
3. **Deep zone:** basin brine water mixes with

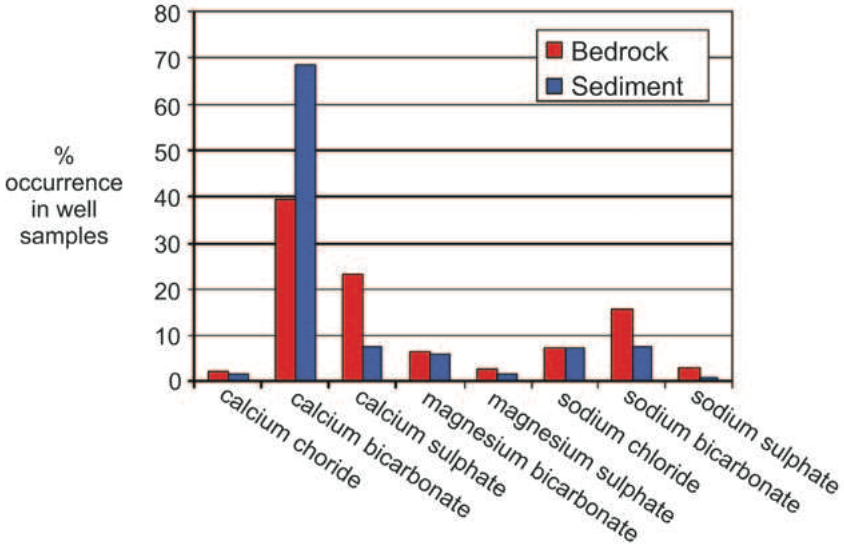


Figure 12.25 Comparing groundwater qualities in sediment and bedrock wells. Type of water sampled (%) in sediment aquifers (blue) and in bedrock aquifers (red) from ~300 wells. Note the relationship between similar water chemistry in sediment and bedrock wells, although this will vary by region. Calcium bicarbonate is an exception; infiltrating, young groundwater dissolves the calcite found in carbonate grains within sediment. Calcium sulphate water is more common in bedrock because gypsum found in rock dissolves to free sulphur.

seawater to produce a sodium- or calcium-rich(Na-Ca-Cl) brine with very high salinity.

In southeastern Ontario and elsewhere across southern Ontario, water that occurs a few metres into bedrock is strongly influenced by the chemistry of water that percolates from overlying sediment (Figure 12.25). This relationship is summarized in regional groundwater quantity and quality attributes, as discussed earlier in this chapter.

12.3.2.2.4 Ambient groundwater geochemistry data for southwestern Ontario, 2007–2010

In 2007, the Ontario Geological Survey initiated a multi-year groundwater sampling program to establish baseline groundwater geochemical conditions in southwestern Ontario. From 2007 to 2010, samples were collected from both domestic water wells and PGMN wells on a grid with 10 by 10 km nodes, with 1 sediment well and 1 bedrock well within each node. Temperature, dissolved oxygen, pH, conductivity and oxidation-reduction potential were measured during sampling using a multi-parameter instrument equipped with a flow-cell (Hamilton et al., 2010). The laboratory analyses of the groundwater samples included groundwater quality parameters, metals, and coliforms (Hamilton, 2011).

The result is a gridded, high-quality groundwater geochemical database which will be used to

1. Establish baseline groundwater geochemistry in major rock and sediment aquifers
2. Relate natural variations in water quality to these rock and sediment aquifers
3. Interpret and integrate other groundwater geochemical datasets
4. Model chemical species

Results show ranges of concentration for all parameters measured in sediment and bedrock. For example, areas of high dissolved oxygen are associated with known subsurface karst (Bruce Peninsula, Beaver Valley and Walkerton areas). Both karst and breathing wells are associated with high dissolved oxygen near Exeter (Hamilton and Freckelton, 2009). Maps and geochemical results can be downloaded from http://www.geologyontario.mndm.gov.on.ca/mndmaccess/mndm_dir.asp?type=pub&id=MRD283.

12.3.2.2.5 Ontario farm groundwater quality survey

Ammonium nitrate is a fertilizer widely used to provide nitrogen to soil in agricultural areas. Nitrogen provided to the soil promotes rapid growth, increased seed and fruit production, in addition to improving the quality of leaf and forage crops.

Nitrate is very soluble and can infiltrate through soil, and move readily into the groundwater system. The ability of nitrate to move through soil may depend on the soil's biological activity, soil type, and, on the nitrate concentration in infiltrating water. The Ontario Drinking Water Quality Standard (ODWQS) for nitrate is set at a maximum concentration of 10 mg/L (10 parts per million) as nitrogen (nitrogen is the main chemical element of nitrate). This concentration was established to prevent any incidence of methaemoglobinaemia, a blood disorder that occurs when red blood cells are unable to carry oxygen to other cells within the body, due to a change in haemoglobin. This condition is most commonly found in infants under 6 months of age.

An Agriculture Canada groundwater quality study sampled ~ 1,300 Ontario domestic farm wells in 1991 and 1992 for nitrate, and fecal coliforms, plus several pesticides (Rudolph et al.,1998).

Nitrate concentrations exceeded the standard of 10 mg/L in water samples from ~15% of the domestic farm wells. Results indicated:

- most nitrate contaminated wells were shallow, dug or bored wells
- nitrate concentrations tend to be higher in areas of high-permeability soils
- nitrate concentrations were consistent at the same location and did not show a seasonal variation
- nitrate concentrations decreased linearly with depth

An Oxford groundwater study in 2000 found nitrate concentrations above the 10 mg/L-N standard, in water samples from 10 of 83 (12%) sampled shallow sediment wells (Golder Associates Ltd., 2001). In Woodstock, nitrate concentrations in groundwater pumped from the Thornton well field have reached and exceeded the 10 mg/L-N standard. Nitrate contamination is likely due to agricultural activity west of the well field.

12.3.2.2.6 Road salt management

The use of road salt as a deicer on roads and parking lots is the preferred method to promote safe motor vehicle and pedestrian travel during winter months. As in all of eastern Canada, road salt is a source of groundwater contamination. Up to 50% of all complaints about well water quality at regional and district offices are related to road salt. Maximum desirable chloride concentrations are 250 mg/L (Ontario Drinking Water Standards), yet concentrations as high as 14,000 mg/L have been found in shallow groundwater near highways in Toronto (Howard and Maier, 2007).

Salt in groundwater may make it unsuitable for human consumption and some industrial applications. Groundwater contaminated with salt may also discharge to urban streams causing degradation of surface water quality. Sodium has been strongly linked to hypertension and associated indirectly with hyper-natraemia (Howard and Haynes, 1993; Howard and Beck, 1993).

Salt contamination of drinking water is generally limited to wells near paved roads (less than 30 m away), and is more likely in areas with many wells along the roadside, areas with heavy salt application (i.e., urbanized areas), and where topography favours contamination (e.g., steep, hilly terrain). Additional factors include shallow, dug or poorly constructed wells, and thin or permeable sediment (MacRitchie et al., 1994).

Over the past few decades, increasing chloride levels in groundwater have been observed in many urban municipal wells (Figure 12.26). Results tracked from two well fields in the Regional Municipality of Waterloo since the mid-1970s clearly reveal the impact of road salting, its link

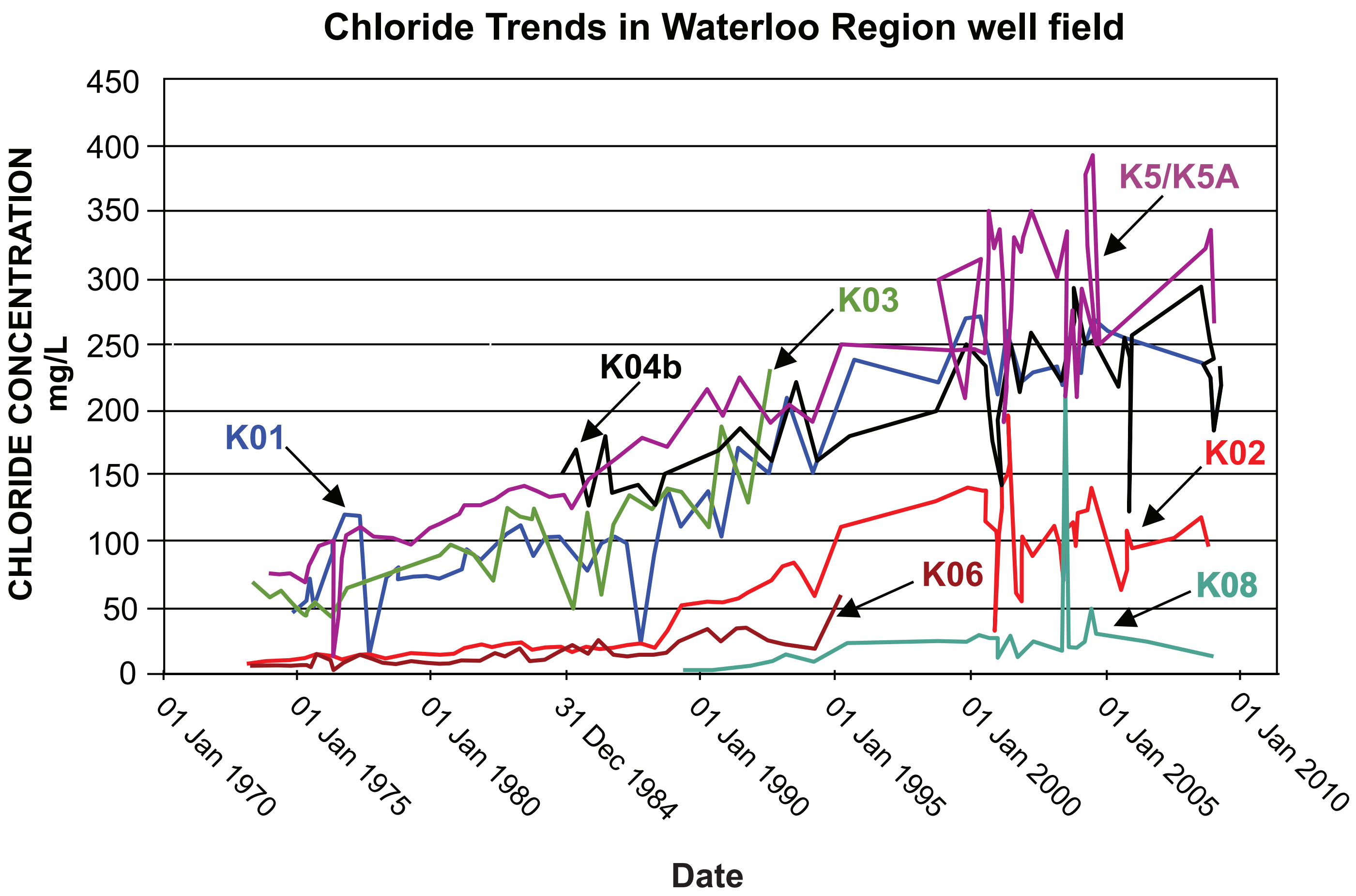


Figure 12.26 Road salt and water quality trends.

Road salt has been identified as a major threat to the groundwater supply of the Regional Municipality of Waterloo (which includes Kitchener, Waterloo, and Cambridge). Some well fields supplying drinking water have chloride concentrations above the 250 mg/L standard. A Road Salt Management and Chloride Reduction Study was initiated in 2003 to stabilize or reduce salt access to the groundwater supply; a field study in 2008 found a 45% reduction in average total mass of chloride. Labels K01 etc. represent individual municipal wells. Y-axis is concentration in mg/L (Figure courtesy of Regional Municipality of Waterloo).

to increased urban growth, and the number of roads in the region. Salt content increased three to four times in five municipal wells, located in two well fields, over a 25-year period. Rural wells also show evidence of increased sodium and chloride concentrations, albeit at lesser levels. The Ontario Drinking Water Objective for chloride (250 mg/L) is an aesthetic guideline, but increasing chloride levels can be a signal of potential land-use impacts.

A three-dimensional groundwater transport model was developed to evaluate the impact and risk to groundwater from winter road salt in Waterloo. The model showed chloride plumes originating mostly from arterial roads and migrating through a complex system of aquitards and aquifers, and into the water supply. Various scenarios of road salt application were postulated for the next 50 years and applied to the model. It was concluded that the impact of road salting on groundwater could be severe and that its reduction or elimination should be considered (Bester et al., 2006).

It should also be noted that the Region of Waterloo is largely underlain by the carbonate and gypsum-bearing rocks of the Salina Group. Where these rocks are buried to greater depths further west, they include beds of halite (rock salt). It is expected that formation waters in these rocks have a naturally elevated salt content. Thus, increasing salt content in water in the high-volume municipal water wells within the area may be due to withdrawal of saline formation water from deeper in the aquifer. Increased salts in Waterloo municipal water may result, in part, from more roads being deiced, and from high urban water consumption, requiring groundwater to be drawn from the deeper, naturally saline waters. This example illustrates the need to understand the groundwater flow system and how water quality may change due to natural and human-induced changes.

12.3.3 Groundwater use

Some 25% of southern Ontario residents rely on groundwater for their drinking water (e.g., Environment Canada, 2005; 2007). Indeed, some communities such as Orangeville and Guelph are entirely dependent on groundwater. Other major municipalities draw on a mix of surface and groundwater sources. The Regional Municipality of Waterloo takes 80% of its water from groundwater sources, with the other 20% from the Grand River. Kingston and Ottawa, depend mainly on surface water sources, but use some groundwater. The reliance on groundwater is much higher in rural areas, with 90% of rural residents using it as their drinking water source. The estimated total value to Ontario users of groundwater for drinking water is at a minimum, hundreds of millions of dollars a year (e.g., Nowlan, 2005; Figure 12.27). However, there is not enough data to be able to estimate accurately how much groundwater is used. The price of water does not include its value in dollars, just the service (cost of delivering reliable groundwater supply). Additionally, dollar valuation of water based on human uses only ignores the enormous value of groundwater for ecosystems.

Many industries rely on groundwater, with some served by groundwater-based municipal water supply systems and others using their own wells (Scharf et al., 2002). Water bottling is an industry that has grown dramatically during the past decade, with resulting conflicts. For instance, a 2007 application to increase water-bottling operations near Guelph produced intense opposition despite its potential economic value. Gravel pits and quarries are other important rural industries using groundwater. To extract aggregate below the water table, large quantities of groundwater must be pumped and may be discharged into nearby surface water bodies or lost to evaporation. In agriculture, farmers use groundwater for many purposes, the most important being irrigation of crops and watering livestock. While agricultural withdrawals of groundwater tend to be small, they can have a large impact locally because agriculture, in contrast to most municipal uses, consumes most of the water it withdraws. Golf course operators also consume groundwater for irrigation, which can add to land-use stress on groundwater-surface water systems.

While human uses are important, groundwater is also essential to the health of southern Ontario's ecosystems by providing baseflow in rivers and streams. For example, during the hot, dry conditions in late summer, water flow in many streams and rivers in southern Ontario comes completely from groundwater. Without this steady, cool groundwater flow, fish and other aquatic life would be in distress and their survival in jeopardy. A critical point in assessing groundwater use is the necessity of recognizing that humans have to share available supplies with aquatic environments. It is essential that human uses be balanced against the needs and limits of aquatic systems. More research is needed to clarify the ecological significance of groundwater (Box 12-7),

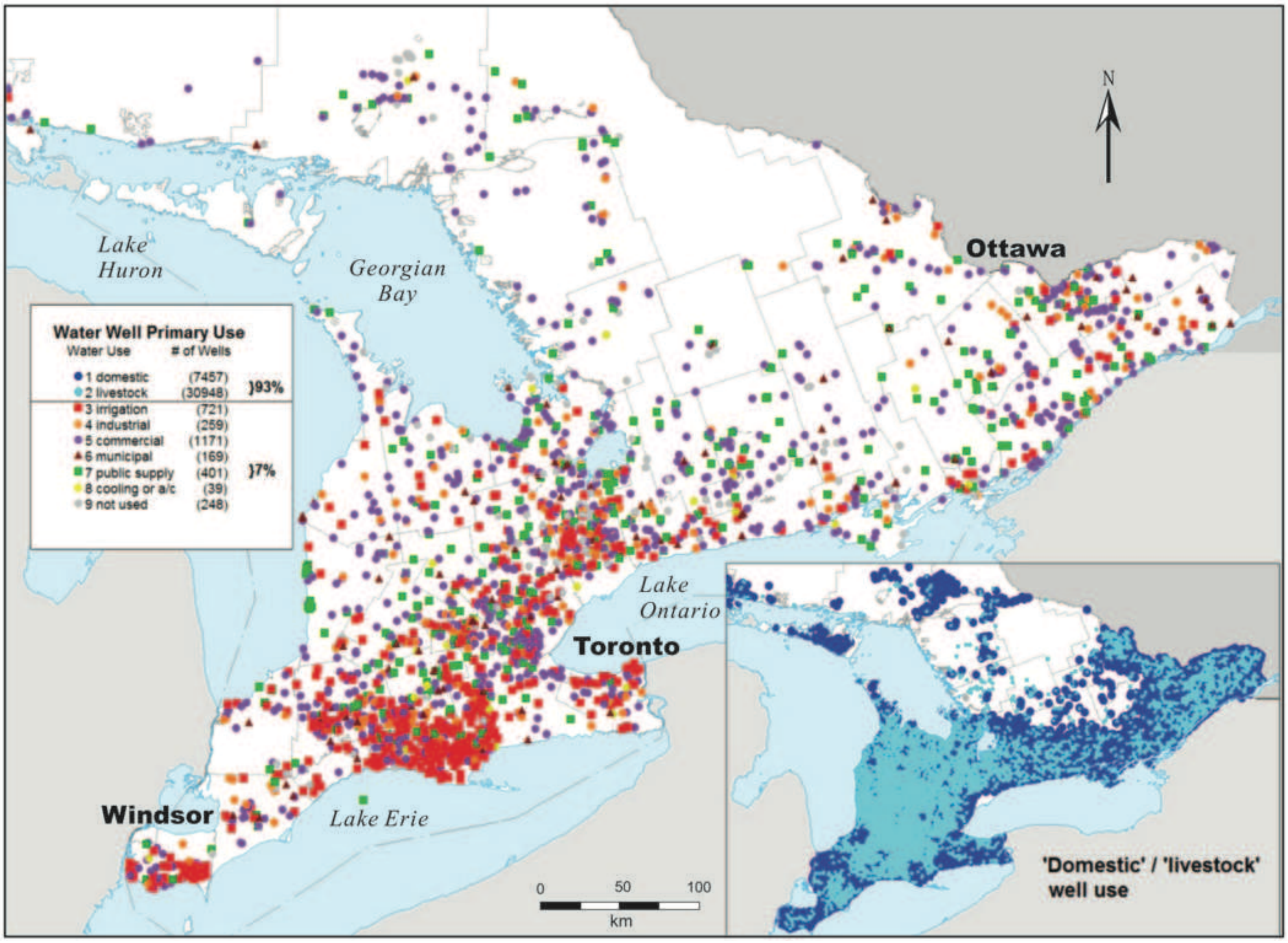


Figure 12.27 Who uses groundwater?
Groundwater use in southern Ontario based on major water uses reported in water well data from Ontario Ministry of the Environment. Note that the inset figure illustrates that there are many more livestock wells than domestic wells.

followed by public awareness building about this shared resource aspect.

12.3.3.1 Patterns and trends

Generally speaking, our understanding of water use in southern Ontario is poor, but improving (de Loë, 2005). There is a wide variation by sector and region in the completeness of water-use data. Data reporting for groundwater is particularly poor, as most levels of government neglected this role until recently (de Loë and Kreutzwiser, 2005). Preparation of aquifer and groundwater susceptibility maps ceased prior to the 1990s due to low budgets and reduced groundwater staff. Groundwater use is in decline in some large centres, like the GTA, due to increase use of piped lake water.

Encouragingly, since the Walkerton Inquiry findings were made public in 2002, there has been an increased emphasis on groundwater resources. Water-use reporting has improved through provincially funded groundwater management and protection studies. New groundwater studies have focused primarily on threats to groundwater quality and groundwater availability. Other initiatives, as well, are contributing to a better understanding of groundwater in the region. These include

- A Provincial Groundwater Monitoring Network

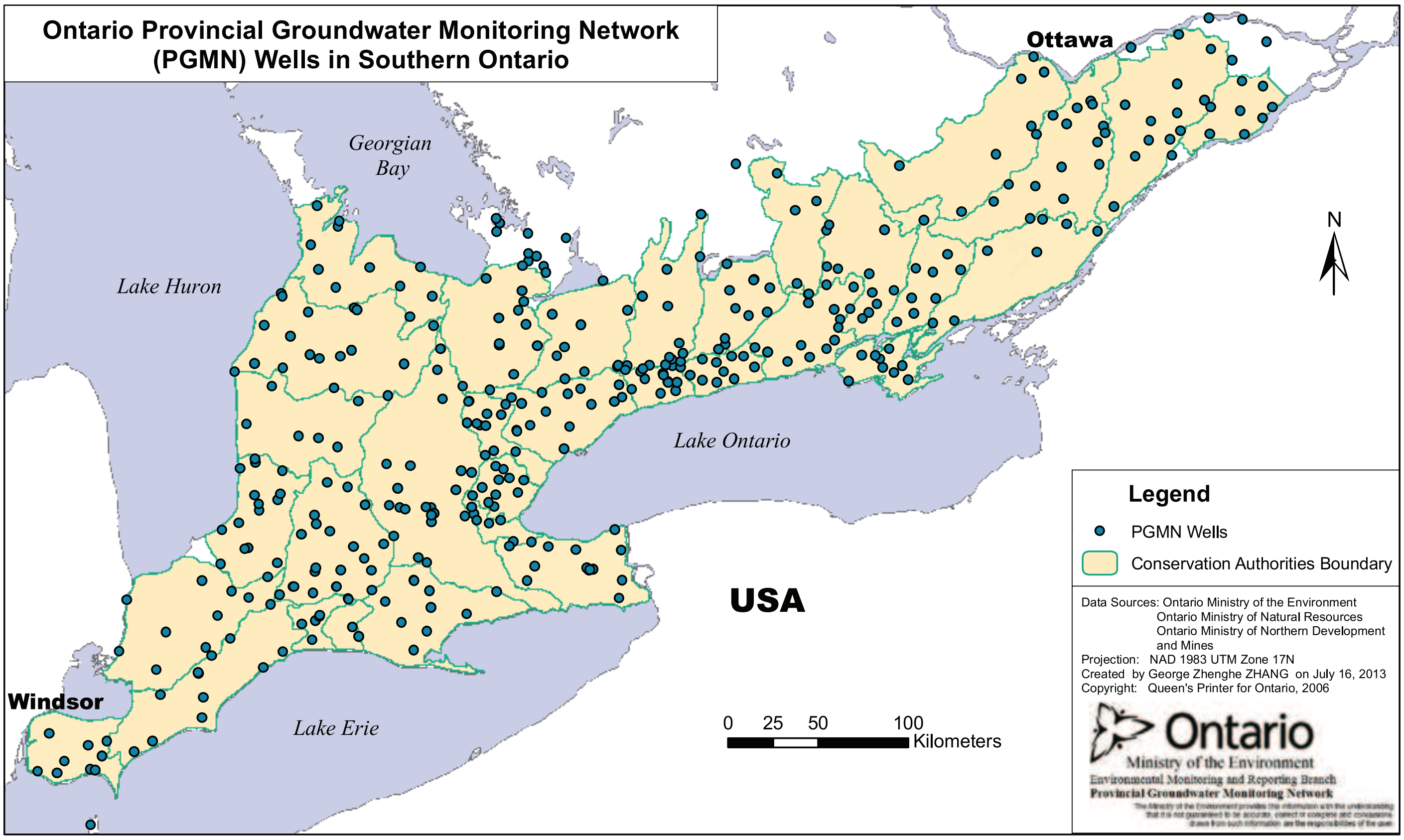


Figure 12.28 Measuring the pulse of the groundwater system.
The Ontario Ministry of the Environment Groundwater Monitoring Network covers most of southern Ontario region with monitoring wells set within the boundaries of conservation authorities, which manage water at the local scale. Note that some wells occur in the Canadian Shield hydrogeological region.

established in 2002, which collects and manages data on groundwater levels and quality in key aquifers across Ontario, including 400 monitoring wells in southern Ontario (Figure 12.28).

- Changes to the Permit to Take Water program (PTTW), Ontario's water allocation system, provides access to higher-quality water-use data. The Water Taking and Transfer Regulation under the Ontario Water Resources Act now requires that permit holders (those using more than 50,000 L/d) collect and record data on the volume of water taken.
- Permits now distinguish surface water from groundwater use. Thus over time, water-use data will improve. Water users who do not require a permit (use of < 50,000 L/d) for domestic use and livestock watering without storage are not counted, and this will create gaps in the database.

In summary, groundwater in southern Ontario is a subject that has been overlooked in the past, and our knowledge of this important resource is poor. In the wake of the Walkerton tragedy and bolstered by growing public awareness about the need to protect water resources, the forecast is improving for better groundwater management based on high-quality data from improved monitoring of this resource.

12.3.4 Understanding groundwater systems within the Grand River watershed

Work on one of the most characterized groundwater systems in Ontario, the Grand River watershed, provides a good example of how to assess, integrate and manage groundwater information and resources for all users. A watershed-wide groundwater flow model has been developed to incorporate new data and information with each model-iteration (e.g., Holysh et al., 2001; Waterloo Hydrogeologic Inc., 2005; AquaResource Inc., 2009). Model results have been very useful for determining a watershed-wide water budget (see Box 12-8) and for determining areas of groundwater recharge and discharge. The groundwater flow models also allow for better understanding of groundwater–surface water hydrologic linkages within the Grand River watershed and help tackle key questions including

1. Where does predicted groundwater recharge water go, to local or deep flow?
2. How are areas of high groundwater discharge evaluated?

These questions are addressed by using forward and reverse flowpath analyses within the groundwater flow model. Flowpaths are used to estimate where groundwater enters, travels through, and exits the groundwater flow system. These results can be tested with focused field data, stream gauging and ecological indicators, to better understand watershed hydraulic linkages. For example, areas of groundwater discharge have been correlated with coldwater fisheries (Figure 12.29).

Understanding and maintaining groundwater discharge is pertinent to ecological function. Groundwater discharge not only maintains baseflow and moderates stream temperature, but overall water quality is improved. Whitemans Creek thus provides habitat to the Silver Shiner, a fish species of special concern.

12.3.4.1 The quality of groundwater within the Grand River watershed

Groundwater within the Grand River watershed is considered to be of good quality where wells are used primarily to serve domestic and livestock uses (Environment Canada and EPA, 2005). Naturally elevated concentrations of inorganic constituents (e.g., calcium, magnesium, sodium, chloride and sulphate) are often found within the watershed's sediment and bedrock aquifers, and hard water is common throughout the watershed. The City of Guelph's wells yield water with hardness three to four times the aesthetic Ontario Drinking Water Objective of 80–100 mg/L.

Of the water wells with reported natural groundwater quality problems, 90% are in bedrock, compared to only 10% within sediment wells. Elevated sulphur concentrations are the most commonly reported problem within these wells; they are often associated with location within Salina or Guelph formations. As discussed in Box 12-6, fluoride can also have high natural concentrations in the groundwater of southern Ontario.

Human-induced changes to groundwater quality in the watershed are associated with urban sprawl, agriculture and industry (Sawyer et al., 2005). Common localized contaminants include organic compounds and bacteria from livestock, and more widespread impacts due to nitrates from agricultural fertilizers and septic systems. Chloride in road salt occurs in urban (Figure 12.26) and rural areas of the watershed.

Industrial contaminants known as volatile organic compounds (VOCs) have caused major problems in municipal groundwater supplies within several communities of the Grand River watershed. By 1998, for example, five of the City of Guelph's 24 wells were permanently removed from service due to low-level VOC contamination. This was a serious problem as these wells produced about 15% of Guelph's permitted water-taking

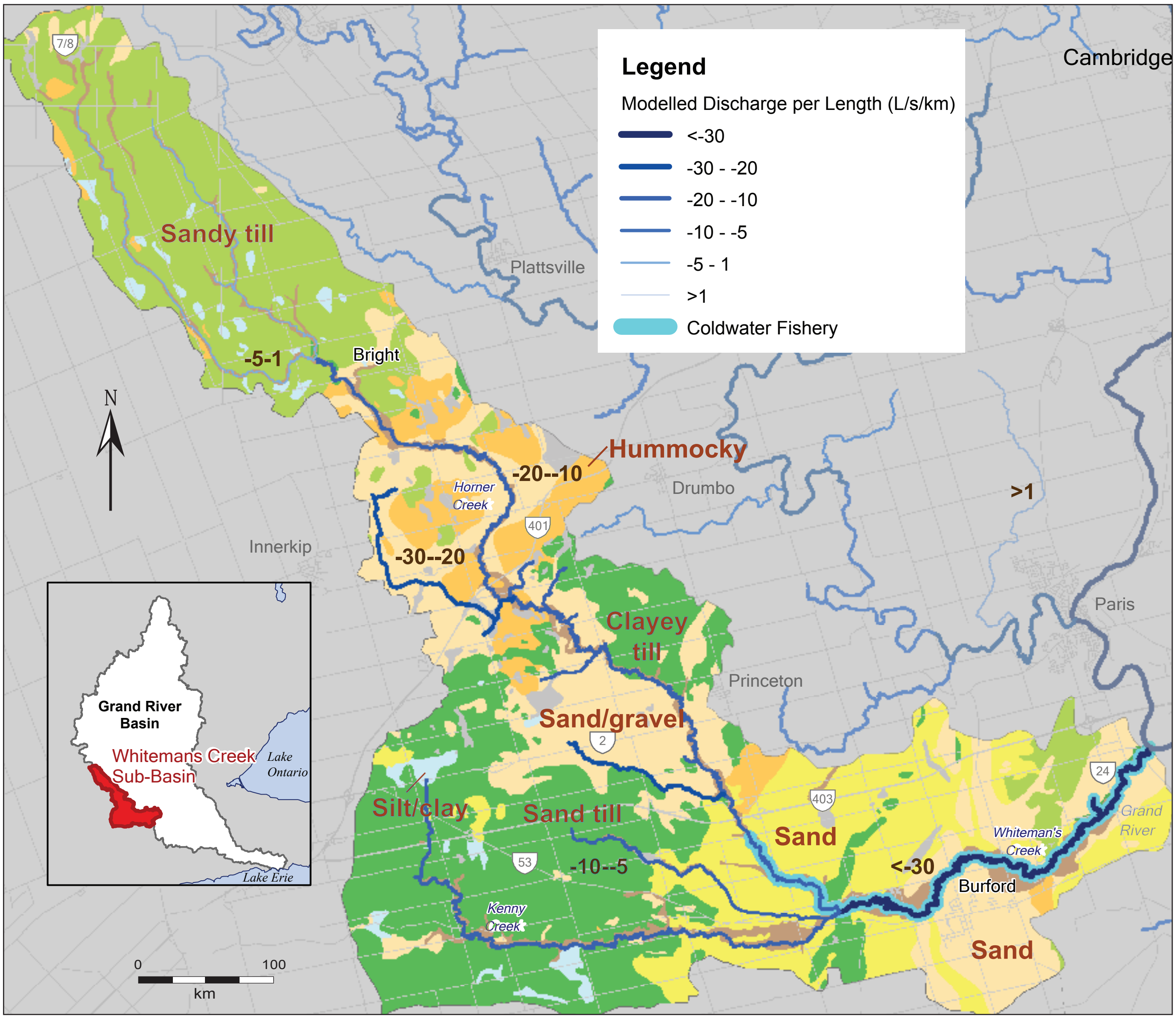


Figure 12.29 Geology controls groundwater discharge.
Variable sediment type in Whitemans Creek sub-watershed relates to areas of higher groundwater discharge and mapped areas of cold-water influx. The local shallow flow regime of the Norfolk sand plain discharges ~30–60 L/s/km of groundwater to Whitemans Creek, a high groundwater discharge zone within the Grand River watershed. Mapped cold-water fish distribution within Whitemans Creek compares well with modelled reaches of groundwater discharge with cold-water regimes.

capacity. Ultimately, new well fields were developed and water conservation measures implemented. In the community of Elmira, both a shallow, sand and gravel aquifer (Elmira Moraine) and a deeper municipal aquifer were contaminated with a variety of chemicals from nearby industrial plants. Elmira now receives its water supply from the Regional Municipality of Waterloo and nearby townships within the region.

12.3.4.2 Groundwater and land use: Agricultural impacts

Agriculture, covering ~67% of the total land area, is the major land use in the Grand River watershed. Agricultural activity can affect groundwater quality in many ways: use of pesticides, application of fertilizer or manure on fields, and improper storage, disposal or spills of animal waste or chemicals.

A significant problem arises from the application of excessive quantities of nutrients to agricultural land. Excess nitrogen is converted to nitrate, then picked up by infiltrating water and transported to the water table, where nitrate can affect groundwater quality. Land use and nitrate levels, measured in surface water from two sub-watersheds, illustrate the effects of agricultural activities on groundwater and surface water quality. In Whitemans Creek, ~78% of the area of groundwater infiltration is used for agricultural purposes, while ~20% is forest cover. In Eramosa River, ~60% of recharge land is for agricultural use and ~34% is forest cover. In both sub-watersheds, rivers receive significant quantities of groundwater discharge. The average annual concentration of nitrate measured in Whitemans Creek (1997 to 2003) was 2.5 to 8 times higher than that measured in Eramosa River. The higher nitrate levels measured in Whitemans Creek show the link between increased agricultural activity and groundwater contamination, and have implications for surface water quality. These high levels may also be a result of the larger number of rural communities in Whitemans Creek, with a correspondingly high density of septic systems leaching nutrients to the subsurface. In addition to nitrates, manure spreading on fields, runoff from waste disposal sites, and septic systems can all provide a source of bacteria to groundwater. Bacterial contamination in wells located within agricultural areas is common. This contamination is often due to poor well construction or maintenance, which allows surface water to enter the well (thus not indicative of widespread aquifer contamination). Shallow, dug wells are most vulnerable to bacterial contamination (Conservation Ontario, 2003).

The Grand River watershed population may increase by ~300,000 by 2020. Urban expansion and industrial development associated with this population growth will place increasing pressure on groundwater quality. Intensification of agriculture may also aggravate pollution caused by nutrients, bacteria and pesticides. Potential effects of climate change may put pressure on groundwater availability, which in turn could concentrate existing contaminants. Protecting groundwater resources will require multi-faceted strategies including regulation, land-use planning, water-resources management, voluntary adoption of best management practices, and public education, as well as improved understanding of the groundwater flow system fluxes and composition.

12.3.4.3 Integrated water management within the Grand River watershed

Conservation Authorities co-ordinate, focus and streamline water management using integrated approaches that extend across jurisdictional boundaries. The Grand River Conservation Authority's Rural Water Quality Program aims to improve water quality by implementation of best management practices. Farmers have access to financial assistance for eligible projects and over 1,600 projects have already been supported. The Authority has also organized a Low Water Response Team that declares low water conditions for each part of the watershed using three low water conditions specified by the Ministry of the Environment. Finally, the Authority has 27 wells which are part of the Provincial Groundwater Monitoring Network. Data from these wells assists in understanding long-term trends in groundwater conditions, and in establishing baseline geochemical characteristics at each site.

12.4 SUMMARY

We have touched on many issues linked to groundwater in southern Ontario in this chapter. We have seen how contamination of groundwater can have tragic consequences, or even close parts of a municipal well system, as in Guelph. We have touched on the issue of groundwater as a shared resource between humans and the rest of the ecosystem. And we have talked about competing demands for groundwater resources, and how these could become a major issue during extended dry spells. To sum up, we identify a few key issues that require pertinent scientific context. The goal is to assist public engagement in an active and informed dialogue regarding science-based approaches to groundwater protection in southern Ontario. This includes key legislation and some important outreach activities that are reshaping the management of groundwater.

12.4.1 Summing up groundwater science

Groundwater is generally abundant, of good quality and occurs in a diverse set of aquifers and aquifer systems across southern Ontario. Shallow bedrock and contact aquifers are important and widespread across the region. The best of these occurs in carbonate rocks west of the Niagara Escarpment, particularly where flow is enhanced by karst. Water quality can be an issue where shale and gypsum rocks occur in shallow bedrock units. Wells that only penetrate a short way into bedrock may, in fact, draw much of their water from the sediment rock interface. Deep bedrock is not a significant source of potable water in southern Ontario as most deep strata retard water flow. Deep regional aquifers occur in a few bedrock formations, either in sandstone or in carbonate rocks with karst zones; however, most deep water is saline and locally sulphurous.

Sediment aquifers are also common, widespread, and their natural water quality is almost always very good. These aquifers are very prominent where sediment is thick, such as in sandy moraines (Oak Ridges Moraine, Waterloo Moraine), in buried valleys (Laurentian valley), and on the north shore of Lake Erie. Different sediment types affect the flux, chemistry and annual movement of water.

In general, clay plains such as the Essex clay plain are characterized by high surface runoff and little infiltration of rain or snowmelt that seeps to groundwater in deep sediment-bedrock interface aquifers. Groundwater levels change very slowly over the year. Sand plains, on the other hand, such as near Norfolk, allow rain and snowmelt to readily infiltrate the surface and transmit water to the water table, where it is stored as groundwater, particularly in the spring. This stored water releases slowly throughout the summer, as discharge to streams, when rainfall inflow is low. Groundwater levels vary in response to these seasonal events. Water levels in wells drilled through till uplands in Grey County behave differently than wells in either the clay plain or sand plain, partly due to the more complex geology and slopes in this region. A dissected till upland in thick sediment in Wellington County is cut by channels containing glacial meltwater sediment, sand and gravel. In such terrains, stream baseflow is high due to enhanced permeability and storage in coarse sediment of the groundwater catchment. Groundwater levels also respond to precipitation and snowmelt events, yet with slightly delayed responses due to the fact that water is stored in near-surface, valley sediment, or wetlands. In addition, streamflow in limestone plains responds rapidly to precipitation and snowmelt that runs off the limestone surface.

Groundwater levels also respond rapidly to these events as karst-enhanced fractures capture some runoff. Groundwater storage levels vary by many metres over the season as karst enlarged chambers fill and empty from spring to late summer. The different hydrogeological settings are important because we can generalize understanding from one setting to similar settings across southern Ontario. We can also improve understanding by comparing or contrasting the type settings to other settings using a simple geological map of type settings across the region.

While general water quality and availability is good, there are some areas where groundwater supply and quality are poor. Agencies are starting to improve understanding by collecting better hydrogeological data, and by providing guidance on interpretation and monitoring. Overall, there is still much work to do to improve the collection and integration of high-quality data into publicly accessible groundwater databases.

12.4.2 Improved information and improved access

Southern Ontario is fortunate to have a considerable amount of regional hydrogeological data relative to most aspects of water resource management. Nevertheless, we need to achieve a better understanding of how groundwater functions at the regional scale, based on climate data, and more high-quality streamflow, water level, geology and borehole records, set within a modern information framework. Such an enhanced framework would aid the systematic mapping of groundwater throughout southern Ontario, including links to surface water. Ideally, the information framework and groundwater understanding can be connected to key properties of the regional hydrogeological system.

The Walkerton tragedy focused much needed attention upon groundwater and triggered the implementation of Source Water Protection as part of the Clean Water Act. This is a good first step, but there is still more that can be done, particularly in the area of quantitative water use and monitoring. Provincial programs, such as the Permit to Take Water program, need to be further integrated with land use information to develop a comprehensive water management strategy for Ontario.

12.4.3 Collaboration

Improved information, understanding and management of groundwater in southern Ontario rely on an ongoing need for cooperative efforts among local watershed authorities, municipalities, provincial ministries, the private sector and, possibly, federal experts. One very effective partnership is the Conservation Authorities Moraine Coalition, an amalgamation of the York, Peel, Durham and Toronto regional municipalities, and nine conservation authorities, with its focus on improving the public's basic understanding of surface water–groundwater resources. Additional similar partnerships would be beneficial at all levels of government. Single agencies in some cases, such as the Grand River Conservation Authority, have developed the vision and commitment to address water resource issues with up-to-date knowledge and understanding. Again, this is a model that could be adapted throughout southern Ontario.

12.4.4 Groundwater topics of interest

Events such as the tragedy in Walkerton have increased public and political interest in groundwater. They have also focused greater attention on a wide range of concerns and topics regarding the sustainability of groundwater resources of southern

Ontario. Science-based approaches must be used to determine the potential for detrimental impacts. In urban settings, for example, there are concerns that the increasing extents of impervious surfaces such as roads and parking lots may reduce recharge and baseflow while also requiring increased use of road salt that could contaminate groundwater. Deteriorating infrastructure such as sewers, water mains, and underground storage tanks certainly have the potential to impact groundwater. In rural settings, there are concerns about agricultural practices such as manure storage and spreading, and the use of chemical fertilizers and pesticides, the disposal of sludge from wastewater treatment plants, and how the increasing number of quarries impact groundwater supplies and dependent habitat and species. Waste disposal facilities such as landfills and the wells that are used to inject liquid wastes into the deep subsurface continue to cause concern, as do the many industrial and commercial sites that handle hazardous materials. Water bottling and other consumptive uses of groundwater, such as the irrigation of crops and golf courses, are topics of discussion in some areas. In others, pipelines are now being used to supply water to homes and businesses that were previously dependent on groundwater. Geothermal heating and cooling systems have the potential to decrease fossil fuel dependence and carbon dioxide emissions, but these installations may also impact groundwater. Climate change may alter the timing and magnitude of recharge and result in more frequent and severe precipitation events. Sequestration of carbon dioxide and the burial of radioactive waste in deep geological formations, and the tracking of shale gas from wells that have been stimulated using hydraulic fracturing, are emerging topics for improved knowledge and discussion.

ACKNOWLEDGEMENTS

We appreciate the assistance of a number of contributors who are not listed as co-authours: Andrea Bradford contributed to the Box 12-7 on the ecological significance of groundwater; Eric Hodgins provided the figure on salt trends in municipal wells, Regional Municipality of Waterloo. Reviews by Bob Betcher, Frank Brunton, Emil and Michael Frind, John Gartner and Bob Leech helped greatly to improve the chapter. Graphic assistance was provided by John Glew (drawings), Richard Franklin (drawing standardization), Rachelle Lacroix, and Charles Logan. Elizabeth O'Discoll provided edits from a lay person perspective. Christie Vodden revised an early draft of the chapter and made recommendations for publication to a general audience.

BOX 12-1 THE WALKERTON TRAGEDY IN 2000

After a heavy rainstorm on May 12, 2000, Walkerton's groundwater supply was contaminated with *E. coli* when surface water washed cattle manure into a town well where it quickly entered the public water system. Seven people died, while another 1,286 were struck with debilitating illness all because an unreported, faulty chlorinating system in the town well failed to kill the bacteria. The tragic events at Walkerton were a turning point in terms of groundwater understanding, policy and management.

One of the key recommendations of the Walkerton Inquiry report, released in 2002 (O'Connor, 2002), was that science-based Source Protection plans be developed for all Ontario watersheds. Ontario's Clean Water Act, passed in 2006, requires that all communities, through local Source Protection Committees, assess existing and potential threats to their water. The Act also empowers communities to take action to prevent any threats from becoming significant. This requires the development of a local Source Protection plan, based, in part, on public input. The Clean Water Act is guiding progress in understanding the availability of groundwater and its annual flow within a watershed under variable conditions such as spring floods and summer droughts. Accordingly, provincial and municipal governments as well as conservation authorities now require accurate and timely regional scientific data and expertise to support their groundwater management plans. These plans are to be coupled with a continuing public dialogue on water science and policy. Further information on the policies and the science behind Drinking Water Source Protection is web-accessible (http://www.ene.gov.on.ca/environment/en/subject/protection/index.htm). Information on Source Protection is also provided in sections 12.1.5 and in 12.4.2.

BOX 12-2 LINKING HYDROGEOLOGICAL SETTINGS TO HYDROGRAPHS

To understand the regional hydrogeological variability in southern Ontario, we link geology to hydrographs with available case studies (Figures 12.30, 12.31, 12.32). These studies are depicted by a conceptual sketch that shows the water movement in key southern Ontario landscape types. Three graphs provide climate data, streamflow and groundwater levels for informed comparisons, all of which are referenced to the same climate year. We note that total streamflow, groundwater recharge/discharge, and groundwater/water level fluctuations are not always directly related to total annual precipitation, owing to seasonal climatic effects. These effects determine the form of precipitation (rain/snow) and the movement of water between the atmosphere, surface and subsurface reservoirs. The well numbers and associated groundwater level data are from a Ministry of the Environment monitoring network that operated from 1974 to 1980. Many of the wells from this historical network have been re-activated since 2001 for inclusion into a recently established Provincial Groundwater Monitoring Network (PGMN). Note that in all hydrographs, streamflow is expressed in millimetres (mm) as a daily volume of flow per unit area of gauged watershed. This allows the data to be directly compared with millimetres of precipitation, and also helps to enable data comparison for different watersheds. Groundwater levels are in metres below ground surface (m bgs; Piggott, 1999).

To help compare hydrogeological settings, relatively small watersheds, of less than 1,300 km^{2,} were chosen in order for the hydrological data to be better linked among weather stations, stream gauges and observation wells.

BOX 12-3 NORFOLK SAND PLAIN: SEDIMENT AQUIFER CASE STUDY

A 23.8 m deep well (413A) samples a sand aquifer in a low-relief sand plain (Figure 12.30). Streamflow in Venison Creek rapidly responds to precipitation and snowmelt, but relatively low peak flows are generated (Figure 12.30c). This, plus the relatively high baseflow, is indicative of significant groundwater recharge and discharge. Baseflow forms a substantial portion of streamflow throughout the year, and likely reflects relatively high permeability and groundwater storage. Adequate storage in sandy strata helps to maintain baseflow, while permeability of the flow system is moderate so that storage is not discharged too quickly. Rapid infiltration of precipitation, through regionally extensive near surface sand, appears to increase the efficiency of groundwater recharge during periods of elevated evaporation and transpiration, and contributes to maintaining baseflow. Groundwater

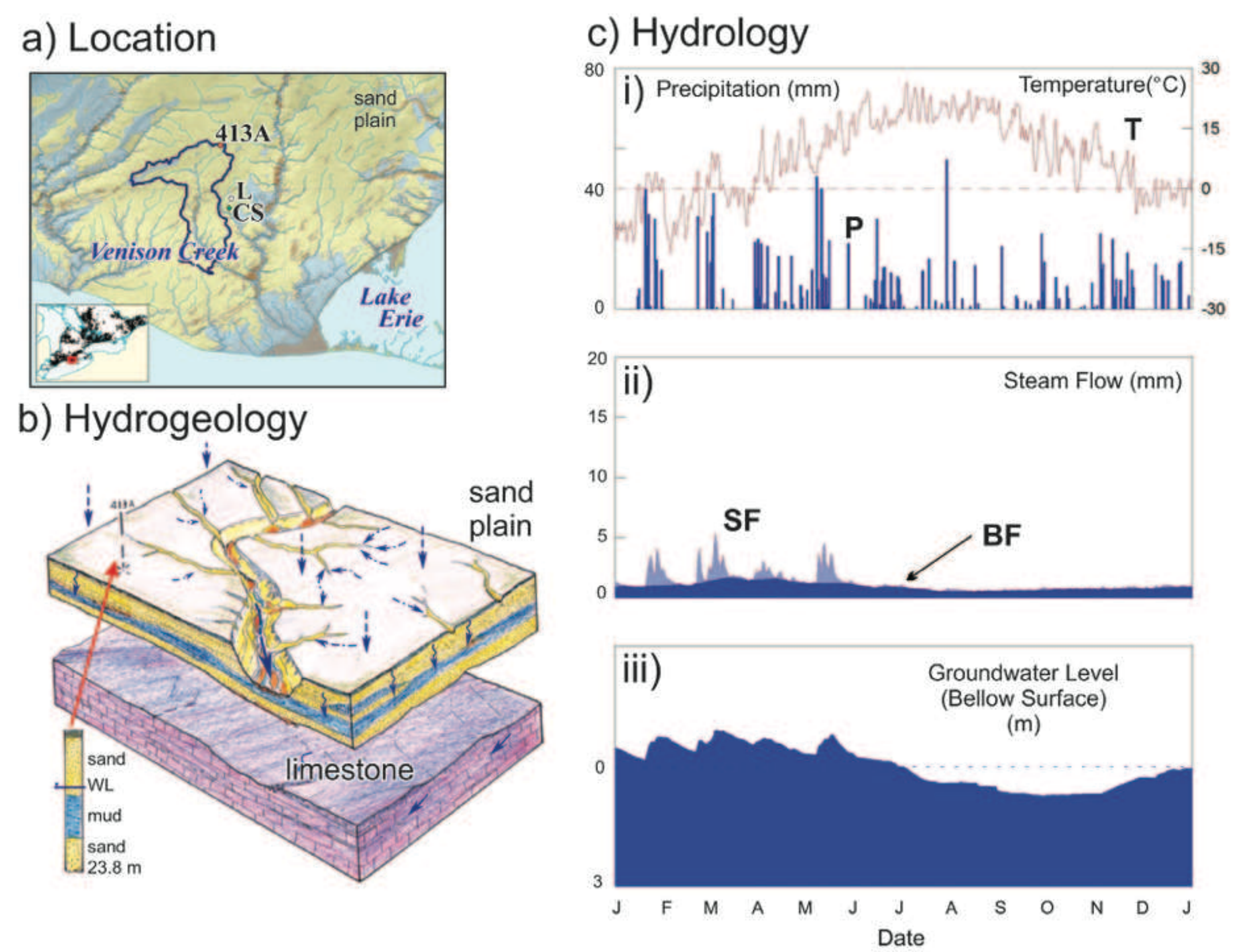


Figure 12.30 Norfolk sand plain hydrogeological setting
a) Location with sand plain geology (yellow); dark areas in inset map show sand plain coverage in southern Ontario; Lawrence Station is marked L. b) Conceptual sketch charts well-bore sediment and rock strata with local surface/ groundwater flow pattern. Arrows indicate relative flux of water movement from atmosphere to surface flow, and to groundwater flow. c) Hydrology for common year 1974 from climate station (CS) with graph scales set to aid comparison: i) precipitation (P), temperature (T); ii) streamflow (SF), baseflow (BF), separated from streamflow to Venison Creek; iii) well water levels change by ~2 m over the year, with noticeable pulses in late winter and spring

levels (Figure 12.30c) rapidly respond to precipitation and snowmelt, but the magnitude is modest, given high estimated recharge; this suggests substantial groundwater storage. The recession of groundwater levels which occurs during summer and early fall is not uniform, and varying rates may reflect recharge events during this period. The rapid response to recharge events and the even distribution of groundwater outflow from storage throughout the year appear to be representative of southern Ontario sand plain settings. Note the different hydrological behaviour of a sand plain when compared to a clay plain (see below), given similar climatic inputs.

BOX 12-4 ESSEX CLAY PLAIN/INTERFACE AQUIFER CASE STUDY

A 58.5 m deep well (164A) samples an interface aquifer with limestone overlain by a sand bed beneath an extensive, ~20 m thick clay plain (Figure 12.31). Streamflow along the nearby Ruscom River responds rapidly to precipitation and snowmelt that runs off the clay surface, resulting in large peak streamflows during the early part of the year. Crop cover in this agricultural area may intercept or reduce peak streamflows during the growing season (Figure 12.31c). These factors, combined with low baseflow (BFI=0.16), indicate limited groundwater recharge and discharge. Groundwater levels

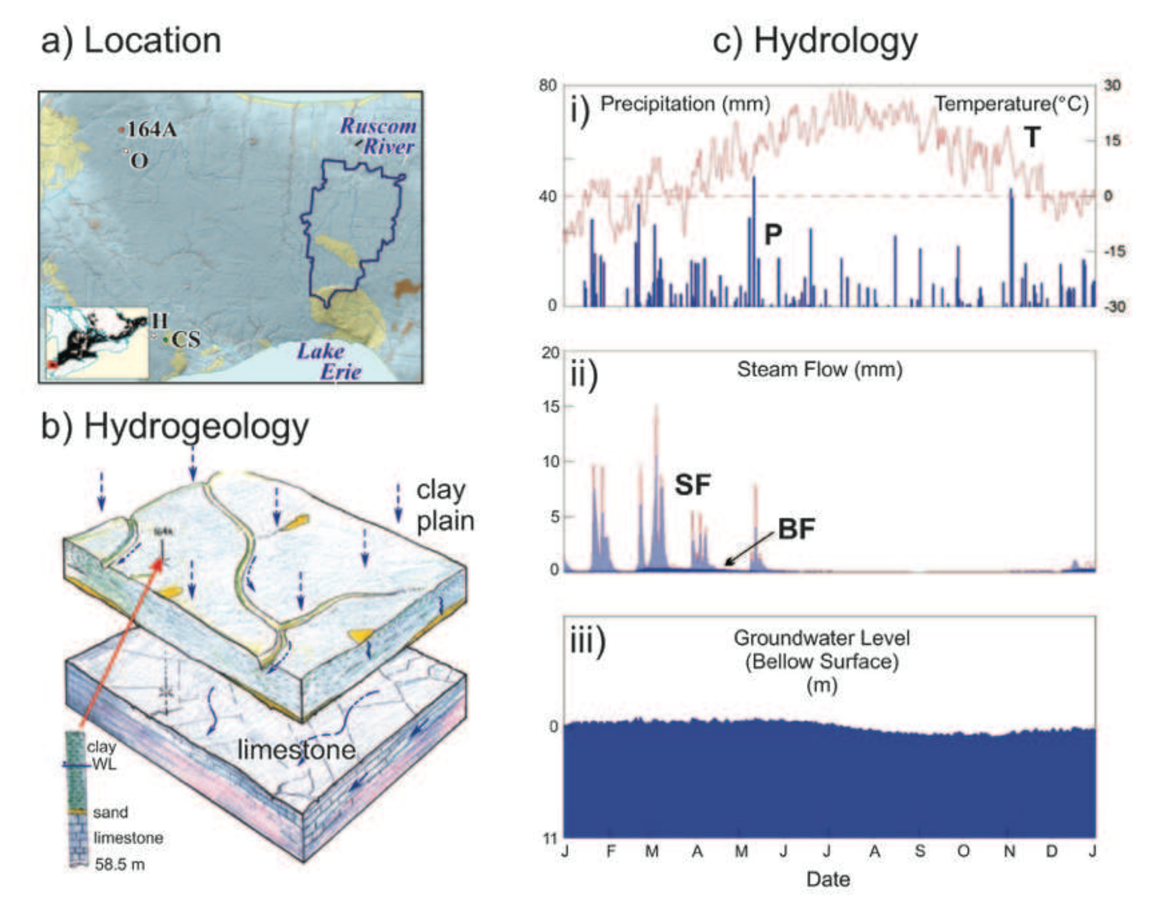


Figure 12.31 Essex clay plain hydrogeological setting.
a) Location and clay plain geology; dark areas on inset map show clay in southern Ontario; Harrow town is marked H. b) Conceptual sketch charts well bore sediment and bedrock with local surface/groundwater flow pattern. Arrows indicate relative ease of water movement from atmosphere to surface flow, and to groundwater flow. c) Hydrology for 1974 from climate station (CS), with graph scales set to aid comparison: i) precipitation (P) and temperature (T); ii) streamflow (SF), baseflow (BF) separated from streamflow; iii) well level varies very gradually <0.2 m over the year.

do not respond to precipitation and snowmelting events, and there is minimal yearly variation of levels. A small recession in water levels during July and August is followed by a gradual increase during November and December. Figure 12.31c). This may be due to seasonal groundwater withdrawals, such as irrigation, followed by redistribution of groundwater within the aquifer. Short-term (~1–2 day) variations in groundwater levels are closely related to changes in atmospheric pressure, and are indicative of confined conditions (e.g., thick clay cover) within the aquifer. Limited shallow groundwater flow and confined conditions at depth typify this aquifer and likely other low-permeability clay-plain settings in southern Ontario. In clay plain interface settings, groundwater in deep clay can be many thousands of years old, and solute transport may be largely by diffusion rather than by flowing groundwater; hence, clay is able to protect groundwater from surface contamination.

BOX 12-5 NAPANEE LIMESTONE PLAIN AQUIFER CASE STUDY

A 31.7 m deep well (478A) samples shallow unconfined fresh water in a limestone bedrock plain near Napanee (Figure 12.32). Streamflow in Wilton Creek rapidly responds to precipitation and snowmelt running off the limestone surface. Thin discontinuous till in the watershed does not modify the pronounced

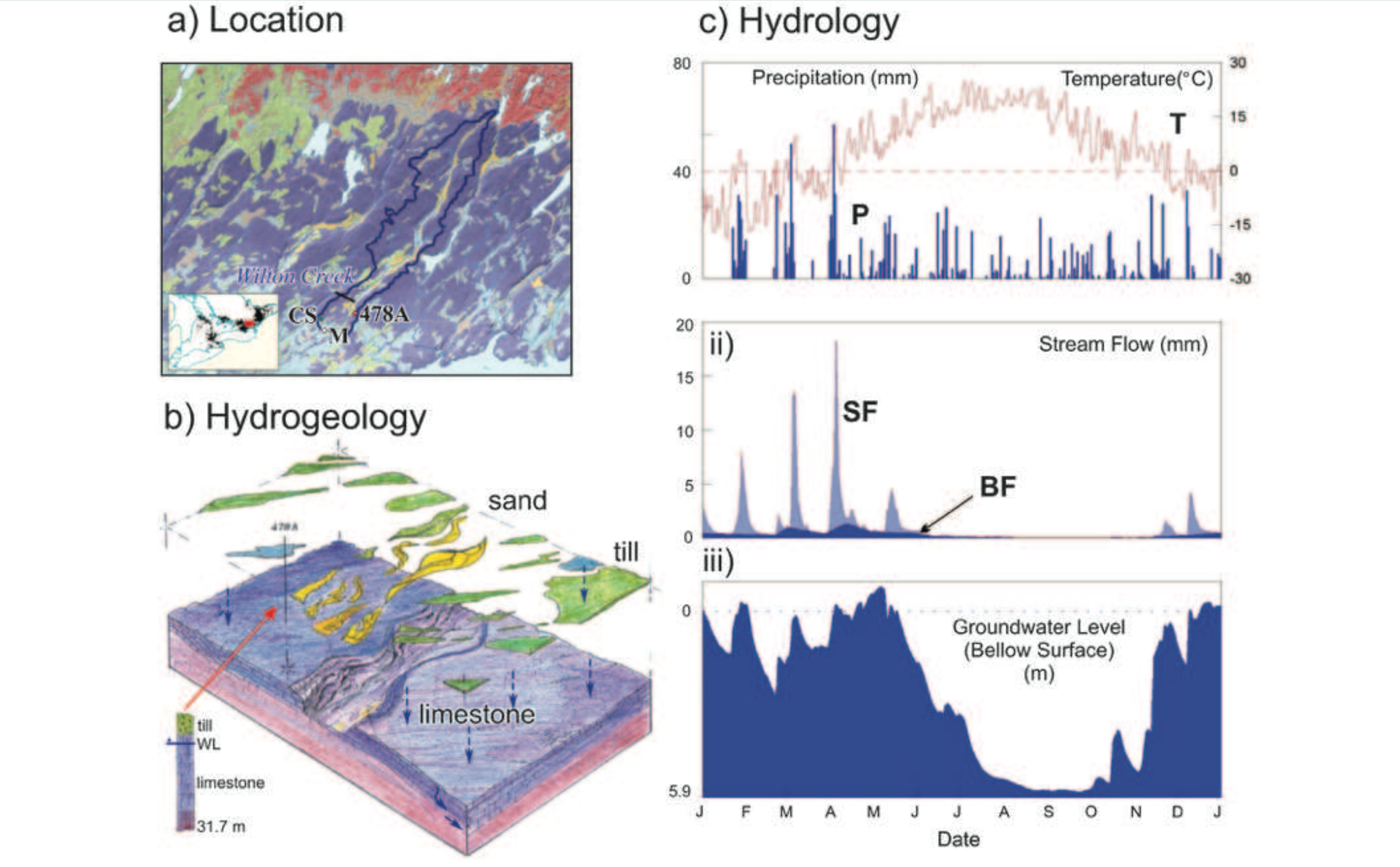


Figure 12.32 Napanee limestone plain hydrogeological setting.
a) Location with limestone terrain geology (purple); dark areas on inset map show exposed bedrock; town of Morven marked M. b) Conceptual sketch charts well bore sediment and rock with local surface/groundwater flow pattern. Arrows indicate relative ease of water movement from the atmosphere to surface flow, and to groundwater flow. c) Hydrology for common year 1974 from climate station (CS), with graph scales set to aid comparison: i) precipitation (P), temperature (T); ii) streamflow (SF), separated from baseflow (BF) separated from streamflow for Wilton Creek; iii) well water level: the large (~6 m) seasonal water level change may relate to karst storage and discharge trends.

high flow to Wilton Creek. Groundwater levels also respond rapidly to precipitation and snowmelt events (Figure 12.32c). A protracted period of low streamflow occurs during summer and early fall. Groundwater levels decline dramatically (~6 m) beginning in mid-May and continuing until mid-October. The relatively constant levels that occurred during this period may indicate that groundwater is slowly yet steadily discharging to surface water. The limestone terrain appears to have variable to low capacity to store groundwater; that is, high water levels may be connected to more storage (karst chambers) which readily discharge; whereas at low levels, stored water only occurs in fractures that provide very modest discharge to streams during low flow periods. Groundwater capacity and function in this terrain is thus influenced by karst enlargement of fractures and cavities. The resultant variations in the stream hydrograph, particularly the very low summer baseflow, may lead to a source of stress to in-stream water quality and the aquatic ecosystem. Note that bedrock groundwater levels are very different than those in clay and sand plains described earlier.

BOX 12-6 FLUORIDE IN GROUNDWATER OF SOUTHERN ONTARIO

Monitoring results from the Provincial Groundwater Monitoring Network and Drinking Water Surveillance Program show that fluoride is commonly found in Ontario groundwater, usually at concentrations below the Ontario Drinking Water Quality Standard (ODWQS) of 1.5 mg/L. However, the majority of exceedances of any of the ODWQS parameters have been for fluoride and these exceedances have primarily occurred in southern Ontario (MacRitchie et al., 2007).

Fluoride occurs naturally in groundwater and is important to bone and tooth development. Typically 0.8–1.5 mg/L natural fluoride in drinking water supports healthy tooth and bone growth. In Ontario, where water samples with higher fluoride levels, 1.5–2.4 mg/L, are found, local boards of health are required to raise public and professional awareness to control fluoride exposure. Concentrations at these levels in drinking water can cause health issues ranging from pitting and alteration of teeth to debilitating fluorosis or bone conditions. Currently, levels of > 2.4 mg/L must be reported to local medical officers to assess potential risks for human intake.

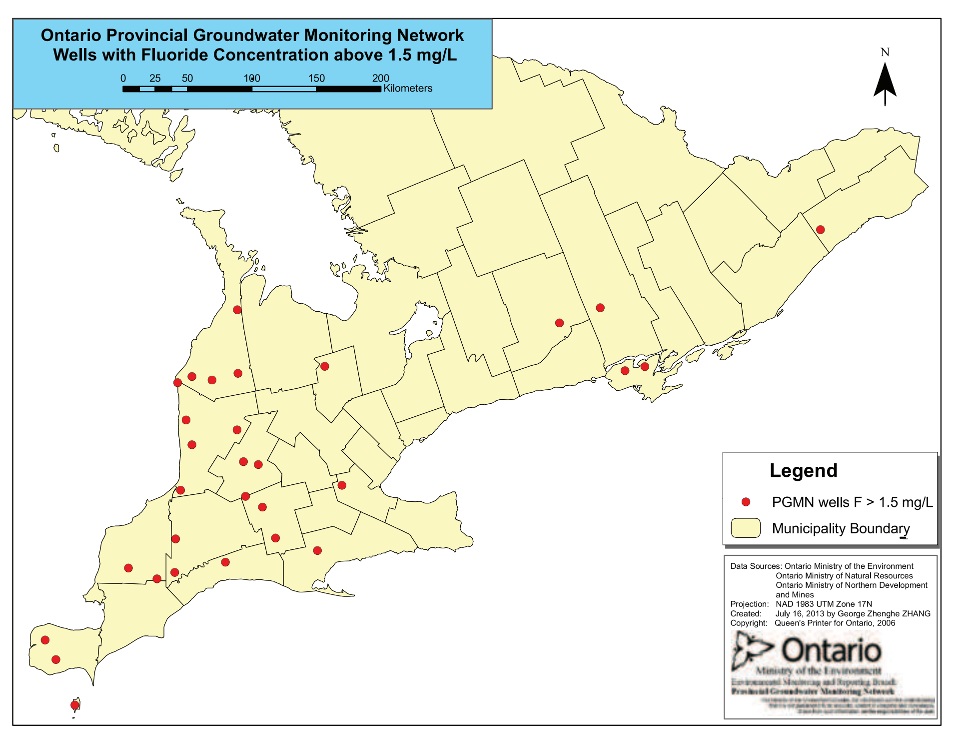


Figure 12.33 Location of PGMN wells with confirmed concentrations above the 1.5 mg/L standard.

Man-made sources of fluoride in groundwater appear to be related to manufacture of phosphate fertilizers, which currently does not occur in Ontario. Natural fluoride occurrence in groundwater results from geological, chemical and physical characteristics of aquifers such as conductive, porous and acidic soil, as well as rock and groundwater temperature and geochemistry. Natural sources of fluoride include dissolution of fluoride-bearing minerals such as fluorite, long residence time of groundwater in deep aquifers, fluoride-rich pore water in clay, and weathering of mica, a mineral that can rapidly leach fluoride.

Southern Ontario sources of fluoride appear to be fluorite, a mineral deposited when warm fluids migrated into fractures and reefs associated with carbonate rock. Clay minerals may also be a fluoride source.

BOX 12-7 THE ECOLOGICAL SIGNIFICANCE OF GROUNDWATER IN SOUTHERN ONTARIO

Surface aquatic habitats such as springs, streams, wetlands and many lakes depend on groundwater. The volume of groundwater discharge, or the elevation of the water table, can play an important role in maintaining surface water depth, or the "living space" used by aquatic organisms. Groundwater can sustain the moisture regime within wetland soils and along stream banks, where healthy vegetation contributes to stream-bank stability. It can sustain moist food production and spawning areas in streams. Groundwater is the source of baseflow in streams that sustain connections along the channel, and it allows fish to access refuge areas during low-flow periods. As an example, low-flow conditions in Grindstone Creek, near Hamilton (Figure 12.1), resulted in the loss of fish habitat and restricted migration to suitable aquatic conditions.

Also of importance to ecosystems are the timing, frequency and duration of groundwater conditions. For example, amphibians depend upon the timing and duration of ponding in wetlands during their breeding season.

Groundwater discharge plays an important role in moderating thermal regimes within streams, and this is particularly important for sustaining southern Ontario's cold-water fisheries (Figure 12.34). On a smaller scale, groundwater discharge can create cooler refuges which help a variety of

Figure 12.34 Brook trout spawn over a groundwater upwelling in the Credit River. Brook trout are dependent on the uniform temperature of groundwater discharge to keep water temperature cooler during the summer and warmer during the winter, and, to provide suitable habitat for their nests and eggs. (Photograph by Jack Imhof, National Biologist, Trout Unlimited Canada)

aquatic organisms survive extreme summer conditions and provide warmer refuges for overwintering. A change in the chemical composition of groundwater, which is different than that of surface water, can result in significant shifts in vegetation communities.

There is a strong link between surface water–groundwater ecology in southern Ontario. Several uncertainties are associated with prediction of the water table within abundant wetlands or with estimating groundwater flux within a brook-trout spawning habitat, so as to evaluate fairly whether impacts might be tolerable by the ecosystem. Quantifying groundwater–surface water links is a key area to target groundwater ecological research.

BOX 12-8 GRAND RIVER WATERSHED WATER BUDGET

A water budget can be defined as a means to assess and account for the movement of water through the hydrologic cycle. By quantifying each component of the cycle, including key processes, pathways and uses, one gains an understanding of watershed trends and stresses to groundwater and surface water.

A typical simple watershed water budget can be summarized as follows (using measurements/ estimates in mm/year converted to volume estimates, based on local climatic norms over 20–30 years). On average, precipitation (number 1 in the following table) minus losses due to evaporation-transpiration (2) leaves a water surplus, or water excess, of ~ 442 mm/year. This surplus/excess is accounted for in two ways: by surface runoff (3), and by subsurface infiltration or recharge (4).

Approximately 58% of the water flowing through the Grand River watershed does so as surface water runoff (3). The remaining 42%, recharge, flows through the groundwater system (5, 6 and 7) at a rate of 180 mm/year. The majority of groundwater flow (~82%) eventually re-surfaces within the watershed as flow to surface water features (5, e.g. base flow discharge to streams or ponds), while a small portion (6), discharges to areas outside of the watershed. Groundwater pumping (7) accounts for ~10% of recharge or flow through the groundwater system.

GRAND RIVER WATERSHED WATER BUDGET COMPONENT	VALUE M^3/S	MM/YEAR
1. Precipitation (P)	200	933
2. Evaporationtranspiration (ET)	105	491
(Surplus, P–ET)	(95)	(442)
3. Runoff (~58% of surplus)	56	262
4. Recharge (~42% of surplus)	39	180
5. Net groundwater discharge to surface water features (~82% of recharge)	33	148
6. Net flow of groundwater from watershed (8%)	2	14
7. Groundwater pumping (10%)	4	18

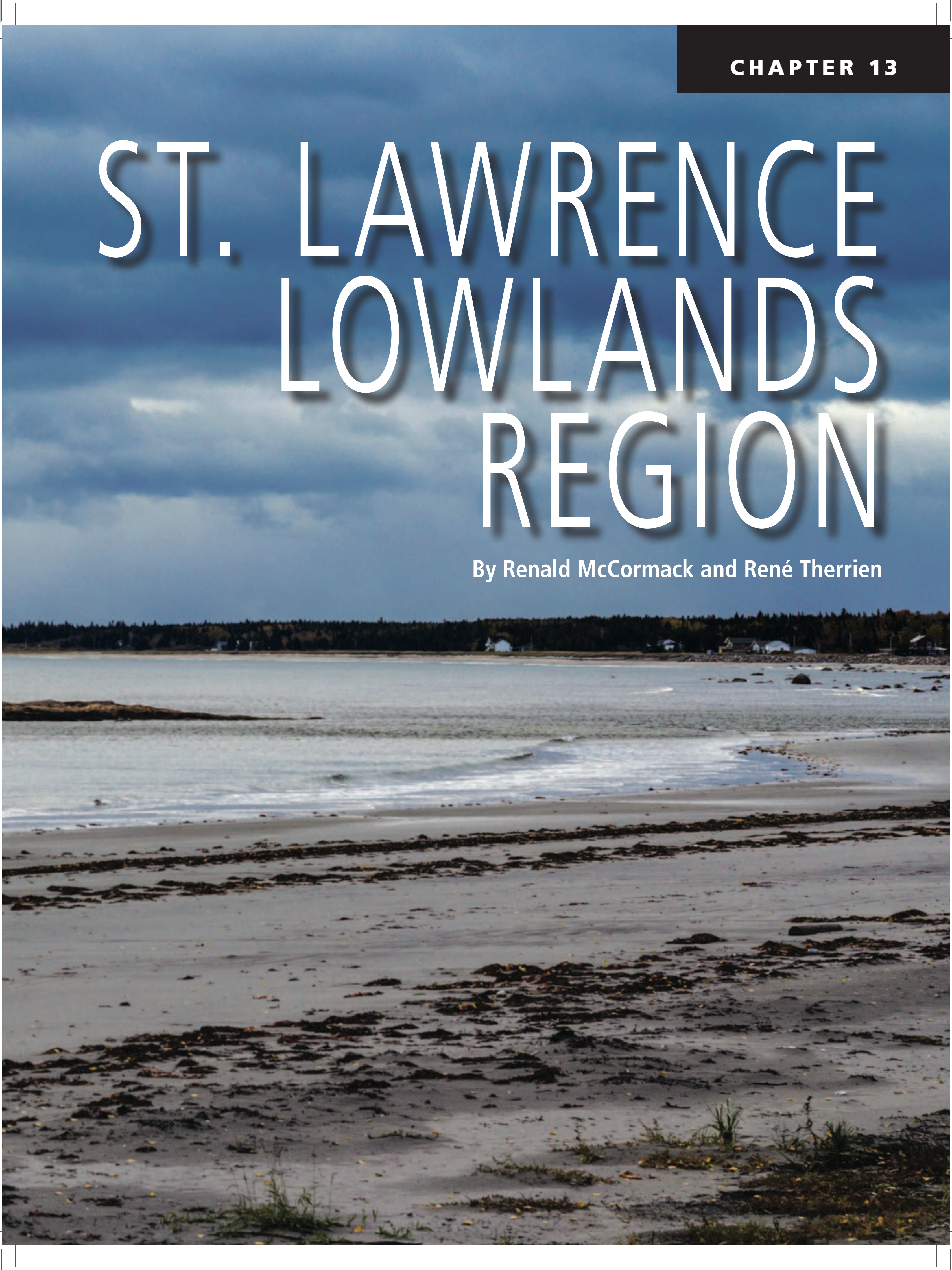
Groundwater storage

Information about groundwater storage is needed to complement a watershed-wide water budget. Without accounting for groundwater storage, we could interpret the above water budget to mean that if there is a low rainfall year, there will be little flow left for baseflow or for water supply pumping. Groundwater storage in the Grand River watershed is very large (>100 billion m^3) in proportion to the renewable water resources (3.3 billion m^3) or annual groundwater pumping (~0.3 billion m^3). This estimate of potable water storage found in the top ~100 metres below ground indicates that with current groundwater recharge rates (~2 billion m^3 / year), it would take >150 years to replace the storage of potable groundwater in the Grand River watershed.

This example of a water budget is a simple approach to estimate the water resources of a watershed. One can refine these estimates with detailed studies of surface soils and subsurface sediment and rocks. This detailed approach is often used at landfill sites to determine any potential landfill leachate effects on groundwater, and to develop protection measures for municipal water-well fields.

ST. LAWRENCE LOWLANDS REGION

By Renald McCormack and René Therrien



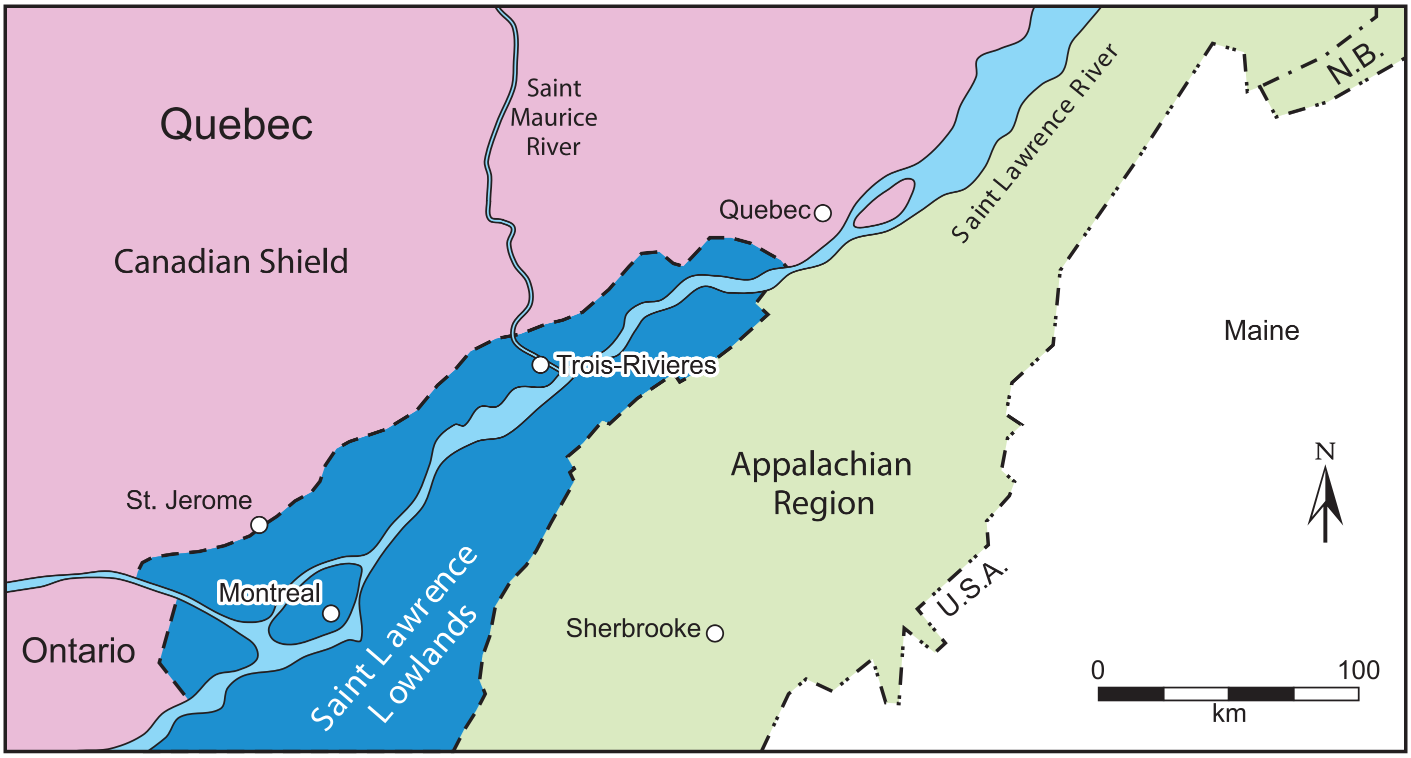


Figure 13.1 Location of the St. Lawrence Lowlands Region.

13.1 INTRODUCTION

The St. Lawrence Lowlands (StLL) Region is the continuation of the Southern Ontario Hydrogeological Region whose framework is described in the previous chapter. Within the province of Quebec (Figure 13.1), this region extends in a northeasterly direction on both sides of the St. Lawrence River from the Beauharnois axis, an expression of the Precambrian Shield, to Quebec City. Outside Quebec, the St. Lawrence Lowlands Region includes the Ottawa Valley as well as a portion of the Lake Champlain Valley.

The St. Lawrence Lowlands Region covers about 29,000 km^2 in Quebec. It is widest (about 150 km) in the southwest, and becomes narrower in the northeast before it touches the Canadian Shield near Quebec City. It is bounded on the northwest by the Laurentian Highlands, composed of Precambrian Shield rock, and to the southeast by the Appalachian Mountains. (Some remnants of the StLL Region appear sporadically to the north of the Gulf of St. Lawrence, especially in the Mingan Islands area, ending at Anticosti Island. However, there is a lack of groundwater data and usage in these latter regions and their hydrogeological characteristics are not presented here.)

The StLL Region includes the central and eastern St. Lawrence Lowland areas defined by Bostock (1970). The Region's topography is relatively flat: ground elevation rarely rises over 150 metres above sea level (m.a.s.l.), except for the Monteregian Hills in the Montreal region, which are 400 metres m.a.s.l. The topography becomes flat to rolling with abrupt changes, along the northwestern and southeastern margins of the area. Figure 13.2 shows surface elevations in Southeastern Canada. The StLL Region is clearly visible as the area of lowest altitude located along the St. Lawrence River.

Climate in this region is humid continental. The mean annual temperature ranges from 2.7°C to 6.6°C, with the northeastern part of the region being significantly cooler because of the Labrador

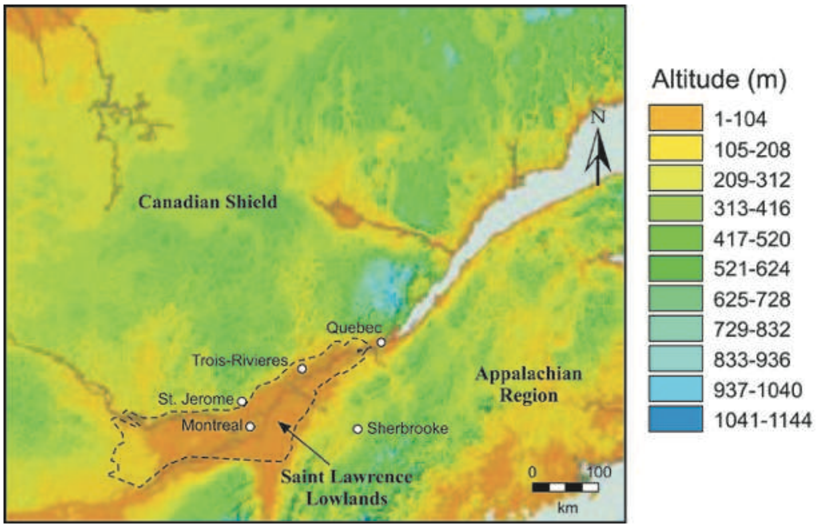


Figure 13.2 Elevations in m.a.s.l. (adapted from Gerardin and McKenney, 2001).

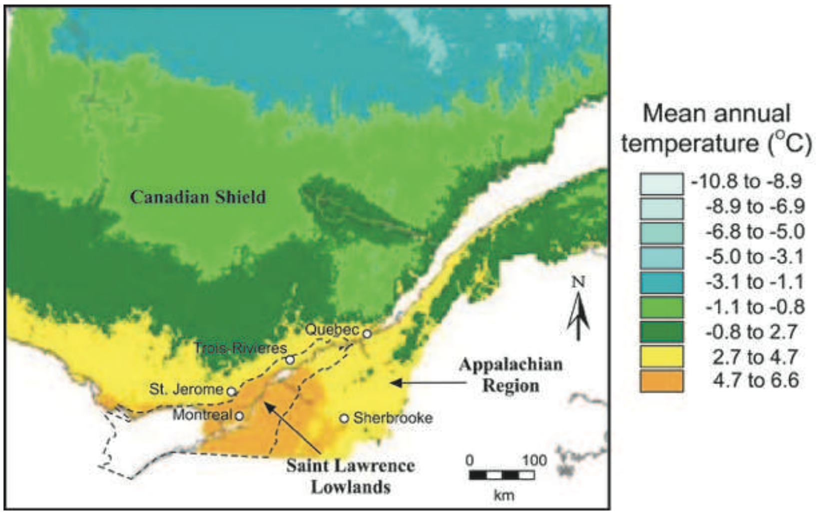


Figure 13.3 Mean annual temperature (adapted from Gerardin and McKenney, 2001).

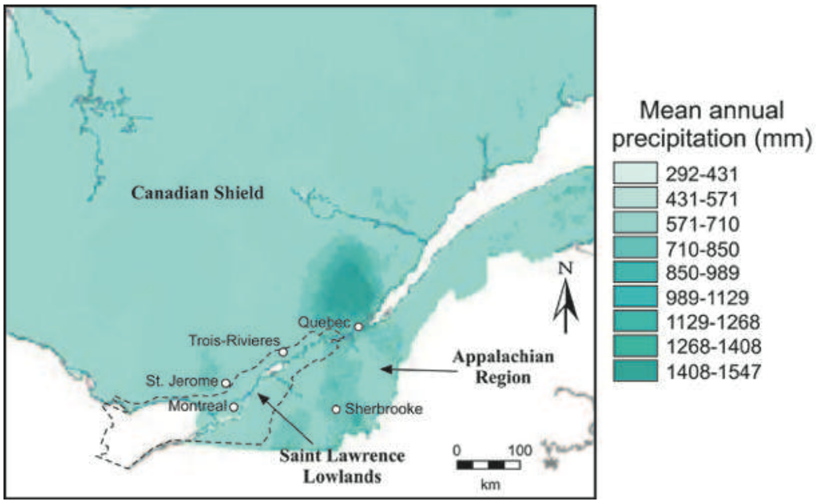


Figure 13.4 Mean annual precipitation (adapted from Gerardin and McKenney, 2001).

Current. The mean summer temperature ranges between 10°C and 16°C; the mean winter temperature ranges between –5.5°C and –7°C (Figure 13.3). Mean annual precipitation is between 800 mm and 1,100 mm, 30% of which falls as snow (Figure 13.4). The mean annual potential evapotranspiration ranges from 406 mm to 610 mm (Figure 13.5). On average, there are 2,000 hours of sunshine per year. Spring arrives in the west in April, and snow may linger in the east until May.

The dominant surface water feature in the StLL Region is the St. Lawrence River, which receives water from all tributaries along its course to Quebec City. Wetlands cover about 9% of the StLL Region.

This area has a population of some 4.6 million, representing 60% of the province's total population. In fact, the StLL Region has the highest population density in Quebec. The majority of the population lives in only a few urban centres (Montreal, Laval, Longueuil, Quebec City, and Trois-Rivières) where surface water is the source of drinking water. Away from these urban centres, groundwater is widely used as the drinking water supply. Table 13.1 indicates the source distribution of drinking water in the St. Lawrence Lowlands Region while Figure 13.6 and Figure 13.7 illustrate percentage use of all types of water for municipalities and residents.

Several industries are located in the Ottawa-Quebec City corridor. Agriculture is also predominant in the StLL Region, especially in an area called The Gardens of Quebec, located in the southwest portion of the province, where groundwater is used on a large scale for crop irrigation and vegetable washing.

13.2 GEOLOGY

13.2.1 Bedrock geology

The Central St. Lawrence Lowlands Region area east of the Beauharnois axis contains rock of Paleozoic age of which only the Cambrian, Ordovician, and Devonian systems are represented. They form strata that are intruded locally by Cretaceous rocks, such as the Monteregian Hills, oriented E-W (Bourque, 2006), which stand out in the otherwise flat Montreal plain area landscape.

Paleozoic sedimentary rocks have been deposited along the stable pre-Appalachian continental margin of North America. This sedimentary succession lies unconformably on the Precambrian terrain (Globensky, 1987). It records development of a passive continental margin and the transition

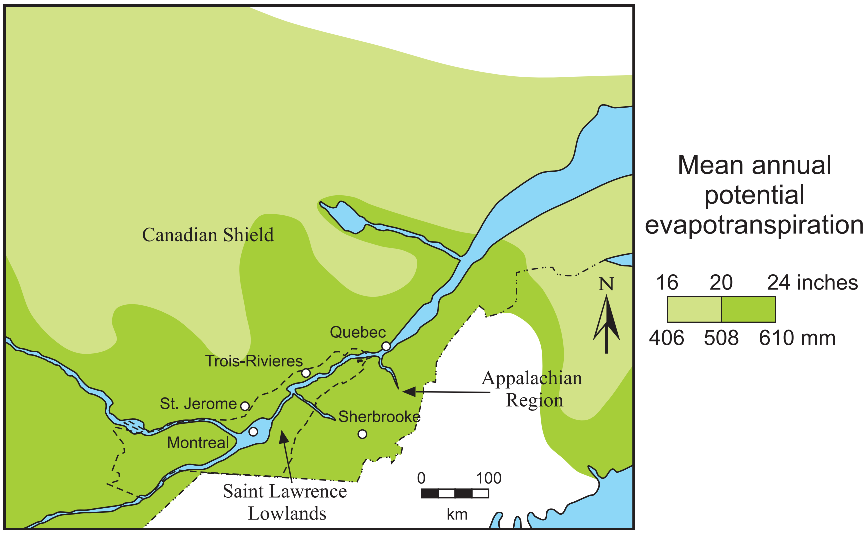


Figure 13.5 Mean annual potential evapotranspiration (based on the National Atlas of Canada, 1974).

TABLE 13.1 SOURCE OF DRINKING WATER IN THE ST. LAWRENCE LOWLANDS HYDROGEOLOGICAL REGION

SOURCE OF DRINKING WATER	NUMBER OF MUNICIPALITIES	NUMBER OF RESIDENTS
Groundwater	151	300,981
St. Lawrence River	51	2,554,981
Other rivers	112	1,524,831
Lakes	9	43,072
Mixed sources	15	181,819
Total	**338**	**4,605,684**

Source: www.mddep.gouv.qc.ca/eau/potable/distribution/index.asp.

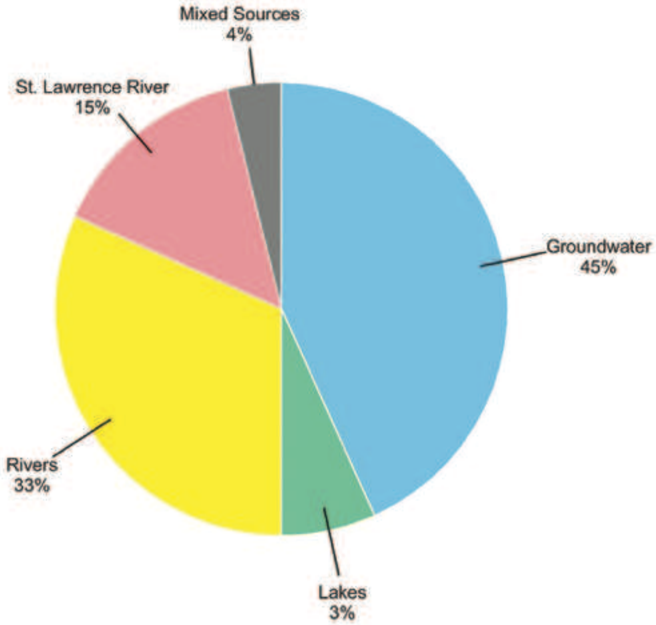


Figure 13.6 Water supply sources of municipalities located in the St. Lawrence Lowlands.

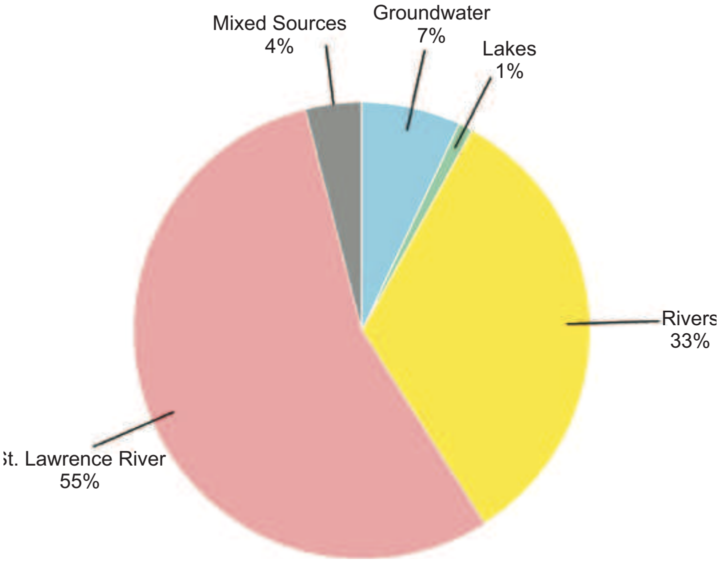


Figure 13.7 Water supply sources of residents of the St. Lawrence Lowlands.

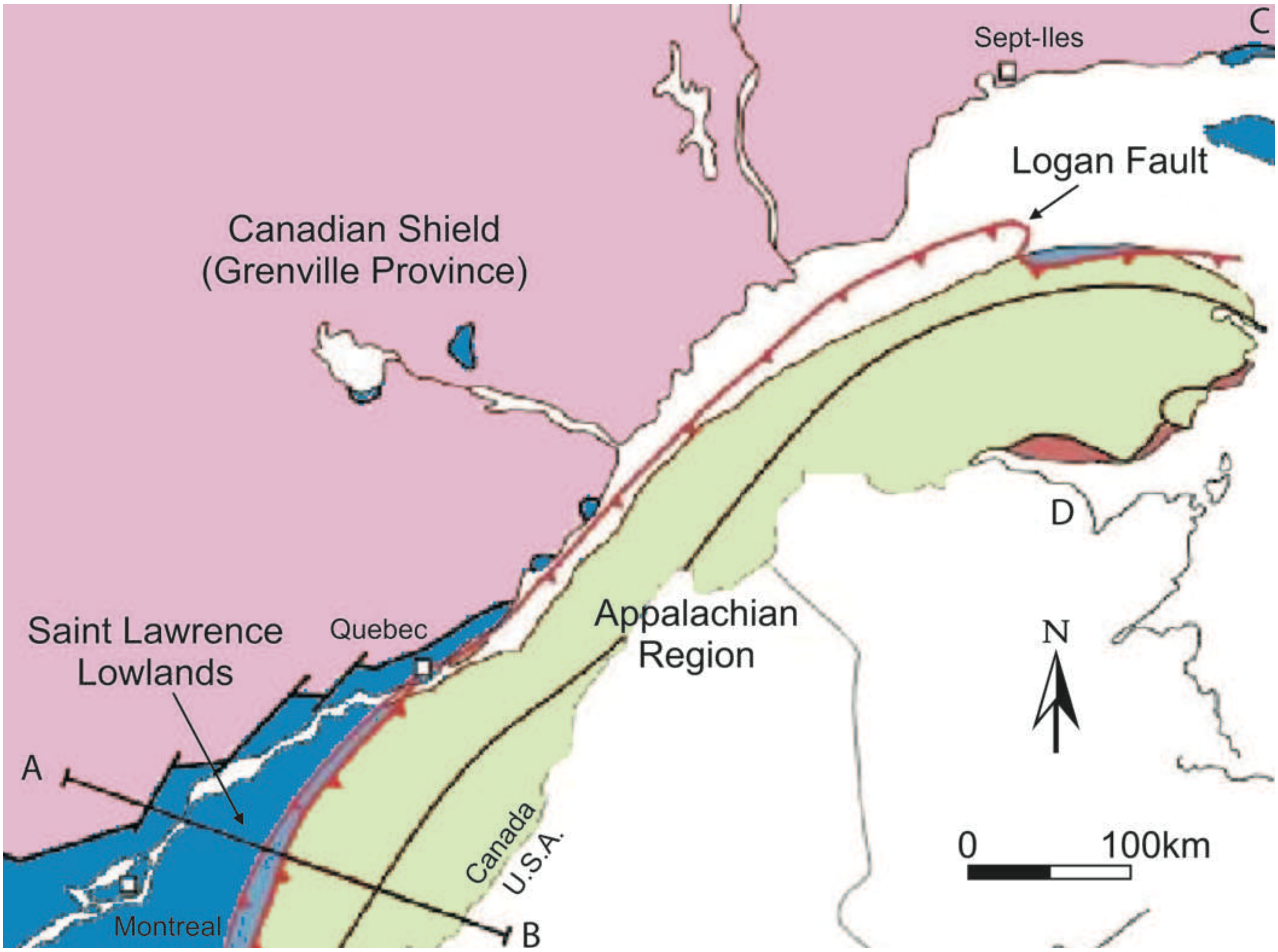


Figure 13.8 Geological setting of the St. Lawrence Lowlands Region.

from continental clastic sediments to continental shelf marine carbonates, then to deeper-water, fine-grained sediments deposited within a foreland basin. The western margin of the Lowlands is characterized by extensive normal faulting, while the eastern margin merges into the external zone of the Appalachians where thrust faulting dominates (Scott, 1967).

The St. Lawrence Lowlands Region can be divided into two sectors between the Canadian Precambrian Shield and the Appalachians: the St. Lawrence Lowlands in the Montreal-Quebec City area, and the Mingan-Anticosti sector to the east (Figure 13.8 and Figure 13.9). The first sector contains mainly rocks of Cambrian and Ordovician ages, even though there is evidence of Devonian rocks in the Montreal area. The Mingan rocks are of Ordovician age and the Anticosti rocks are of Silurian and Devonian age. This distribution suggests that Cambrian to Devonian rocks once covered a large area of North America between the Canadian Shield and the Appalachians.

13.2.2 Stratigraphic sequence

The Cambro-Ordovician rocks of the StLL Region have a total thickness of between 1,500 and 3,000 metres (Globensky, 1987). They are generally flatlying and form the Chambly-Fortierville Syncline, a regional-scale feature oriented SW-NE and parallel to the Logan Line. The strata are slightly

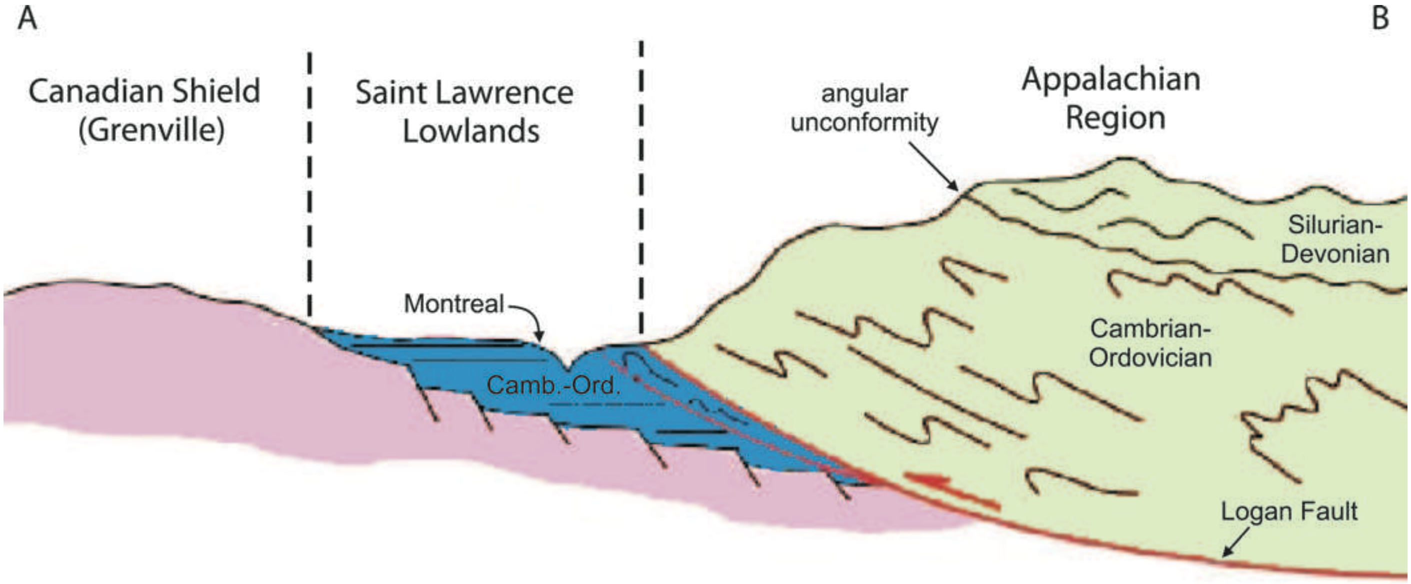
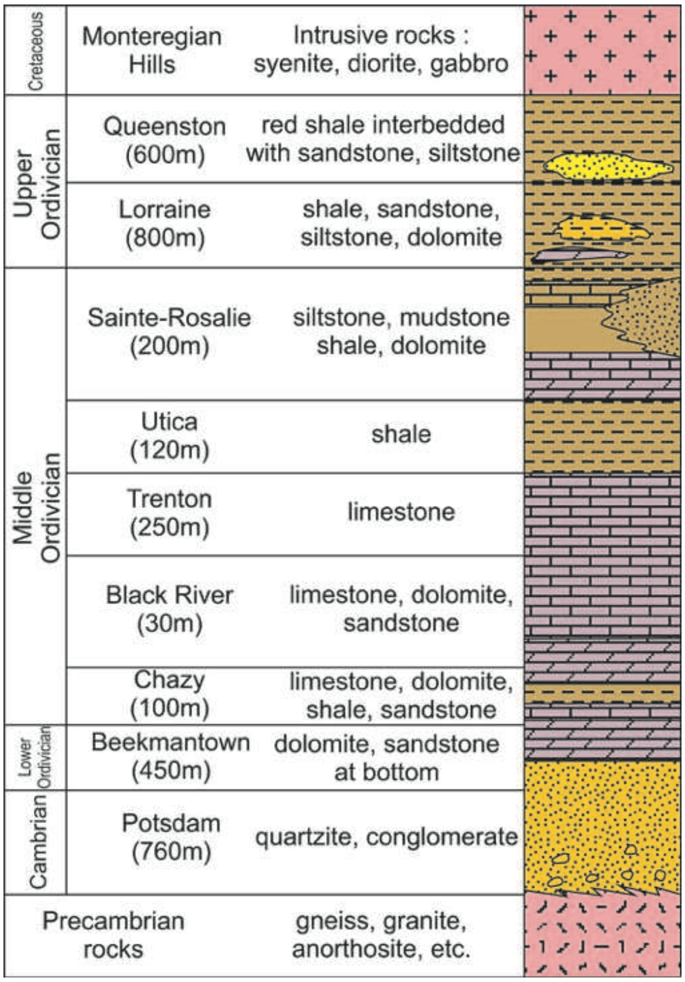


Figure 13.9 Vertical cross section A-B, whose location is described in Figure 13.8, illustrating the succession of rocks from the northwest Canadian Shield to the southeast part of the Appalachian Region.

folded due to the formation of the Appalachian Mountains during the Ordovician. Local karst development can be found in the carbonate rocks, notably along major rivers or escarpments, as well as rare occurrences of pre-glacial regolith.

There is currently minor natural gas production from the Ordovician carbonates of southern Quebec. Exploration for shale gas, focusing on the Utica shale in the StLL Region, has recently begun in Quebec. This exploration is aimed at producing natural gas by hydraulically fracturing the shale. Because of public concerns about the impact of shale gas exploration and exploitation, including the impact of hydraulic fracturing on groundwater resources, the provincial government created, in 2010, a committee within the Bureau d'audiences publiques sur l'environnement (BAPE) to conduct public hearings and to propose a framework for shale gas development within the province. The committee released a report recommending that a strategic environmental assessment be conducted prior to further exploration (BAPE, 2011). Several concerns were raised by the committee with respect to groundwater, including the fact that



Cretaceous	Monteregian Hills	Intrusive rocks : syenite, diorite, gabbro
Upper Ordovician	Queenston (600m)	red shale interbedded with sandstone, siltstone
	Lorraine (800m)	shale, sandstone, siltstone, dolomite
Middle Ordovician	Sainte-Rosalie (200m)	siltstone, mudstone shale, dolomite
	Utica (120m)	shale
	Trenton (250m)	limestone
	Black River (30m)	limestone, dolomite, sandstone
	Chazy (100m)	limestone, dolomite, shale, sandstone
Lower Ordovician	Beekmantown (450m)	dolomite, sandstone at bottom
Cambrian	Potsdam (760m)	quartzite, conglomerate
Precambrian rocks		gneiss, granite, anorthosite, etc.

Figure 13.10 Typical bedrock stratigraphic column.

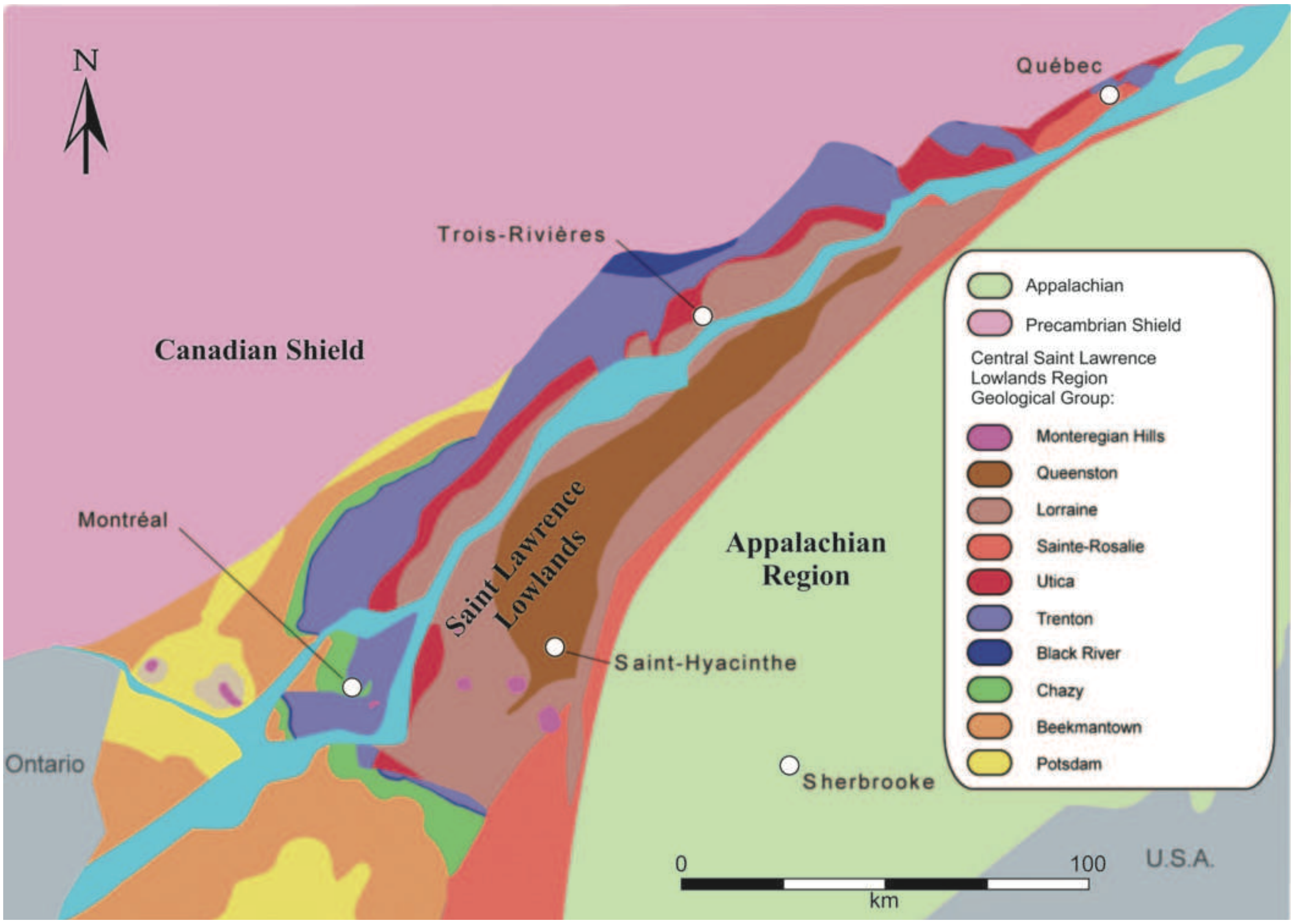


Figure 13.11 Main bedrock units of the St. Lawrence Lowlands Region.

there was insufficient knowledge on the regional hydrogeology of the Region to adequately assess the impact of shale gas exploration and exploitation on groundwater resources (BAPE, 2011).

The typical stratigraphy of the StLL Region is depicted in Figure 13.10. The Precambrian rocks are first overlain by thin- to medium-bedded, white quartz sandstone and conglomerate of the Upper Cambrian Potsdam Group that occur in thin to medium beds and transected by a well-developed joint system. Except for a few small elongated patches north of Montreal, this Group is located mainly in the southernmost part of the StLL Region close to the U.S. and Ontario border. The thickness of the Upper Cambrian Potsdam Group reaches 760 metres.

An interval of marine regression followed deposition of the Potsdam sediments as indicated by the presence of reworked sands in the basal beds of the overlying Lower Ordovician Beekmantown Group. Formations within the Beekmantown Group include minor sandstone and dolomite in the lower part of the group and grey dolomite with thin shale partings in the upper part. Bedding characteristics of these rocks vary from thin to thick and a joint system has been moderately developed. The thickness of this Group reaches 458 metres. Unlike the Potsdam Group, the Beekmantown Group is also located in the southwesternmost part of the StLL Region (Figure 13.11).

Further up in the stratigraphic sequence, Middle Ordovician strata of the Chazy Group are separated from Beekmantown strata by a stratigraphic break representing an erosion interval. Rocks of the Chazy Group (about 100 metres thick) are mainly limestone with dolomite, shale, and sandstone layers. They are located in the southernmost area of the StLL Region (Figure 13.11).

A minor unconformity separates rocks of the Chazy Group from the overlying limestone of the Black River and Trenton Groups. These groups range in total thickness from 30 metres (Black River) to 250 metres (Trenton). The carbonate sequence in the upper portion of the Trenton Group, however, gives place to fine-grained sediment represented by the Utica shale formation, which can reach a thickness of 120 metres.

The Utica Group is overlain by the Sainte-Rosalie Group, which is composed largely of siltstones, mudstones, shale and dolomitic beds whose thicknesses reach 200 metres at the Montmorency Falls east of Quebec City. The Sainte-Rosalie Group is, in turn, overlain by the Lorraine Group, composed mainly of shale, sandstone, siltstone and limestone; the Lorraine Group is also the thickest (> 800 metres) and most widespread rock group within the St. Lawrence Lowlands Region. The Queenston Group overlies the Lorraine Group and constitutes the youngest rocks of the StLL Region. Rocks from the Queenston Group are red shales interbedded with sandstone and siltstone: their thickness reaches 600 metres.

The oldest rock Groups (Potsdam, Beekmantown, Chazy) were deposited in shallow seas and subjected to chemical sedimentation. Moving northeast from this area, the younger rock sequences (Black River, Trenton, Sainte-Rosalie, Lorraine and Queenston) are characterized by fine sediment deposited in a deep-sea environment; these groups show rather regular elongated and smooth geological contacts until the end of that hydrogeological region northeast of Quebec City. Another distinction between older and younger rocks, which will be discussed below, is that the oldest rocks in the southwestern part of the StLL are also the most permeable and productive from a hydrogeological perspective.

Figure 13.12 diagrams the distribution of geological units along a cross section at the east end of Lake Saint-Pierre, with an approximately NW-SE orientation. Two main fault systems, normal faults and thrust faults, are present in the St. Lawrence Lowlands Region (Globensky, 1987):

- Normal faults, found in the western part of the region, were produced by the collapse of Cambro-Ordovician rock units during the presence of the Iapetus Ocean (end of Precambrian to Ordovician). These faults played a very important role in the sedimentary history of the region.
- Thrust faults, found in the eastern part of the region, were produced by the Taconic orogeny which gave birth to the Appalachians during the Ordovician period. The impact of this orogeny on the sedimentary basin decreased from SE to NW, and compressed the rock units into the SW-NE Chambly-Fortierville Syncline, mentioned previously, that extends across Quebec's entire StLL Region.

13.2.3 Geology of surficial deposits

Unconsolidated Quaternary sediments, whose spatial distribution is depicted in Figure 13.13, cover the StLL sedimentary rocks. The origins of these sediments are:

1. Glaciation during the Wisconsin stage
2. Marine invasion during the recessional phases of glaciation

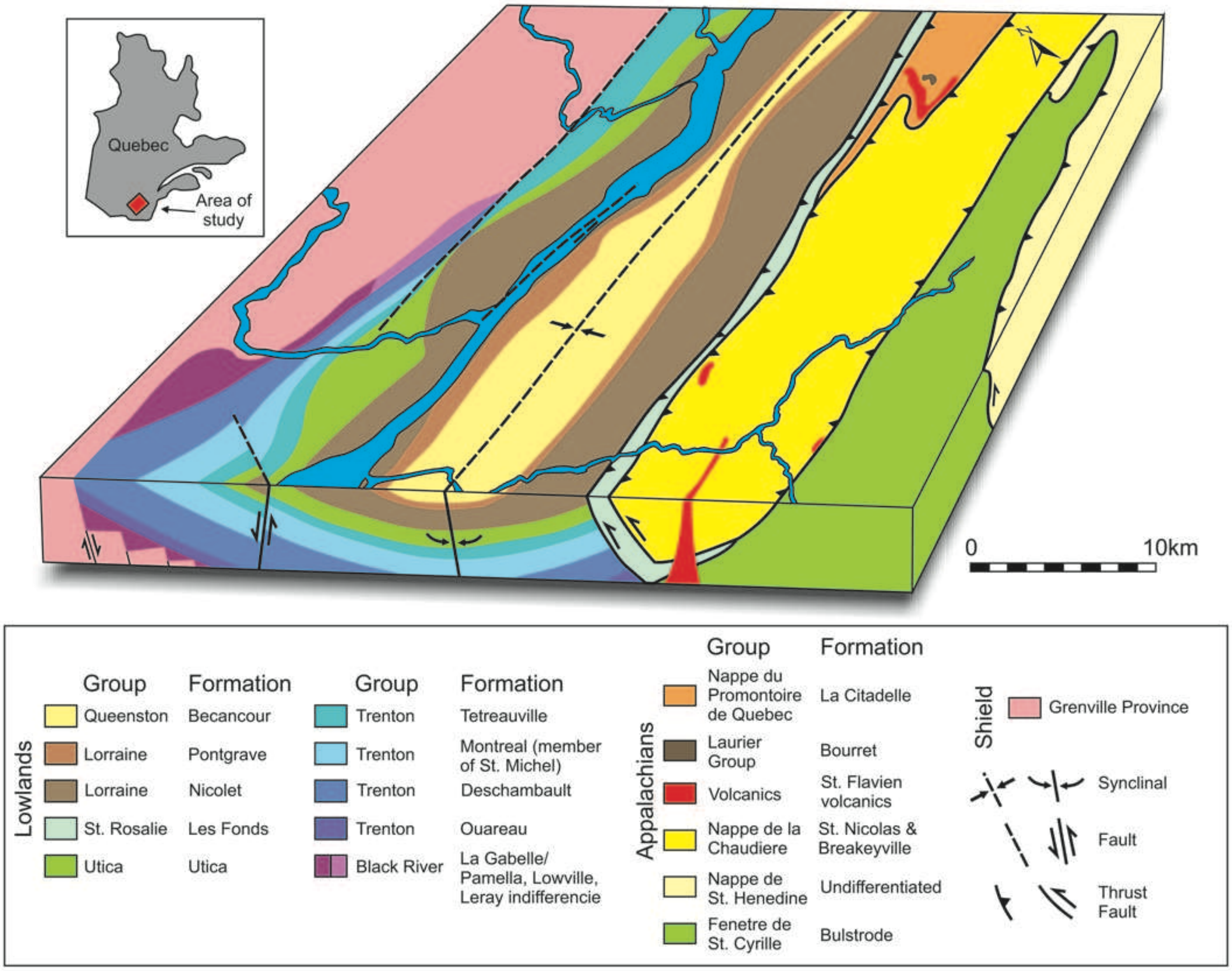


Figure 13.12 Schematic block diagram showing bedrock geology and structural features across the St. Lawrence Lowlands Region (adapted from GÉO 1022, 2000).

3. Alluvial deposition during withdrawal of the sea from the area (Brown, 1967)

Tills deposited over the bedrock during the early stages of the Wisconsin glaciation are generally the oldest glacial deposits found in the area. During the late Wisconsin, recession of the glacier from the western side of the Appalachian highland led to marine water invasion from the east into the St. Lawrence, Ottawa and Champlain Valleys. This marine invasion lead to the formation of the Champlain Sea, whose maximum extent (10,000 years ago) is illustrated in Figure 13.14. Marine silts, clays and minor amounts of sands deposited in the Champlain Sea form the thickest and most extensive sequence of surficial deposits throughout the StLL Region.

Differential uplift of the St. Lawrence Valley due to the northward recession of the glacier subsequently caused the Champlain Sea to drain from the lowland area. The sea was thereby gradually replaced by estuarine, lacustrine and fluvial ancestors of the present-day freshwater drainage system. Erosion of preexisting sediments and deposition of extensive terrace sand deposits followed the transition from the Champlain Sea to the present-day fluvial system. The youngest sediments in the region

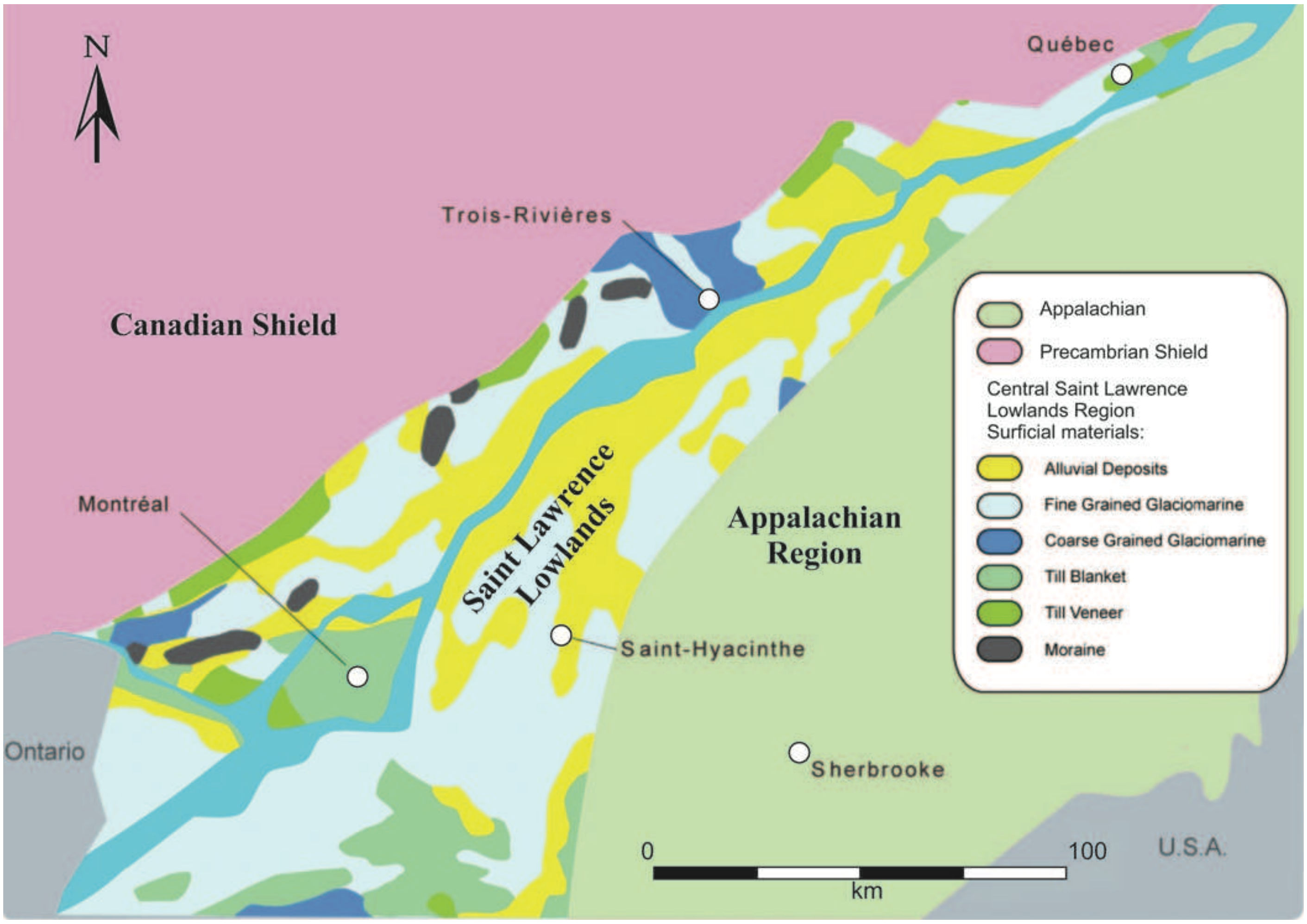


Figure 13.13 Distribution of surficial deposits (based on the Atlas of Canada, Surficial Deposits Map).

are deposits of glacial outwash composed of sand and gravel, and are of more local occurrence than the terrace deposits (Ochietti, 1989). The terrace and alluvial deposits, as well as the glacial outwash deposits, are major aquifers used mostly for municipal water supply, especially on the north shore of the St. Lawrence River.

The thickness of the surficial deposits in the StLL ranges from a few meters to 30 m, and can reach thicknesses of 80 m in buried bedrock valleys (Prévôt, 1972). Surficial sediments can be divided into three age classes: pre–late Wisconsinan organic rich sediments, Late Wisconsinan sediments, and recent, predominantly alluvial and marine sediments. The most significant sediments from a hydrogeological perspective are the Late Wisconsinan glacial, glaciofluvial and glaciomarine.

Prévôt (1972) provides an excellent description of the chronological deposition and groundwater potential of unconsolidated sediments in the StLL Region. He presented the following succession, from the oldest Quaternary deposits to the most recent, (see also Figure 13.15):

- **Glacial deposits**: Reddishbrown deposits (washed and sorted silt, sand, gravel and boulders) reworked by the Champlain Sea. Groundwater potential is largely dependent on the sorting of these sediments, and can reach 450 L/min locally. Otherwise, these deposits are heterogeneous, (such as tills) and do not represent good aquifers. On the other hand, groundwater in these deposits often has high salinity

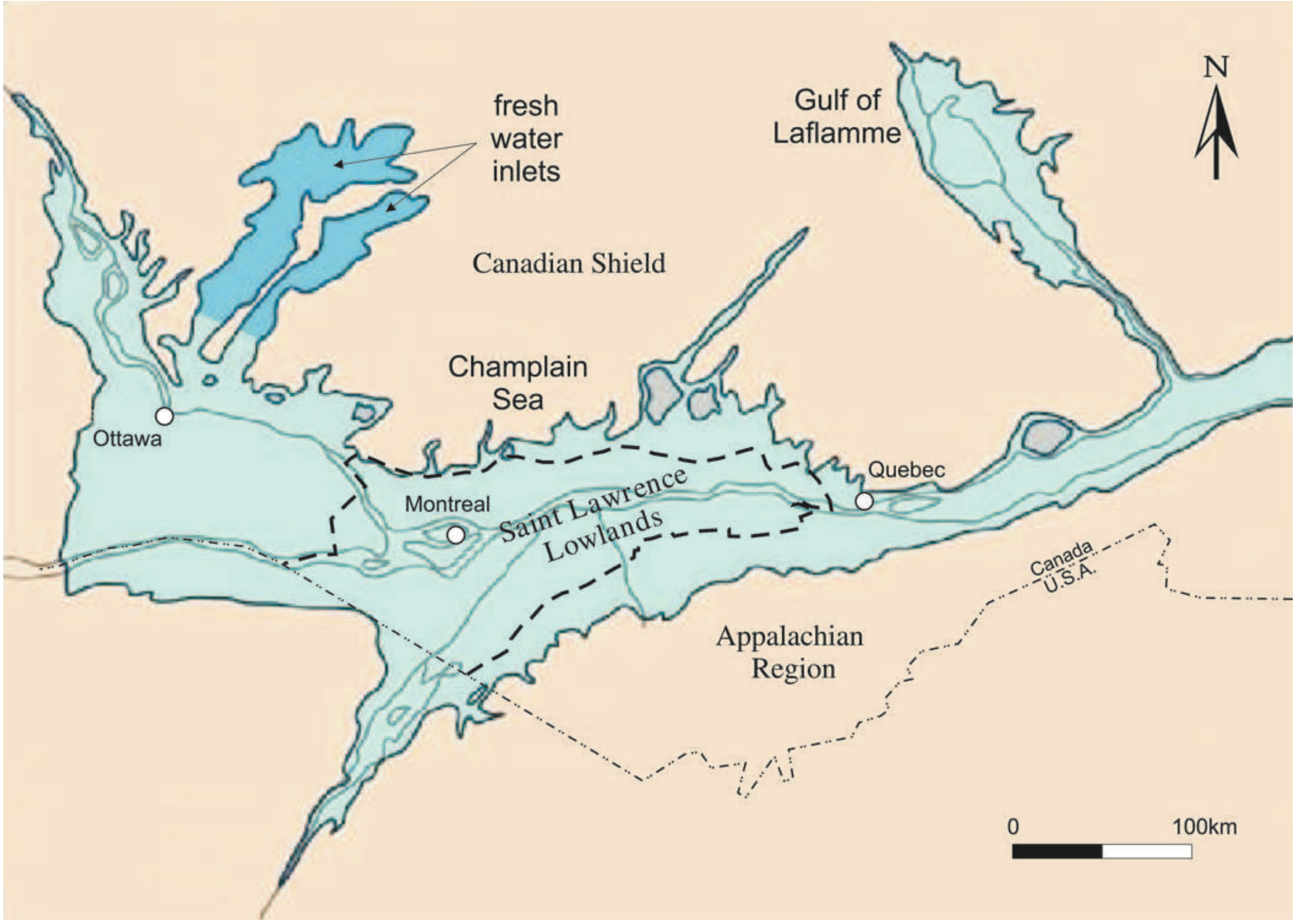


Figure 13.14 Maximum extent of the Champlain Sea (Bourque, 2006).

because it is overlain by marine clays of the Champlain Sea, whose thickness can reach 45 metres in deep bedrock depressions.

- **Marine clays:** Widespread fine-grained deposits (silty clay) over till or bedrock. Because of their blue-grey colour, these deposits are known locally as "blue-clays". Their thickness is variable, but usually less than 45 m.
- **Marine sands:** Beach sands 5 to 6 metres thick, generally well-sorted and deposited above the 60 m.a.s.l. elevation. They are good aquifers but, because of their thinness, groundwater yields rarely exceed 125 L/min.
- **Dune sands:** Well-sorted medium to very fine sands. Their groundwater potential is very low, and they are drained by springs. These sands are used locally by farmers and groundwater yields do not exceed 50 L/min.
- **High-terrace sands:** Fine to medium-grain sand, generally at elevations between 30 to 85 m.a.s.l., they are considered very good aquifers, because of their large spatial extent, with yields reaching 225 L/min in some locations.
- **Low-terrace sands:** Alluvial medium-grained sands lying on slopes at elevations less than 23 m.a.s.l.: thickness is usually less than 3 metres. These are considered good aquifers and are generally tapped by large-diameter shallow wells. Yields can reach 90 L/min in such sediments, but can increase when horizontal drains are used for pumping.
- **Organic deposits:** Brown and fibrous peat with

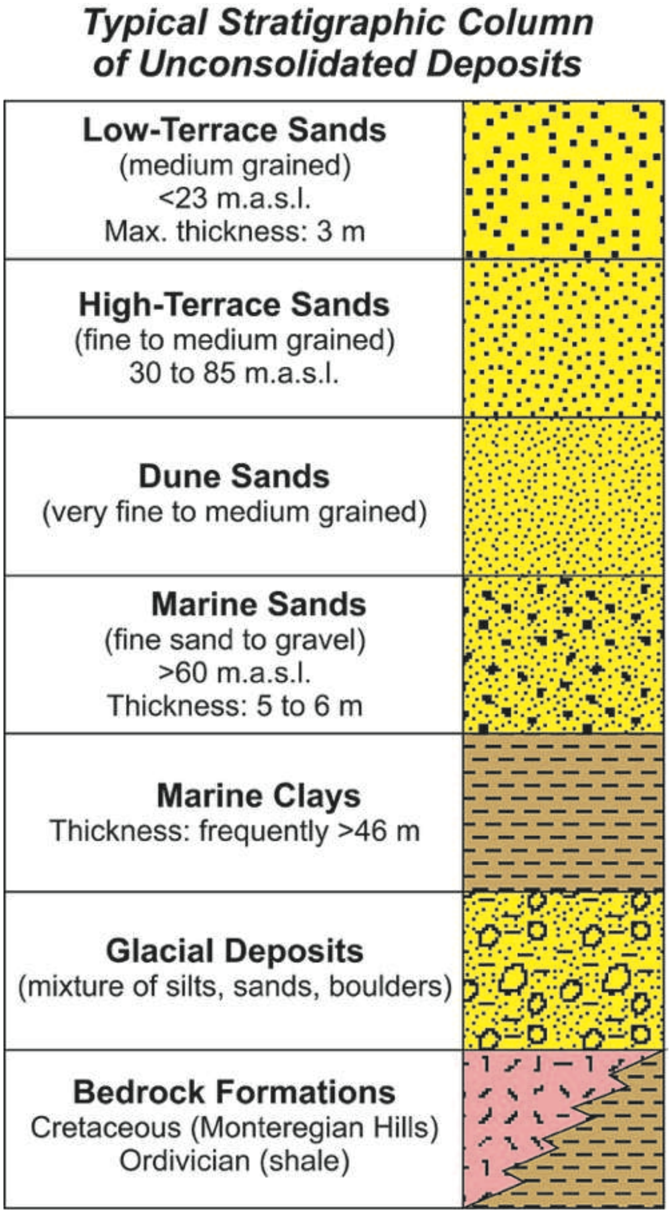


Figure 13.15 Typical stratigraphic column of unconsolidated deposits in the St. Lawrence Lowlands Region.

an average thickness of 3 metres, usually located in depressions centred on old river channels.

13.3 HYDROGEOLOGICAL FEATURES

The Lower Paleozoic sedimentary rocks of the StLL represent regional aquifers in the western part of the region. Primary groundwater flow pathways are bedding planes, joints and solution-enhanced channels. The finer-grained foreland basin sediments to the east, near the Appalachians, are less fractured and commonly supply enough water only for single dwellings. These bedrock aquifers are usually at depths less than 100 m: groundwater quality and yield decrease at greater depths. Coarse Quaternary glaciofluvial sand and gravel overlie the bedrock in some areas. These Quaternary deposits, when combined with solution-enhanced fractures in the bedrock, constitute a "contact" zone aquifer at the base of the unconsolidated deposits.

Bedrock aquifers and the contact-zone aquifer are confined over most of the Region because they are overlain by low-permeability till and clayey marine sediments. Groundwater recharge for these regional aquifers has been established in the southern portion of the area and ranges from 5% to 6% in marine clay-covered terrain to (more typically) 9% to 10% of total precipitation. Usually, groundwater levels in surficial deposits fluctuate by up to 3 metres, while levels in the bedrock are more stable. Typical groundwater temperatures, shown in Figure 13.16, are between 7 C and 10 C (Simard and Des Rosiers, 1979).

13.3.1 Bedrock aquifers

Simard and Des Rosiers (1979) mapped the distribution of bedrock aquifers in Quebec by using the potential yield of wells listed in the *Système d'information hydrogéologique* (SIH) of the Quebec Ministry of Sustainable Development, Environment and Parks (MDDEP), a database of water well records in the province. They classified bedrock aquifers into three categories, from low to high permeability, based on the potential yield of existing wells:

- Low-permeability bedrock: potential yield lower than 2.7 m^3/h and 0% probability to obtain a potential yield greater than 9 m^3/h
- Moderate-permeability bedrock: potential yield between 4 m^3/h and 5.5 m^3/h and a 10% to 30%

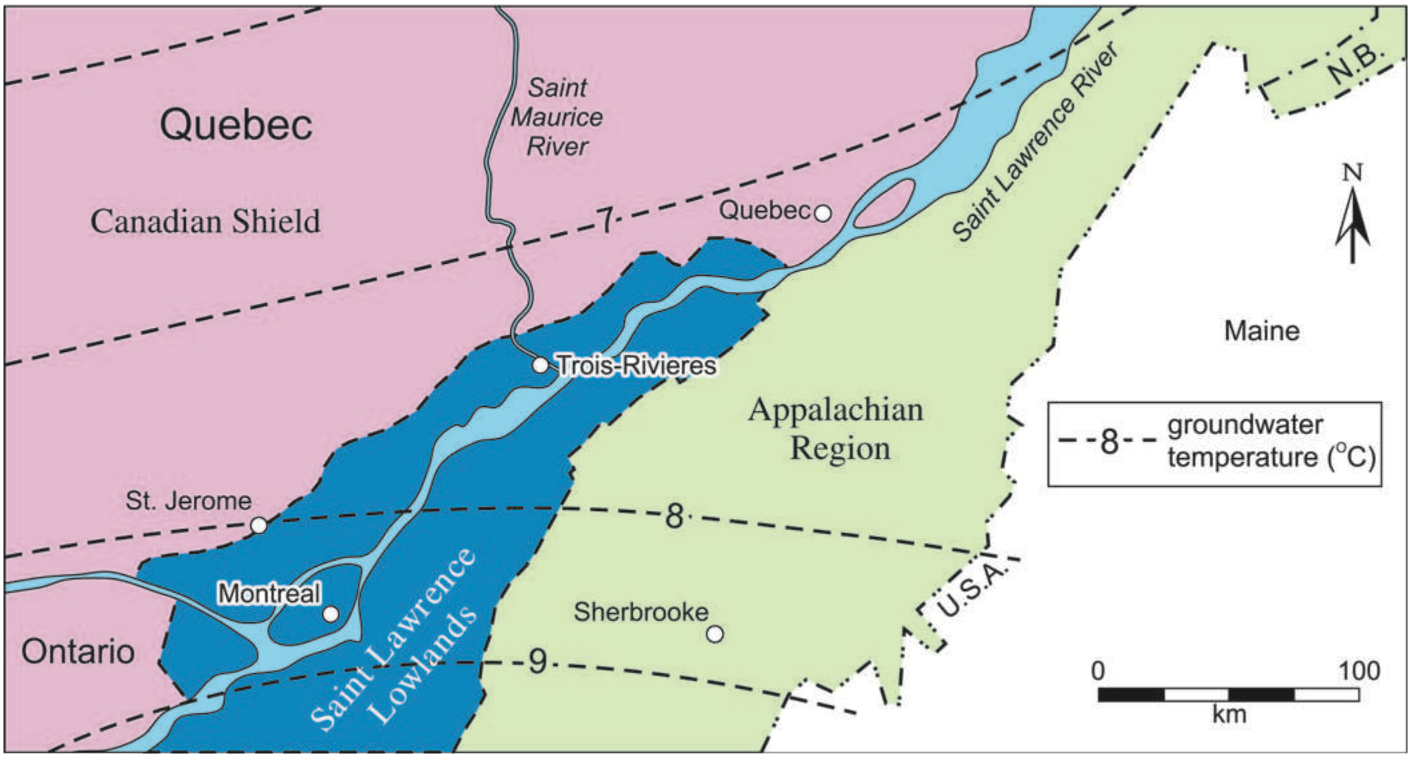


Figure 13.16 Groundwater isotherms in bedrock aquifers.

probability to obtain a potential yield greater than 9 m^3/h

- High-permeability bedrock: potential yield greater than 8 m^3/h, with a 15% probability to obtain a potential yield greater than 27 m^3/h

Based on these three classes, Simard and Des Rosiers (1979) identified a series of hydrostratigraphic units for the bedrock aquifers within the StLL Region. Distribution of these units is shown in Figure 13.17.

Rasmussen et al. (2006) used a more recent version of the well record database, incorporating more records, compared to Simard and Des Rosiers' (1979) version. The study also updated statistical descriptions of the hydrostratigraphic units (Table 13.2). The spatial distribution of transmissivities within the StLL Region is illustrated in Figure 13.18.

13.3.1.1 High-permeability category

Figure 13.17 indicates that the rock units with the highest permeability (2A, 2Z, 3A) are mostly located in the southwestern part of the StLL Region, where they cover nearly 60% of the area. One exception is unit 2A, which corresponds to the Trenton limestone and stretches in a northeasterly direction toward Quebec City. Recently, various local studies have been conducted in that part of the St. Lawrence Lowlands Region, containing the highest-permeability units. These studies seek to address local water needs for municipal, industrial, agricultural or recreational use, as well as on a regional scale (Côté et al., 2006; TechnoRem, 2008 a, b, c, d, e and f). Results have helped provide a better understanding of groundwater dynamics on a larger scale, in addition to furnishing transmissivity and hydraulic conductivity values for regional bedrock aquifers. Most values were obtained for geological formations corresponding to hydrostratigraphic unit 2Z (Potsdam, Beekmantown, Chazy and Trenton Groups), which reflects not only the wide variety of permeability of

TABLE 13.2 CHARACTERISTICS OF HYDROSTRATIGRAPHIC UNITS OCCURRING IN THE ST. LAWRENCE LOWLANDS REGION, FROM RASMUSSEN ET AL. (2006)

HYDROSTRATIGRAPHIC UNIT (PERMEABILITY)	AVERAGE YIELD OF WELLS (MAXIMUM YIELD) IN M^3/H	LOCATION (NUMBER OF WELLS)	GEOLOGICAL UNIT
2A (high)	8.1 ± 18.8 (188)	Discontinuous arch around the heart of the St. Lawrence Lowland Syncline (329)	Trenton Group (mainly limestone)
2Z (high)	14.9 ± 25.6 (217)	West of the St. Lawrence Lowland Region (335)	Potsdam (quartz sandstone); Beekmantown (dolomite); Chazy (limestone); Black River (limestone)
3A (high)	8.3 ± 18.1 (51)	In the centre of the St. Lawrence Lowland Syncline, north of Unit 3C (113)	Utica and Lorraine (shale, sometimes calcareous); Queenston (sandstone)
3B (low)	3.2 ± 4.9 (24.5)	In the centre of the St. Lawrence Lowland Syncline, north of Unit 3A (84)	Queenston (red shale and sandstone with some gypsum deposits)
3C (moderate)	5.6 ± 9.2 (52.4)	South of Unit 3A (91)	Utica and Lorraine (shale, sometimes calcareous); Queenston (sandstone)
3Z (low)	2.5 ± 24.3 (24.8)	In the centre of the St. Lawrence Lowland Syncline (148)	Utica, Lorraine and Queenston (shale interbedded with sandstone and limestone)
4Z (moderate)	4.4 ± 77.2 (88)	Southeastern limit of the St. Lawrence Lowland between the U.S. border and Quebec City (352)	Argillaceous and slatey shales, more strongly folded and faulted with slabs of Utica, Lorraine and Queenston rocks called Saint-Germain complex

these rock formations, but also the high median value of their hydraulic parameters. A summary of transmissivities and hydraulic conductivities for these geological formations is given in Table 13.3. The Black River Group also belongs to unit 2Z but, because of its small thickness (30 metres according to Globensky, 1987), no specific data useful for the determination of transmissivity and hydraulic conductivity is currently available.

Transmissivities on the order of 10^{-3} m^2/s imply that groundwater is generally easily available. It is therefore no surprise that groundwater is a major part of the water supply for all types of needs in the regions covered by the highest-permeability formations. Because rocks from the Potsdam Group contain cemented intergranular fine material, groundwater flow is controlled largely by fractures and bedding planes. For similar reasons, bedding planes represent preferential pathways for groundwater flow in the Beekmantown, Chazy and Black River Groups.

The high-permeability unit 3A is located in the centre of the St. Lawrence Lowland Syncline. Although sedimentary rocks of this unit are mainly composed of fine-grained sediments, not related to high-yield wells, they are more folded and faulted than the same rocks farther north and south of this unit. This increased folding and faulting is due to the intrusion of the Monteregian Hills during the Cretaceous period. Volcanic rocks of the Monteregian Hills intruded sedimentary rocks, increasing the latter's secondary porosity, therefore, providing more openings and increasing the permeability within the intrusion vicinity.

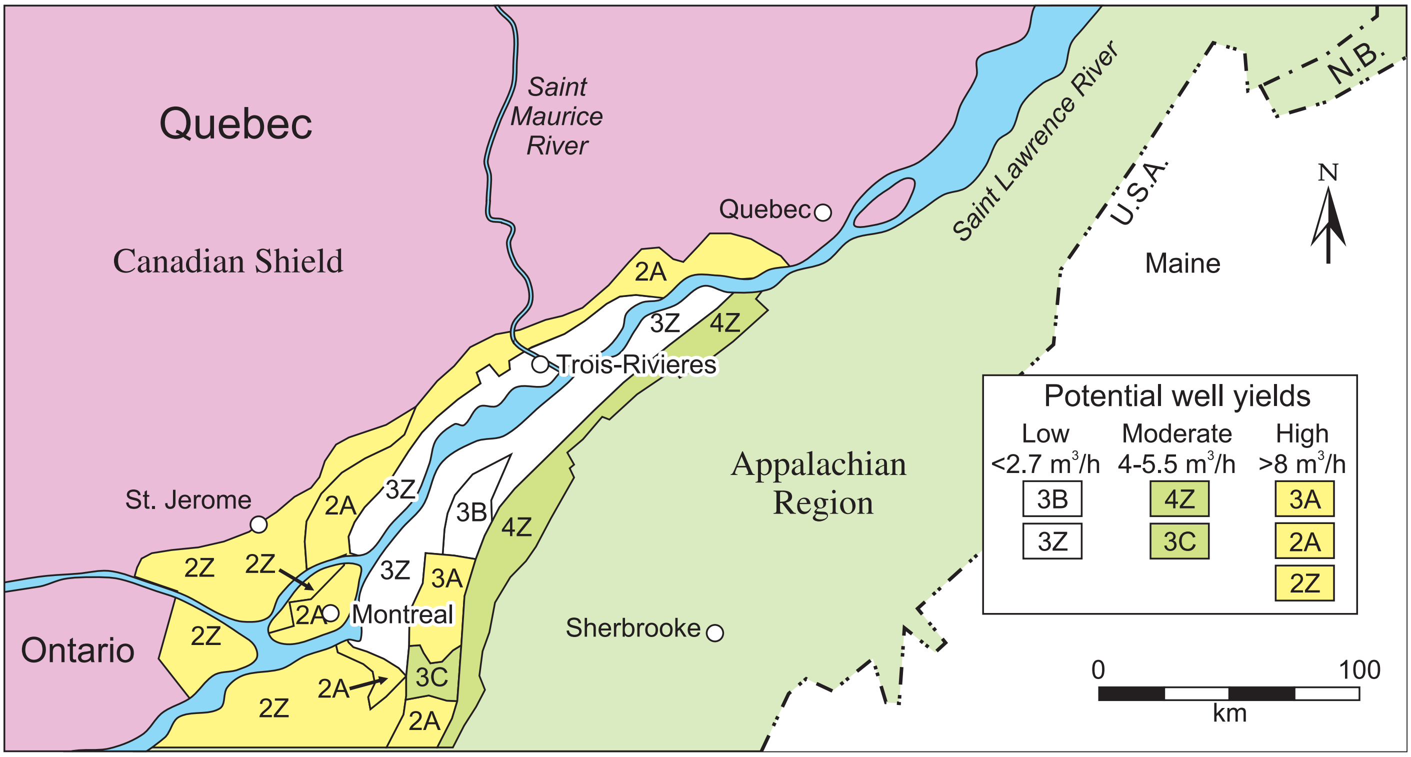


Figure 13.17 Distribution of potential well yields in bedrock aquifers (from Simard and Des Rosiers, 1979).

13.3.1.2 Moderate-permeability category

This category includes units 3C and 4Z which cover approximately 10% of the St. Lawrence Lowlands Region. Unit 3C, covering a small area squeezed between Units 3A and 2Z, is located just south of unit 3A and is comprised mainly of Utica, Lorraine and Queenston Groups. Its rock composition is the same as for Unit 3A, but because of the greater distance from the Monteregian Hills, rock permeability for unit 3C has not been influenced as greatly, and is therefore lower than that of unit 3A.

Unit 4Z is located on the eastern margin of the St. Lawrence Lowlands Region, at the foot of the Appalachians. It is an elongated stripe of argillaceous and slaty shales stretching between the U.S. border and Quebec City, marking the transition between the StLL and the Appalachians. Unit 4Z was affected by the formation of the Appalachian rocks in the Cambro-Ordovivian period: these rocks were folded and uplifted, creating openings that contribute to greater permeability.

There have been no regional groundwater studies for the 3C and 4Z units: the only transmissivity values available come from Simard and Des Rosiers (1979). They report transmissivities of 5.8×10^{-4} m^2/s and 2.9×10^{-4} m^2/s for units 3C and 4Z, respectively, or about two orders of magnitude lower than transmissivities for the previous category.

13.3.1.3 Low-permeability category

This category, located on both sides of the St. Lawrence River, includes units 3B and 3Z and covers about 25 % of the St. Lawrence Lowlands Region. Both units are in the centre of the St. Lawrence Lowlands Syncline, forming a large basin oriented in a northeasterly direction from the southwestern high-permeability units to Quebec City. The rock composition of these units is the same as the moderate-permeability units described in the preceding section. Units 3B and 3Z, however, were affected to a lesser extent by the

TABLE 13.3 TRANSMISSIVITY (T) AND HYDRAULIC CONDUCTIVITY (K) OF GEOLOGICAL UNITS REFERRING TO HYDROSTRATIGRAPHIC UNIT 2Z

AREA INVESTIGATED	HYDROSTRATIGRAPHIC UNIT							
	POTSDAM GROUP		BEEKMANTOWN GROUP		CHAZY GROUP		TRENTON GROUP	
	T, m^2/s (Median)	K, m/s (Median)	T, (m^2/s) (Median)	K, (m/s) (Median)	T, (m^2/s) (Median)	K, m/s (Median)	T, m^2/s (Median)	K, m/s (Median)
South of St. Lawrence River (1,425 km^2)	$1.8\cdot10^{-5}$ to $1.1\cdot10^{-2}$ ($1.8\cdot10^{-3}$)	$2.9\cdot10^{-7}$ to $1.9\cdot10^{-4}$ ($2.8\cdot10^{-4}$)	$4.3\cdot10^{-6}$ to $1.3\cdot10^{-1}$ ($1.8\cdot10^{-3}$)	$2.5\cdot10^{-6}$ to $1.2\cdot10^{-3}$ ($3.5\cdot10^{-4}$)	$3.0\cdot10^{-4}$ to $7.1\cdot10^{-3}$ ($2.1\cdot10^{-3}$)	$1.5\cdot10^{-5}$ to $1.3\cdot10^{-4}$ ($5.4\cdot10^{-5}$)	No data available	No data available
North of St. Lawrence River (1,800 km^2)	$1.0\cdot10^{-6}$ to $1.0\cdot10^{-4}$	$2.5\cdot10^{-7}$ to $2.5\cdot10^{-5}$	$7.5\cdot10^{-5}$ to $2.0\cdot10^{-1}$ ($4.9\cdot10^{-2}$)	$2.2\cdot10^{-6}$ to $3.8\cdot10^{-3}$ ($5.4\cdot10^{-4}$)	$3.0\cdot10^{-4}$ to $1.1\cdot10^{0}$ ($1.4\cdot10^{-1}$)	$2.5\cdot10^{-5}$ to $9.3\cdot10^{-3}$ ($3.6\cdot10^{-3}$)	$1.2\cdot10^{-2}$ to $1.3\cdot10^{0}$ ($2.9\cdot10^{-1}$)	$4.2\cdot10^{-6}$ to $7.3\cdot10^{-3}$ ($1.4\cdot10^{-3}$)

Appalachian orogeny because of their greater distance from the Appalachians. The fine-grain-sediment geological units, coupled with very poor joint system development, explain the low permeability for this area. Wells drilled into these formations confirm that this category is really not suitable for high-yield production wells. Additionally, because most of these rocks are covered by marine clays from the Champlain Sea, they often contain brackish water, a situation observed in several wells.

No regional groundwater studies have been done in this part of the St. Lawrence Lowlands Region. The source for transmissivity values is Simard and Des Rosiers (1979), who report transmissivities of 1.3×10^{-4} m^2/s and 1.1×10^{-4} m^2/s for units 3B and 3Z, respectively. These transmissivities are about two orders of magnitude lower than those for the high-permeability category.

13.3.2 Surficial deposits aquifers

Almost all major surficial deposits aquifers within the St. Lawrence Lowlands Region overlie bedrock directly or were deposited on marine clays after the withdrawal of the Champlain Sea, 5,000 to 7,000 years ago. As a result, melting snow originating from the Appalachians or the Precambrian Shield deposited sediments of varying grain size during the late stage of the sea, thus creating large coarsegrained aquifers in various locations. These coarse-grained aquifers contribute to the recharge of the bedrock aquifers because they overlie the bedrock.

Large deposits of sand and gravel occur on both sides of the St. Lawrence River (Figure 13.19). The thickness of these deposits, on the North Shore, can reach 50 metres: nearly all of the communities located between the Precambrian Shield and the St. Lawrence River use these aquifers for their water needs. The exception is the city of Trois-Rivières (Trois-Rivières sector) between Berthierville and Portneuf, which uses surface water for its water supply. Drinking water for the Cap-de-la-Madeleine district of Trois-Rivières is supplied by 32 wells with a total yield of 8,500 m^3/d. Groundwater supplied at a rate of 6,000 m^3/d is also used in the Trois-Rivières-Ouest district of the same city. West of Berthierville, in the direction of Montreal, where population increases, the surficial

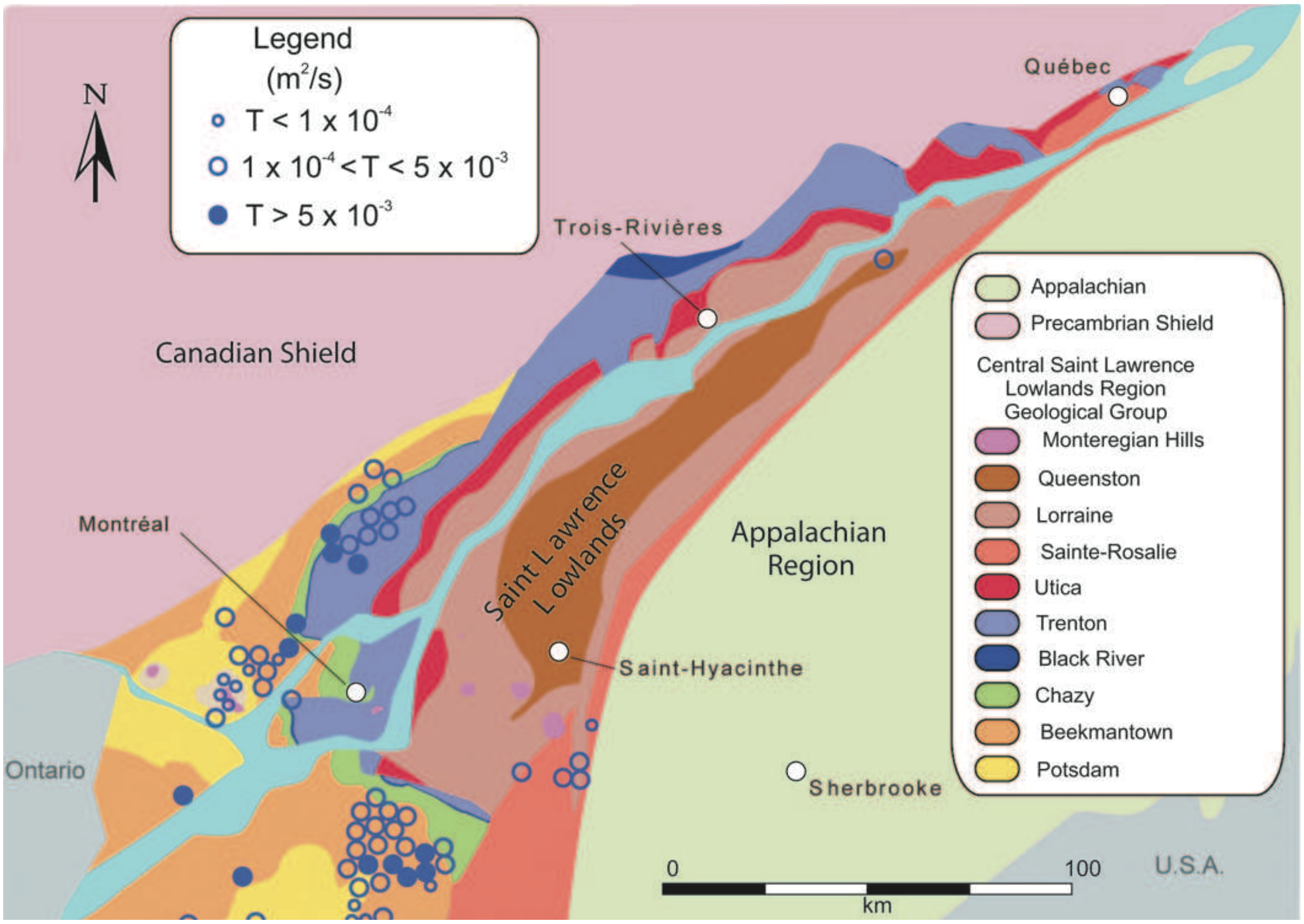


Figure 13.18 Transmissivity (m^2/s) of the bedrock in the St. Lawrence Lowlands Region.

deposits thin out and the volume of water obtained from them is less than that obtained to the east of the city. As a result, groundwater is less attractive, and most communities west of Berthierville rely on surface water for their water supply.

Granular deposits are also present on the south shore of the St. Lawrence River: these represent aquifers currently exploited by several municipalities. However, potential yield is limited to 225 L/min, because sand and gravel units north of the Monteregian Hills consist mainly of terrace sands with a maximum thickness of about 6 metres. South of these hills, granular deposits are of glaciofluvial or glaciomarine origin and of thicker sequence, raising the potential yield to about 550 L/min. These valuable aquifers currently serve as the water supply for the municipalities of Saint-Césaire and Saint-Paul d'Abbotsford. Moreover, an aquifer beneath clay material was discovered south of Mount Rougemont in a regional study undertaken during the late 1960s (Prévôt, 1972); this aquifer is still used for drinking water today.

Regional groundwater resources of granular deposits within the Portneuf Regional County Municipality were mapped, during the late 1990s, by a consortium composed of the Geological Survey of Canada (GSC), the Water, Land and Environment division of the Institut national de la recherche scientifique (INRS-ETE), Laval University and the Quebec Ministry of Sustainable Development, Environment and Parks (MDDEP). That area studied is located on the north shore

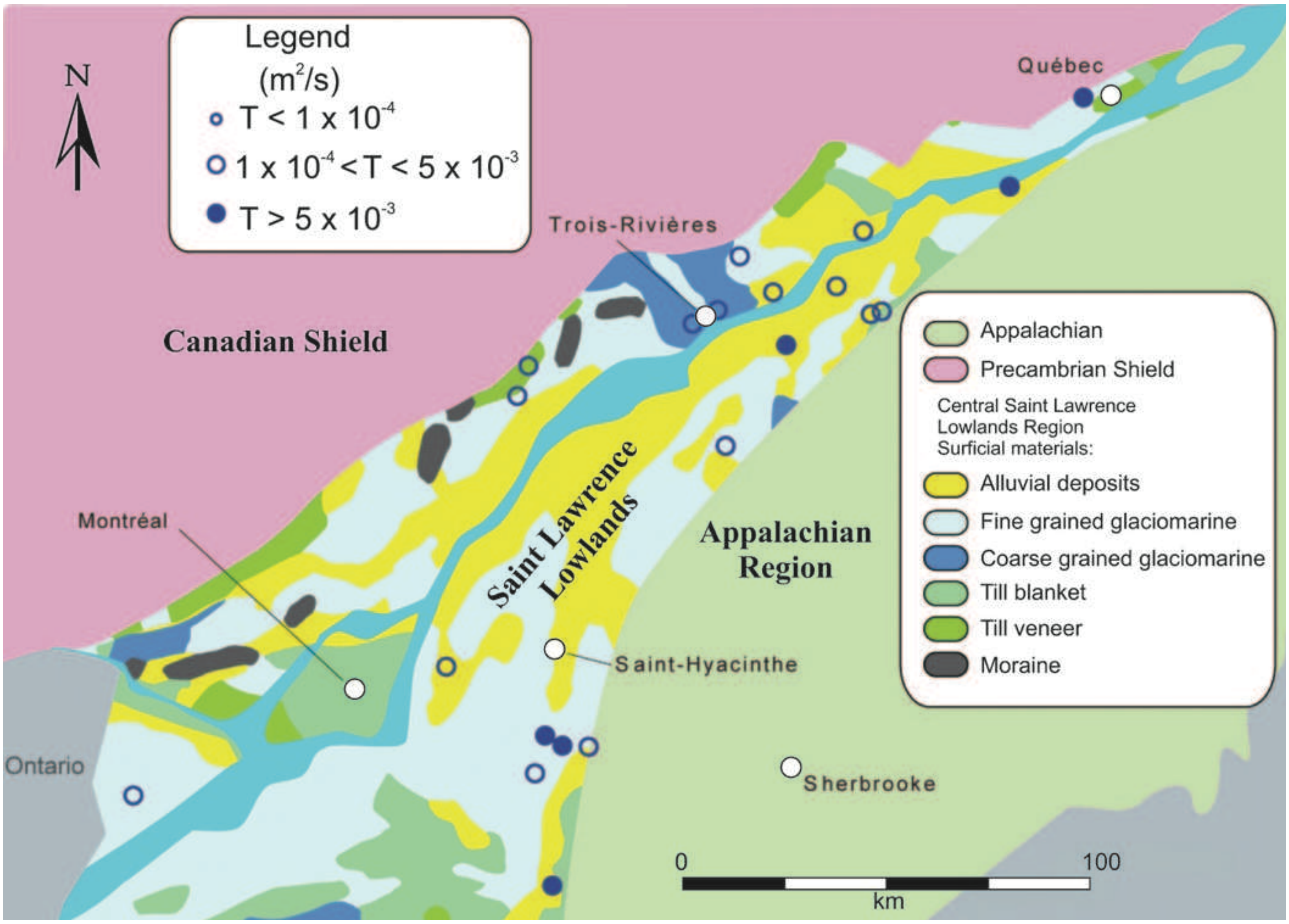


Figure 13.19 Transmissivity (m²/s) of surficial deposits in the St. Lawrence Lowlands Region.

of the St. Lawrence between Trois-Rivières and Quebec City (Figure 13.19). Sand and gravel units representing high-permeability aquifers were characterized during that project, and recommendations were outlined for the improvement of groundwater management by local authorities (see Box 13-1).

13.3.3 Maps of groundwater vulnerability (DRASTIC)

A series of vulnerability maps, both general and detailed, were produced for the Quebec government, during the late 1980s, for populated areas within the StLL Region. These maps delineate areas where groundwater is more susceptible to contamination from ground surface (McCormack and Grenier, 1985; McCormack, 1985a, b, c, d and 1986a, b, c, d, e). The first series of maps provide a rough idea of vulnerable zones across a large area, usually at the 1/250,000 scale, based on geological settings and topography. The second series of maps covers smaller areas, at the 1/50,000 scale, and uses the DRASTIC method (Aller et al., 1987) to compute groundwater' vulnerability to contamination. Human activities and types of water supply within local communities are superimposed on the vulnerability categories. General maps have been produced for the entire St. Lawrence Lowlands Region, while detailed maps have been produced for the regional county municipalities of Montcalm (Champagne, 1990), Portneuf (Parent et al., 1998; Fagnan et al., 1998; Bourque et al., 1998), Joliette, L'Assomption and Francheville (McCormack, 1986a, b and c). The DRASTIC method has also been used in the regional studies of the Chateauguay Watershed (Côté et al., 2006) and the northwest Montreal area (Paradis et al., 2002).

13.3.4 Temporal trends in groundwater levels

The Quebec Ministry of Sustainable Development, Environment and Parks (MDDEP) operates a network of 65 groundwater monitoring piezometers located in different parts of the province. The network covers a range of hydrogeological contexts, including bedrock, surficial deposits, unconfined, and confined aquifers. The piezometers are located away from wells currently used for water supply so that water levels being monitored will not be affected by pumping within the vicinity (www.mddep.gouv.qc.ca/eau/piezo/). These piezometers have been installed gradually since the late 1960s and are the result of regional studies carried out during the 1960s and 1970s. Fifty-one piezometers are located in the StLL Region; the oldest ones began recording water levels more than 30 years ago, but not all records are continuous, and some gaps exist in the time series.

The piezometer at station No. 03047011 (Sainte-Angèle-de-Monnoir) is one of the oldest in the network and was installed in 1969 during the hydrogeological study of Rouville-Saint-Hyacinthe counties (Prévôt, 1972). This piezometer is located in a sand and gravel confined aquifer, recommended as a water supply source for the municipality of Rougemont (which began using groundwater from that aquifer a few years later). Although piezometers within the network must be installed at locations supposedly outside the influence of nearby groundwater wells, the water level in piezometer No. 03047011 decreased by more than 6 m after water began to be pumped from municipal wells in the neighbourhood (Figure 13.20). This specific decrease has, so far, proved to be an exception, as water levels recorded at all the other stations do not indicate a decreasing trend that might be associated with pumping effects or climate change. Figures 13.21 to 13.24 illustrate typical readings measured in various hydrogeological environments within the St. Lawrence Lowlands Region.

13.4 GROUNDWATER QUALITY

Groundwater in bedrock and surficial deposits of the StLL Region is generally of good quality, with a pH between 7.5 and 8.0, which meets Canadian drinking water quality standards (Health Canada, 2006). Exceptions are for a large area of brackish water stretching between the Monteregian Hills and the St. François River, around the Saint-Hyacinthe area, on the south shore of the St. Lawrence River (Prévôt, 1972), as well as for smaller patches of brackish or saline water located (1) along the Chateauguay River in the southwesternmost part of the St. Lawrence Lowland Region, (2) at the junction of the L'Assomption River and the St. Lawrence River area just north of Montreal and (3) in the Oka area. These areas with higher groundwater salinity are shown in Figure 13.25.

The high chloride content in groundwater in the Saint-Hyacinthe area of the StLL is caused by the saltwater that invaded fractures within the bedrock when it was covered by the Champlain Sea. As the sea began to retreat, groundwater in the bedrock was trapped by the clay overlying the bedrock; remnants of that episode are still found today in groundwater samples. Local residents have known about this lower-quality water for a long time and for that reason, hydrogeological studies for

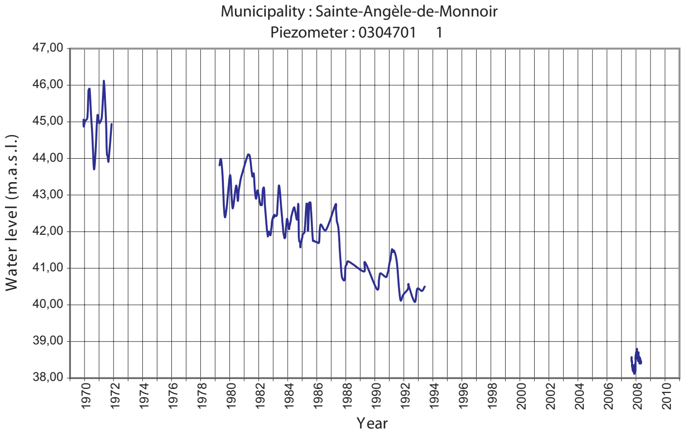


Figure 13.20 Water level recorded in the piezometer at Station 03047011 located in surficial confined deposits in the municipality of Sainte-Angèle-de-Monnoir.

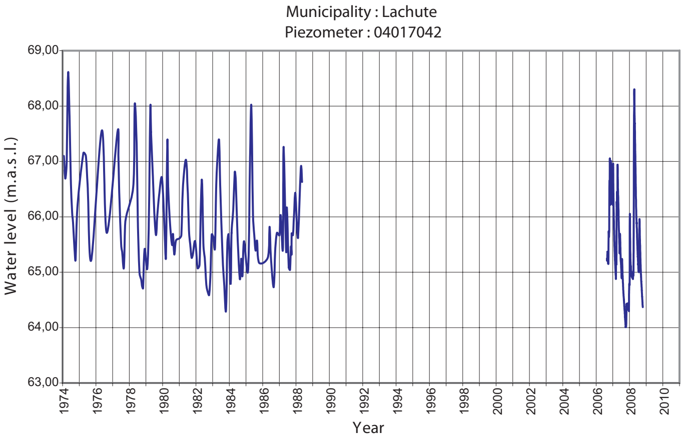


Figure 13.21 Water level recorded in the piezometer at Station 04017042 located in the confined Potsdam formation (bedrock) in the municipality of Lachute.

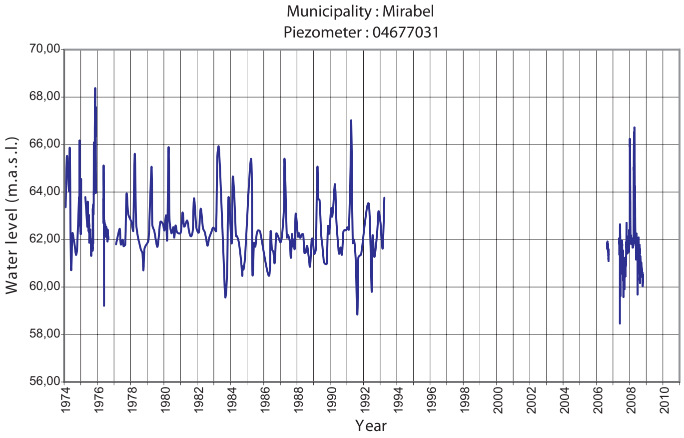


Figure 13.22 Water level recorded in the piezometer at Station 04677031 located in the unconfined Potsdam formation (bedrock) in the municipality of Mirabel.

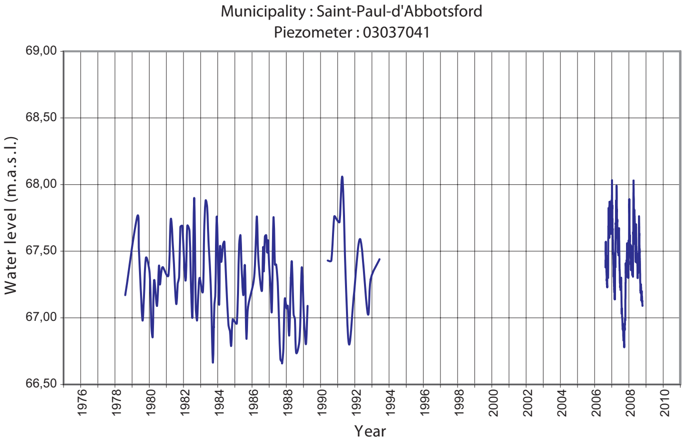


Figure 13.23 Water level recorded in the piezometer at Station 03037041 located in the unconfined surficial deposits in the municipality of Saint-Paul-d'Abbotsford.

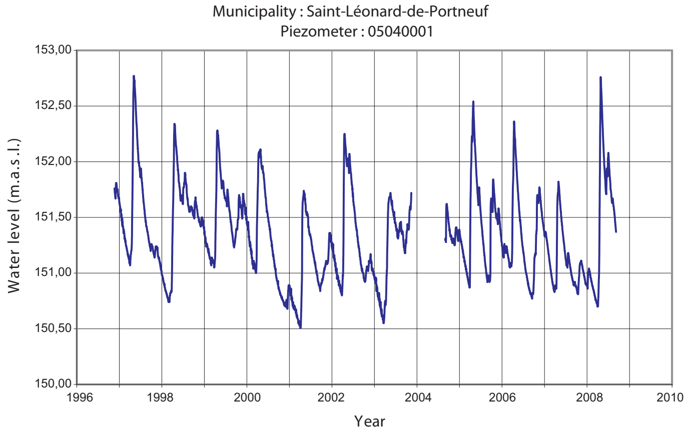


Figure 13.24 Water level recorded in the piezometer at Station 05040001 located in the unconfined surficial deposits in the municipality of Saint-Léonard-de-Portneuf.

drinking water are not conducted in these areas. One additional caution: great care must be taken to avoid saltwater invasion when extracting groundwater from nearby freshwater aquifers.

There are other concerns regarding local groundwater quality issues in the StLL, as some groundwater samples have mineral and non-mineral components which exceed drinking water standards. Examples include elevated concentrations of fluoride in the Contrecoeur area, and barium concentrations over the accepted standard of 1 mg/L throughout the St. Lawrence Lowlands Region. Radioactive elements have been reported in the Oka area, while concentrations of uranium exceeding

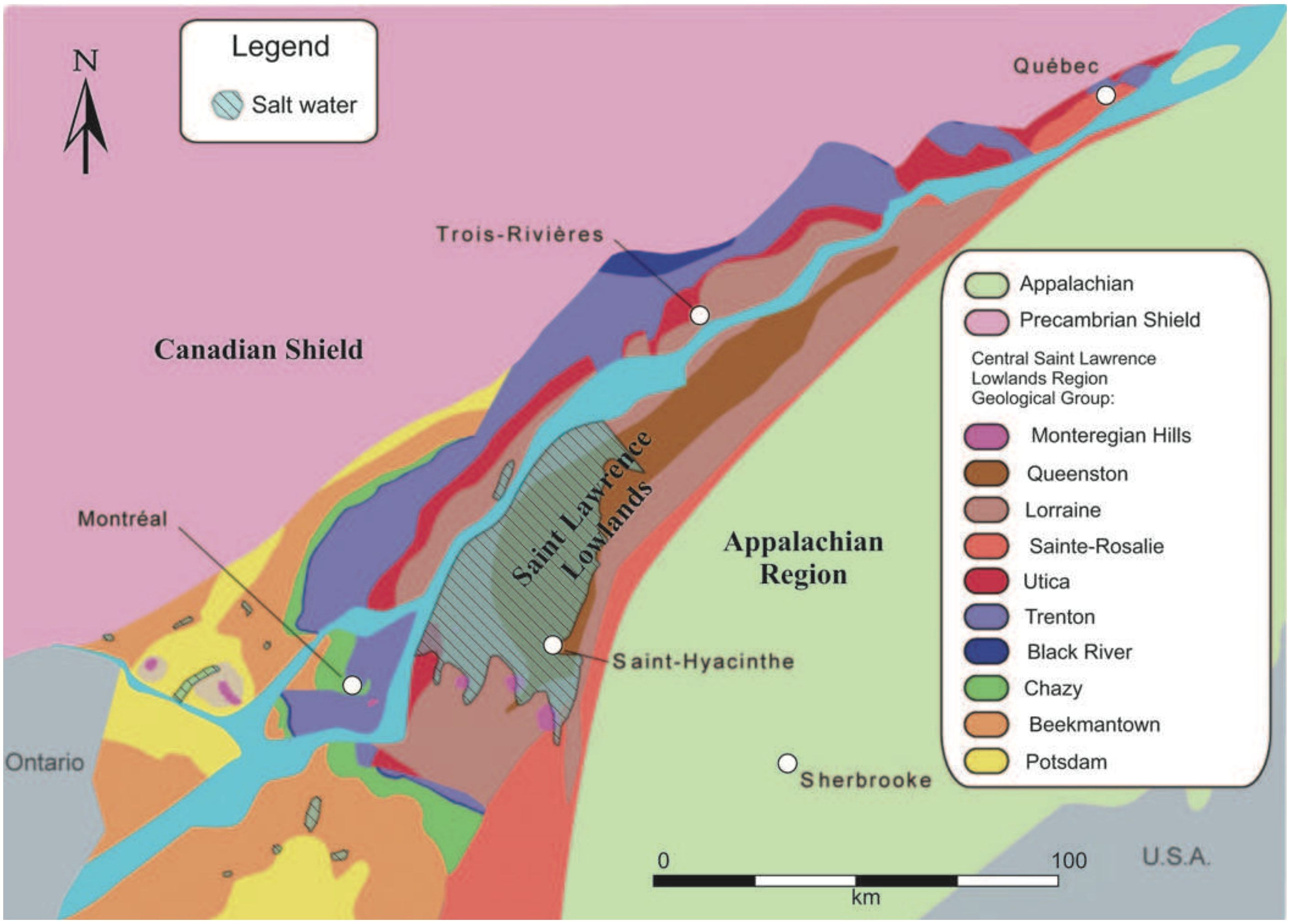


Figure 13.25 Occurrence of brackish groundwater in the St. Lawrence Lowlands Region.

the upper limit of 0.02 mg/L were found in private wells by Dessau et al. (1999). These concentrations are related to a carbonatite-type rock mined for the production of niobium. Radon associated with these radioactive elements has also been reported in the same area, where groundwater concentrations as high as 1,590,000 Bq/m^3 have been found (BAPE, 2002, 2005). Other chemical substances such as lead, chromium, arsenic, mercury and cadmium, which can be hazardous to health, are absent from the naturally occurring groundwater of the St. Lawrence Lowlands Region.

Groundwater in surficial deposits is usually of good natural quality, with pH values generally ranging from 6.0 to 6.8, lower than that of bedrock aquifers. Based on drinking water standards, the quality of groundwater in surficial deposits is usually better when compared to water from bedrock. However, aquifers in surficial deposits are more exposed to human activities and thus more susceptible to contamination because of their high vulnerability.

Other components, not listed in the drinking water standards, can still affect the overall groundwater quality based on aesthetic criteria, even when the water meets drinking water standards. Iron and manganese produce a metallic taste and create stains on water pipes and hardware when their concentrations exceed prescribed values. Elevated iron and manganese concentrations are widespread in bedrock as well as in surficial deposit aquifers (Figure 13.26).

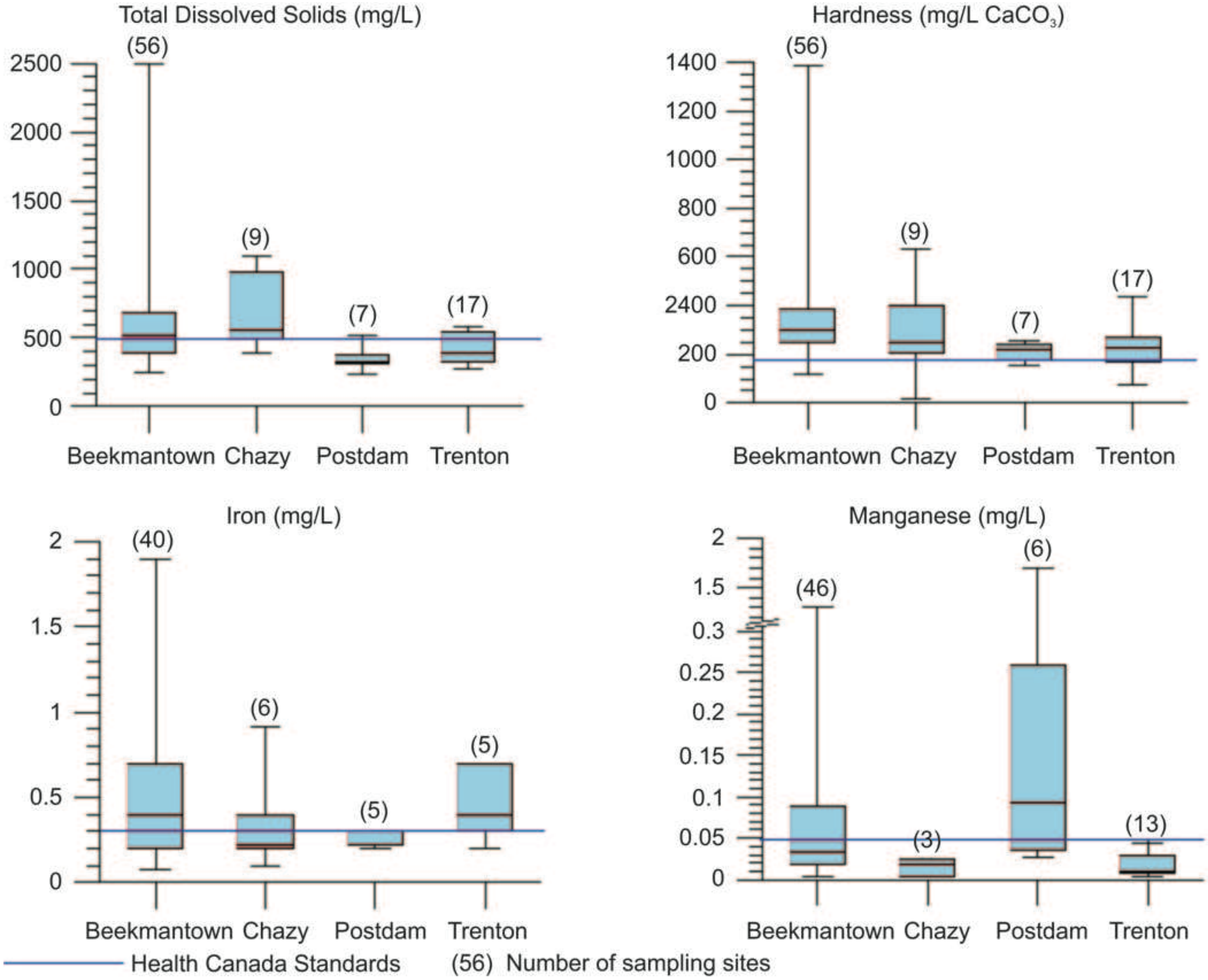


Figure 13.26 Occurrence of aesthetic parameters in groundwater in the Central St. Lawrence Lowlands Region. Blue lines refer to the maximum concentration guidelines for drinking waters.

There is one particular feature in the Trois-Rivières area where the St. Maurice River marks the limit between high and low iron concentrations in groundwater (Figure 13.27). On the west side of the river, the upper limit is greatly exceeded, with values as high as 4.5 mg/L in the Trois-Rivières-Ouest district (McCormack, 1983), while concentrations below 0.3 mg/L are frequent on the east side. This high iron content in groundwater is related to the presence of the mineral vivianite, which was used in the iron industry during the early days of the French colony.

Other aesthetic issues are related to hardness which regularly exceeds the upper limit of 180 mg/L $CaCO_3$ wherever limestone and dolomite rocks are present, as in the Beekmantown, Chazy and Trenton Groups (Figure 13.26). The distribution of hardness in bedrock and surficial deposits is illustrated in Figure 13.28 and Figure 13.29, respectively. Domestic water treatment units are often used by groundwater users to improve the water quality. High hardness also increases the total dissolved solids content, which sometimes exceeds the upper limit of 500 mg/L (Health Canada, 2006), as shown

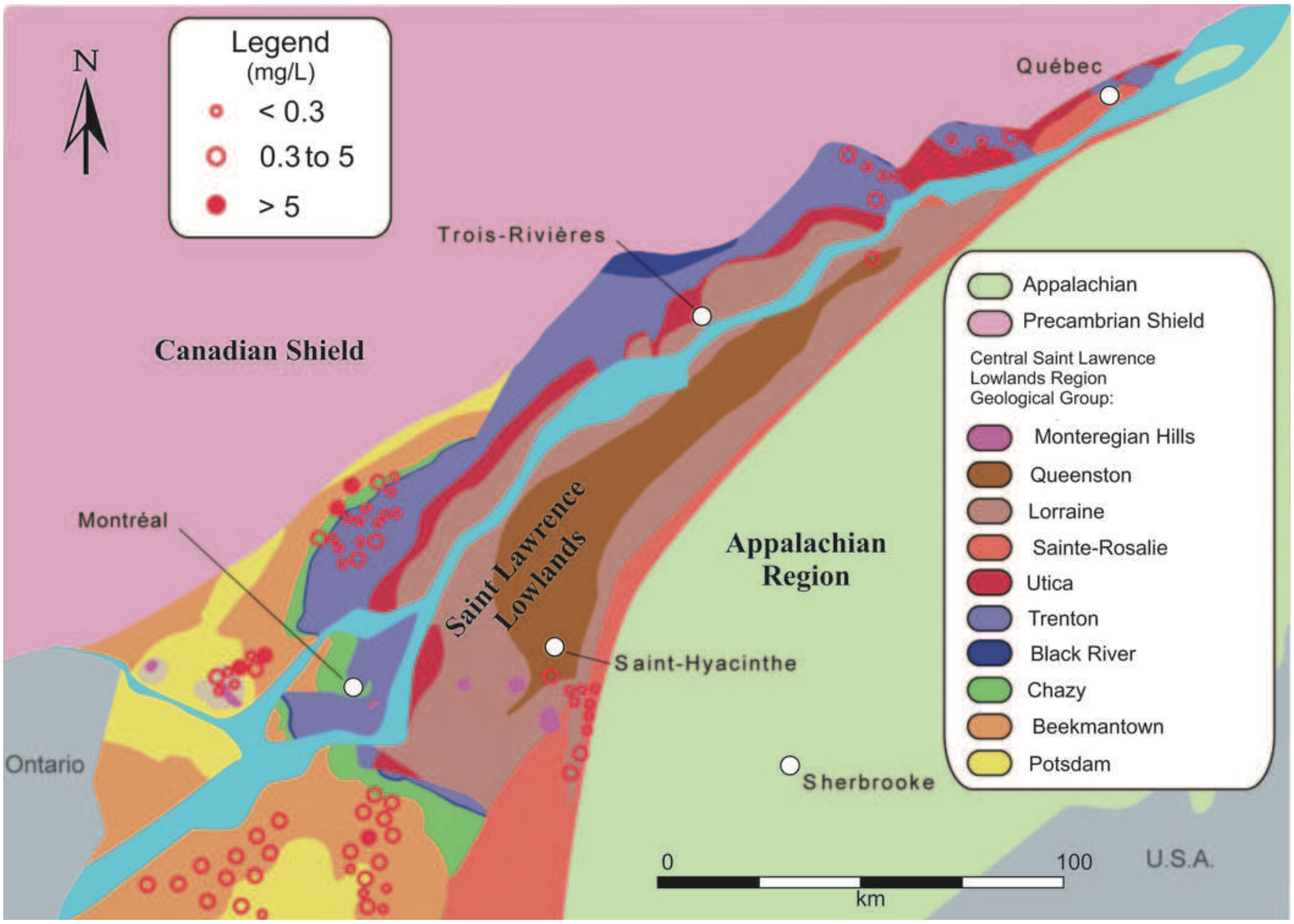


Figure 13.27 Spatial distribution of iron in groundwater of bedrock aquifers.

in Figure 13.26 and Figure 13.30.

The sections above cover the quality of naturally occurring groundwater in the StLL. Groundwater quality issues are also impacted non-naturally, as a result of human activity. The section below presents issues related to diffuse and point-source pollution originating from human intervention.

13.4.1 Diffuse pollution

Diffuse pollution sources within the StLL come from large-scale agricultural activities including the spreading of manure, fertilizer and pesticides, plus road deicer. One relevant example of this type of groundwater contamination was reported in the Regional County Municipality of Portneuf, southwest of Quebec City, on the north shore of the St. Lawrence River. Here large volumes of fertilizer used for potato growing contributed to higher groundwater concentrations of nitrates over the standard of 10 mg/L N to an unconfined sand aquifer (Paradis et al., 1991).

Quebec's most productive farmlands, however, where agriculture and irrigation are the most concentrated, can be found in the Montérégie region south of Montreal, where the highpermeability bedrock aquifers are protected from ground surface contamination by the presence of overlying thick, low-permeability marine clays and glacial tills.

13.4.2 Point-source pollution

Few cases of point-source groundwater pollution have been reported in the St. Lawrence Lowlands

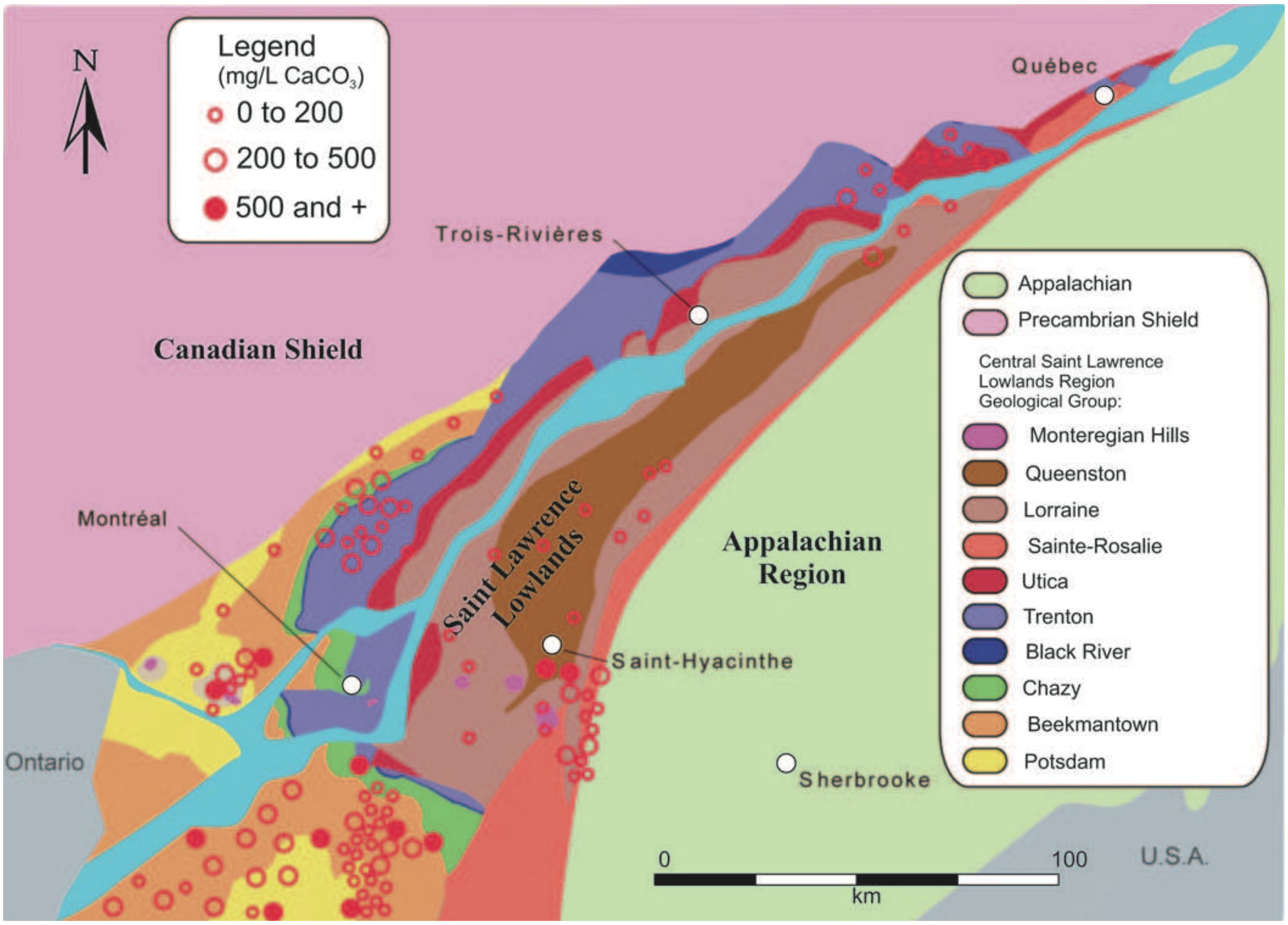


Figure 13.28 Spatial distribution of hardness in groundwater of bedrock aquifers.

Region. One of the province's most publicized incidents occurred in the Mercier area, within the Montérégie region, 20 kilometres southwest of Montreal, during the late 1960s. Some 170,000 km^3 of chemical waste from Montreal refineries were disposed of in lagoons located in sand and gravel pits excavated within an esker. The chemicals in this waste (hydrocarbons, dense non-aqueous phase liquids [DNAPL] and light non-aqueous phase liquids [LNAPL] of all kinds) migrated downgradient into underlying bedrock fractures. Once in the bedrock, the contaminants created a plume, roughly oriented NE-SW, which reached the first private wells in 1971. Moreover, the LNAPL contaminants generated a dissolved phase that moved through the granular aquifer. As a preventive measure against groundwater contamination, the Mercier and Sainte-Martine municipal wells, located 1.5 km and 6 km north and southwest of the lagoons, respectively, were shut down. Water was provided to residents of those two municipalities and affected rural residents by extending the City of Chateauguay water mains. The contamination forced the government to introduce regulations in 1982 (*Regulation respecting the protection of ground water in the region of the Town of Mercier*, Order-inCouncil No. 1525-82) prohibiting the pumping of groundwater inside a 4.7 km^2 area and restricting the use of groundwater across a 315 km^2 area surrounding the lagoons. In 1984, a pumping unit called the Groundwater Treatment Unit (GWTU)

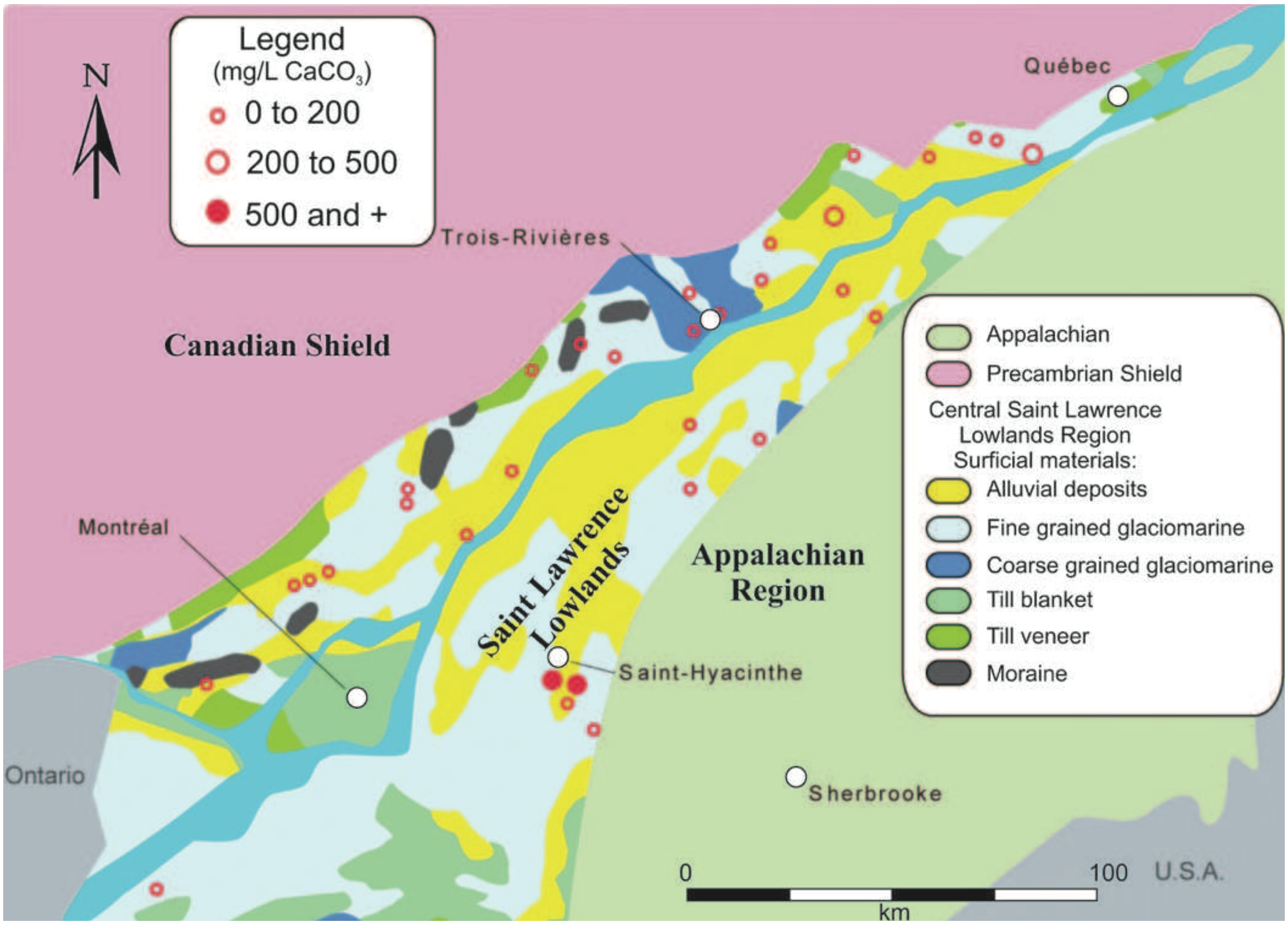


Figure 13.29 Spatial distribution of hardness in groundwater of surficial deposits aquifers.

was built to pump and treat the contaminated groundwater, and a hydraulic trap created to prevent spread of the contaminated plume. As part of the ongoing environmental monitoring process, samples of the treated water leaving the treatment plant, fumes emitted from the chimney plant, and groundwater in the area around the site are analysed at specific times to determine changes have occurred over the years. So far, there has been compliance with all environmental criteria, but because of the hydrogeological complexity and of contaminants involved, it is nearly impossible to fully decontaminate the site and restore it to its prior state. Box 13-3 includes a summary of the event and the remediation work undertaken to prevent the spread of contaminants.

13.5 GROUNDWATER ISSUES

Groundwater's abundance and relative availability in Quebec meant that this resource received very little attention from government officials until the Walkerton incident in 2000. Quebec's first groundwater regulation (*Regulation respecting underground waters*), enforced in 1967, were intended mainly for water well drillers. They were required to submit artesian well records to the government for each well drilled in the province. Later, after the City of Mercier case, this groundwater was given further consideration and included in many types of impact studies (industrial waste; sewage and waste disposal sites; sand, gravel, quarry and mining projects; removal of petroleum-storage tanks; road deicing, etc.). Quebec's Soil Protection and Rehabilitation of

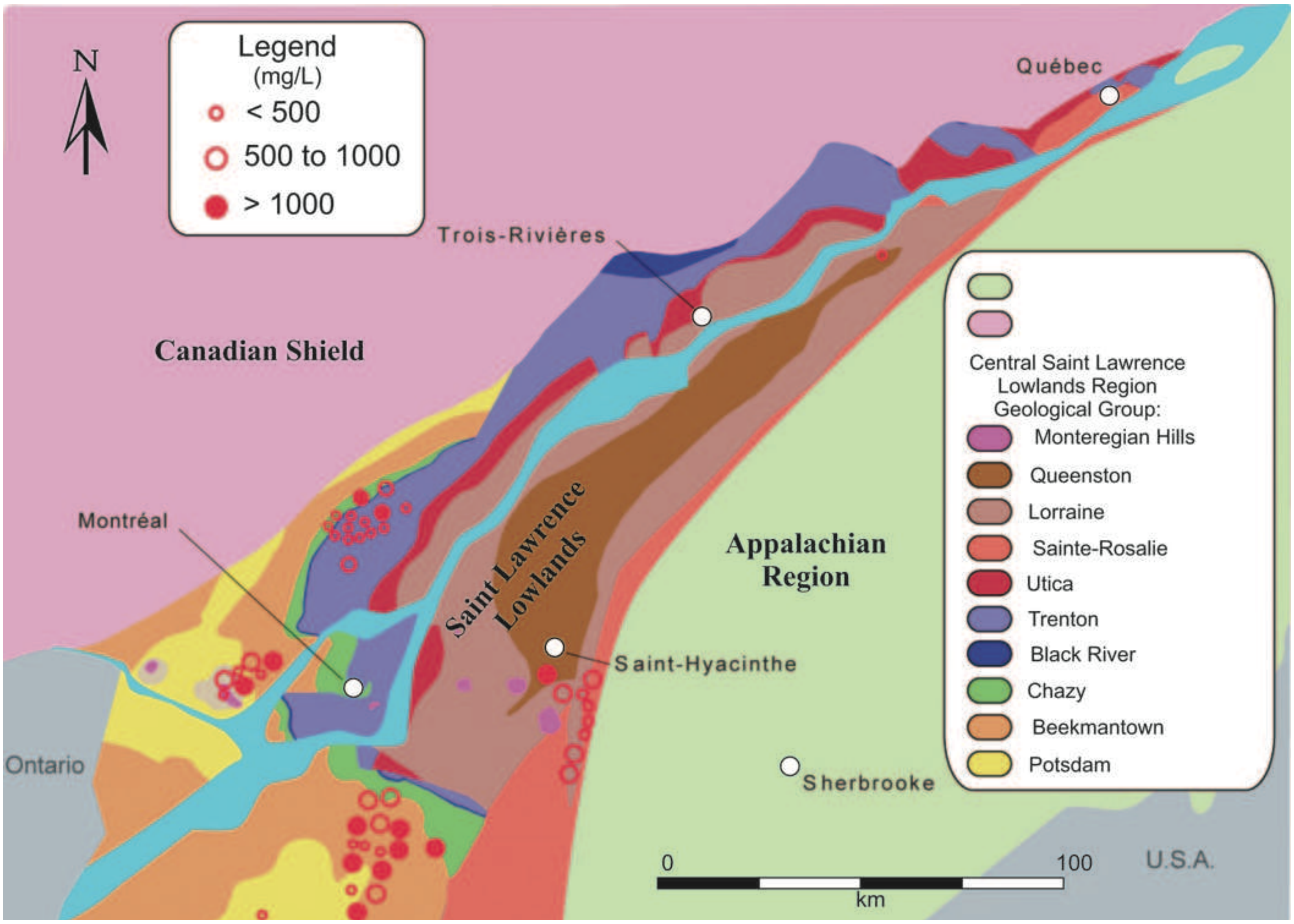


Figure 13.30 Spatial distribution of total dissolved solids in groundwater of bedrock aquifers.

Contaminated Sites Policy provides the necessary framework for preserving the integrity of both soil and groundwater.

In 1999, Quebec's environmental review agency, the Bureau d'audiences publique sur l'environnement (BAPE), held public hearings on water management issues. Serious concerns about the lack of hydrogeological data on groundwater were highlighted in the report published in 2000 (BAPE, 2000). Following these hearings, the Quebec government adopted the Province of Quebec National Water Policy in 2002, which sets out government priorities with respect to the protection, storage and acquisition of hydrogeological data.

The Quebec government authorities now recognize that the protection and conservation of groundwater must be taken into consideration before those projects with any potential to contaminate this resource are undertaken. The first regulations respecting groundwater were updated in 2002, in a new set of standards called the Groundwater Catchment Regulation, R.Q. c. Q-2, r.6, which placed greater emphasis on groundwater protection and conservation. These rules require communities to delineate a wellhead protection area for each groundwater catchment site producing more than 75 m^3/d for human consumption. In the central St. Lawrence Lowlands Region, 136 municipalities are subject to this requirement; by the end of 2007, 114 of them (84%) had complied. The regulations also include the requirement that a visible sign be installed on all groundwater pumping sites used for drinking water supply purposes. The sign must state that the small fenced-in area (usually 30 metres across) serves as the community's water supply (Figure 13.31).

In Fall 2008, the Quebec government tabled a new bill (Bill 92), *An Act to Affirm the Collective Nature of Water Resources and Provide for Increased Water Resource Protection*, to confirm the legal status of water (both surface and groundwater), as part of the common heritage of Quebec. The act sets out those legal principles that pertain to the accessibility of water and the public and provincial duty to prevent harm to water resources and to repair such harm as may have occurred. The act also sets out water governance rules based on an integrated, joint management strategy as well as new rules for water withdrawl. This legislation underlines Quebec's serious concern about water resources in general, and groundwater in particular. Provincially, the government also took into consideration recommendations suggested in the report on water management in Quebec of the Bureau d'audiences publiques sur l'environnement (BAPE, 2000) after the environmental review agency conducted public hearings across the province in 1999 and 2000.

The Quebec Ministry of Sustainable Development, Environment and Parks plans to build monitoring wells in undisturbed terrains (bedrock or surficial deposit aquifers) and, as is currently the case, the data collected is expected to be posted on Department's website (http://www.mddep.gouv.qc.ca/eau/piezo/). This process should help scientists and managers obtain a better understanding of the dynamics of groundwater resources during the upcoming years of anticipated climate change.

The provincial water well database (Système d'informations hydrogéologiques or SIH) includes data for about 145,000 wells, of which 98% are drilled wells. Since the adoption of the 2002 regulations, requiring municipalities to include water well permits for private wells in municipality construction permits, some 6,000 new wells are added to the database every year, including drilled wells, shallow wells, point systems and spring catchments. Drilled wells, however, are by far the highest percentage of wells in the database. Information on these wells is available on the Ministry's website (http://www.mddep.gouv.qc.ca/eau/souterraines/sih/index.htm).

13.5.1 Groundwater classification system

In 1999, Quebec's then Ministry of the Environment adopted a groundwater classification system to force local area managers to consider the implications any urban development planning might have on groundwater.

The entire hydrogeological system, wellhead protection areas, limits of hydrostratigraphic units, uses and potential uses of groundwater, and links with surface water or wetlands, must be taken into consideration in order to identify potential groundwater use and its relative value. Once all these components have been identified, the hydrogeological units can be characterized, and a classification system divided into the following three classes can be established:

Class I:	Hydrogeological unit that constitutes the sole drinking water source
Class II:	Hydrogeological unit that constitutes a current or potential drinking water source in terms of quality and quantity
Class III:	Hydrogeological unit that, even while saturated, cannot constitute a drinking water source because of its poor quality, poor potential or high cost of withdrawal.

Figure 13.31 Example of required signage at a drinking water catchment site.

Class I

Class I corresponds to an aquifer that would be called a *unique and irreplaceable* drinking water source. The term "unique" corresponds to a situation where such an aquifer cannot be replaced because proposed alternative methods would be too costly for the community.

The limits of a wellhead protection area associated with the groundwater catchment site used for drinking water purposes must be included in this category.

Whenever a hydrogeological unit is identified as the only cost-effective drinking water source for a community's future development needs, the whole aquifer unit will be included within this category. Such a situation, however, forces municipal authorities to indicate clearly on urban development plans in those areas which will be preserved for drinking water withdrawal only.

Class II

Class II refers to an aquifer that is a current or potential drinking water source because of its good quality and high potential. When the drinking water source is current, the presence of a groundwater catchment site is sufficient for including the exploited aquifer within this category. When the drinking water source is a potential source only, the aquifer under consideration must meet the following conditions:

- Transmissivity must be greater than 1 m^2/d, which is usually enough for domestic use.
- Quality requirements must be met or can be met using usual domestic water treatment devices.
- Portions of the area located above aquifers must be reserved for future development projects.

Class III

Class III refers to a geological unit that does not satisfy any of the Class II conditions. One unit, for example, would have low groundwater potential, such as slaty, argillaceous or shaly materials, confining it to Class III, even though the water quality might be acceptable. Alternatively, a geological unit with high groundwater potential could belong to Class III because of its poor water quality. In Quebec, especially in the Central St. Lawrence Lowlands Region, brackish water is found in Class III units.

And finally, a geological unit which meets Class II conditions would belong in Class III in those cases where groundwater is available, but will not be used as a drinking water source, as, for example, in urban areas where municipalities already have a current source of drinking water and groundwater is not a suitable alternative.

13.6 HYDROGEOLOGICAL REGIONAL MAPPING

The first hydrogeological regional mapping projects carried out in Quebec, by the provincial government (Ministry of Natural Resources), were undertaken during the 1960s (Rivière-du-Loup/Trois-Pistoles area, Saint-Cuthbert, Island of Orleans, Lac Saint-Jean, Rouville–Saint-Hyacinthe). Budget cuts in 1977 meant that no additional regional projects were undertaken until 1995, when the Quebec Ministry of the Environment, the Geological Survey of Canada, the Institut national de la recherche scientifique (INRS-ETE), Laval University and the Regional County Municipality (RCM) of Portneuf carried out and concluded a hydrogeological mapping project involving the surficial granular deposits of the Portneuf RCM. Eight additional hydrogeological regional mapping projects have been concluded since then, including six in the StLL Region completed in 2007–2008 (TechnoRem, 2008, a, b, c, d, e, and f). These mapping projects resulted in the drafting of two hydrogeological mapping methodology guides:

- Surficial Granular Deposits Mapping (Michaud et al., 2008)
- Bedrock Aquifers Mapping (Savard et al., 2008)

Boxes 13-1, 13-2 and 13-4 refer to the mapping of the Portneuf RCM, Chateauguay River Watershed, and the Mirabel area, respectively.

In Fall of 2008, the Ministry of Sustainable Development, Environment and Parks launched two new programs to expand the knowledge about groundwater in Quebec's populated areas. One of the programs involves hydrogeological mapping of aquifers in order to provide a better understanding of their characteristics (quantity, quality and vulnerability), a project which, in turn, could be very useful for aquifer management.

BOX 13-1 REGIONAL COUNTY MUNICIPALITY OF PORTNEUF

Between 1995 and 1998, hydrogeological mapping of granular surficial aquifers was undertaken in the Regional County Municipality (RCM) of Portneuf which is located southwest of Quebec City, on the north shore of the St. Lawrence River, between the Precambrian Shield and the St. Lawrence Valley (Figure 13.32). The map includes about 3,000 km^2 in the southern part of the RCM. This region was selected in order to (1) obtain an understanding of groundwater behaviour in the area's Laurentian Piedmont surficial deposits, (2) determine, on a regional scale, uses made of groundwater in rural and urban communities, and (3) to assess the impacts of human activities on the quality of groundwater flowing through unconsolidated sediments.

The mean annual temperature, taken at 12 meteorological stations in the area over a period of 30 years, is 2.4°C, while mean annual precipitation is as much as 1,190 mm/year. The Laurentian Piedmont unconsolidated sediments include large granular unconfined aquifers whose distribution and thickness are controlled by the stratigraphy and geometry of surficial deposits as well as by the subsurface bedrock underneath. Although complex episodes of Quaternary periods succeeded one another over 200,000 years, the current deposits are largely associated with the retreat of the last ice cover, which was followed by the marine episode of the Champlain Sea. All of those phenomena shaped the current landscape of the area. Granular deposits of various origins (deltaic, alluvial, glaciofluvial),

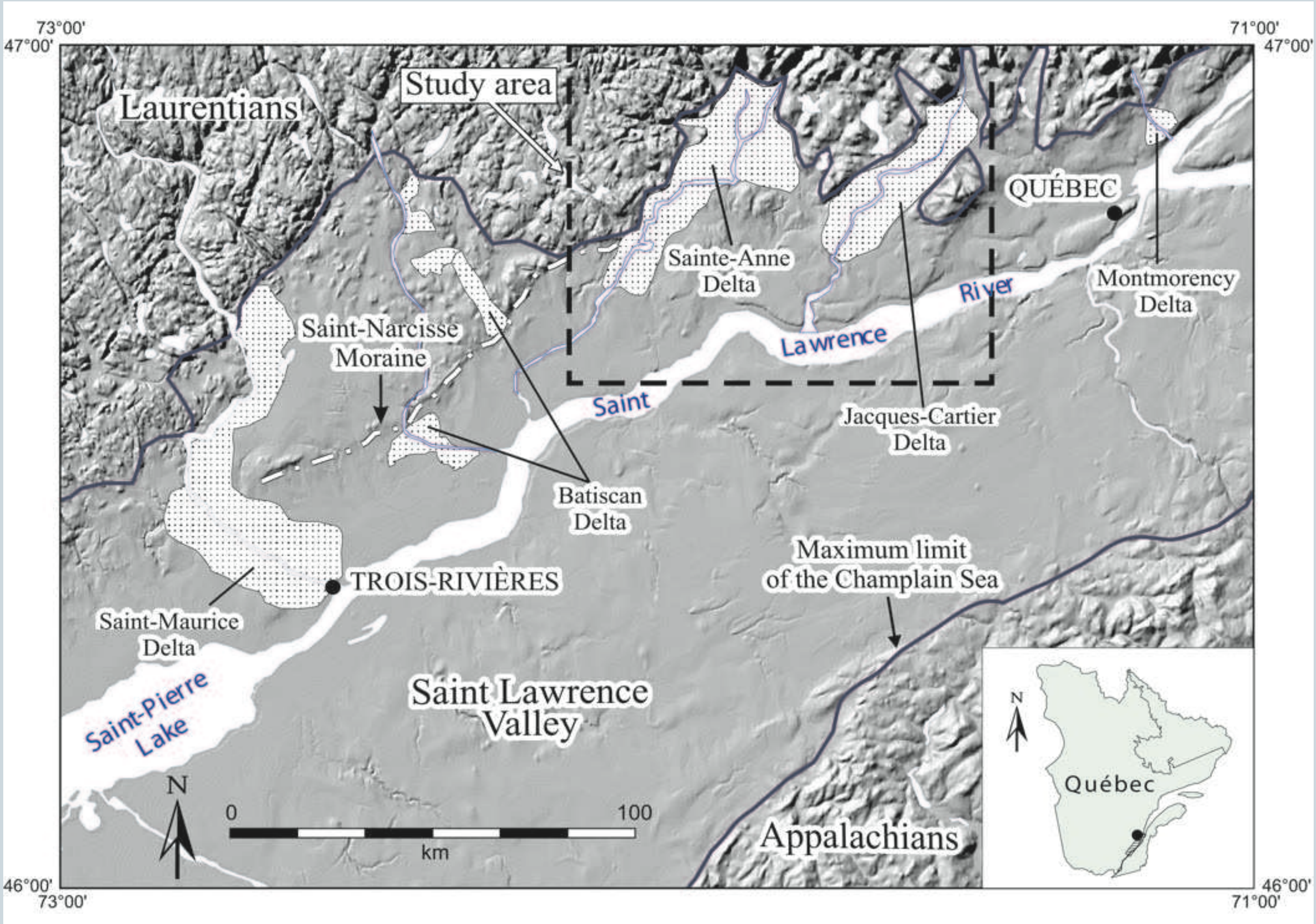


Figure 13.32 Location of Portneuf RCM study area (Fagnan et al., 1999).

which can be more than 70 metres thick along the Ste. Anne and Jacques Cartier rivers, have been mapped. Another important feature is the St. Narcisse moraine, which is close to the Precambrian terrain limit, and crosses the area in a northeasterly direction. This unit is below the topographic marine invasion limit and is of great hydrogeological interest, particularly where covered by glaciomarine sediments.

Over the years, with the deposition of those unconsolidated sediments, small watersheds have been created, linked to the main rivers (Ste. Anne and Jacques Cartier), so that today 13 separate aquifers corresponding to those watersheds have been identified, a matter of great importance for groundwater management issues.

Figure 13.33 illustrates the regional groundwater flow regimes within the granular surficial deposit aquifers occurring in the area under study.

Groundwater accounts for 85% of the total

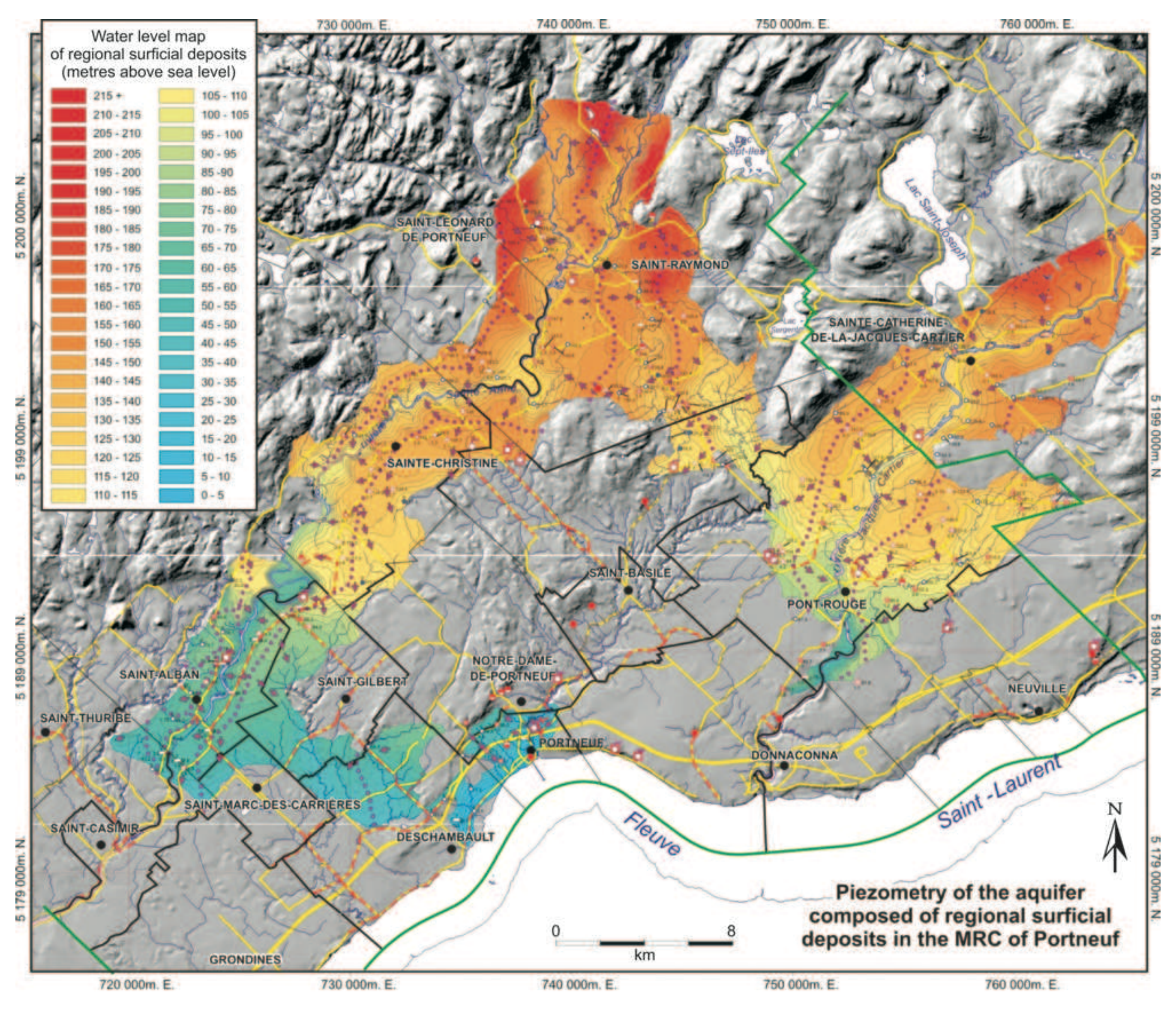


Figure 13.33 Water level map of regional surficial deposits aquifers in the MRC of Portneuf.

amount of drinking water consumed in the area under study. Groundwater is also used on a large scale for agricultural purposes.

Groundwater quality is normally good in these unconsolidated strata, but, because there is no confining bed overlying the sediments, they are more vulnerable to contamination related to human activities (private septic tanks, fertilizers, pesticides, hydrocarbon spills, etc.). Groundwater flowing through these sediments is low-mineralized with pH values usually below 7.0, and, sometimes, below the lower limit standard of 6.5. The low pH values notwithstanding, natural groundwater usually meets all Canadian drinking water quality standards. Because the groundwater in this area is highly vulnerable, managers and scientists have raised major concerns related to intensive fertilizer use, which increases the nitrate content to above the 10 mg/L N standard, and, sometimes, as high as 19 mg/L N within the boundaries of four municipalities of the study area (Paradis, et al., 1991). Notices not to consume water with concentrations above 10 mg/L N have been sent to local residents faced with this problem. Meetings and/or discussions have been held for the purpose of reducing the amount of fertilizer used and improving groundwater quality; these information sessions, attended by potato producers and citizens committees, have been successful. Aesthetic issues are usually of no concern to people using water from these aquifers; iron and manganese have sometimes been detected in the area's water, but not on a widespread basis.

When compared to groundwater from the surficial granular sediments, the quality of groundwater from bedrock units is usually of lower quality, often exceeding Canadian drinking water quality standards for TDS and fluoride (mostly from the Utica and Trenton Groups). Additionally, pH values for this water are largely basic, often exceeding the upper limit of 8.5. The natural presence of volatile organic components (BTEX) has been reported in three wells installed in the Utica and Trenton Groups. And finally, a mixture of high amounts of dissolved organic carbon, phosphorus and ammonium has been detected in samples from three other wells, also installed in the Trenton and Utica Groups.

As is the case with unconsolidated aquifers, aesthetic issues are usually of no concern to people using water from these bedrock aquifers.

BOX 13-2 CHATEAUGUAY WATERSHED

A study was carried out in the Chateauguay River Watershed between 2003 and 2006. This is a transboundary watershed of approximately 2,500 km^2, 57% of which is located in Quebec, and 43% in the State of New York. The watershed is located in the southwesternmost part of the St. Lawrence Lowlands Region. Because of its location in the province, the mean annual temperature recorded in 10 meteorological stations is one of the highest (6.3°C) for the StLL hydrogeological region. Precipitation ranges between 918 mm/year (Hemmingford station) and 1,039 mm/year (Franklin station) for the same period. Figure 13.34 shows the location of the Chateauguay watershed.

There are two main types of bedrock aquifers in the watershed: sandstone aquifers (Potsdam Group) and dolomite/limestone aquifers (Beekmantown and Chazy Groups). In both cases, groundwater flows mainly along the bedding planes; wells drilled in these aquifers can yield large volumes of water for various requirements. The municipality of Huntingdon uses surface water for its drinking water needs, however all other communities, within the study area, use groundwater for their consumption.

Figure 13.35 charts regional groundwater flow regimes in bedrock aquifers occurring in the Chateauguay River watershed.

It has been estimated that 310 Mm^3 (million cubic metres) of groundwater are used every year to meet water use requirements in the Canadian portion of the watershed. The pie chart in Figure 13.36 depicts distribution of groundwater used in the area. On a regional scale and, assuming a mean regional porosity of 1%, this volume represents 0.2% of the total groundwater reserve in the basin of approximately 18,680 Mm^3 A recharge volume of 262 Mm^3/year, occurring mainly in the south half of the basin, has been estimated to represent 14% of groundwater in storage. The study also found that the drawdown generated by groundwater pumping was on the order of 1.6 metres, while the annual fluctuation of the aquifer was in the order of 2.1 metres. This data indicates the bedrock aquifers of the study area are currently in safe condition (hydrodynamic equilibrium) and that, at present, there is no over-pumping that might endanger the aquifers' sustainability. It is always possible, however, that a situation of groundwater overuse could occur locally, particularly if a community of groundwater users pump large volumes of groundwater for its individual needs.

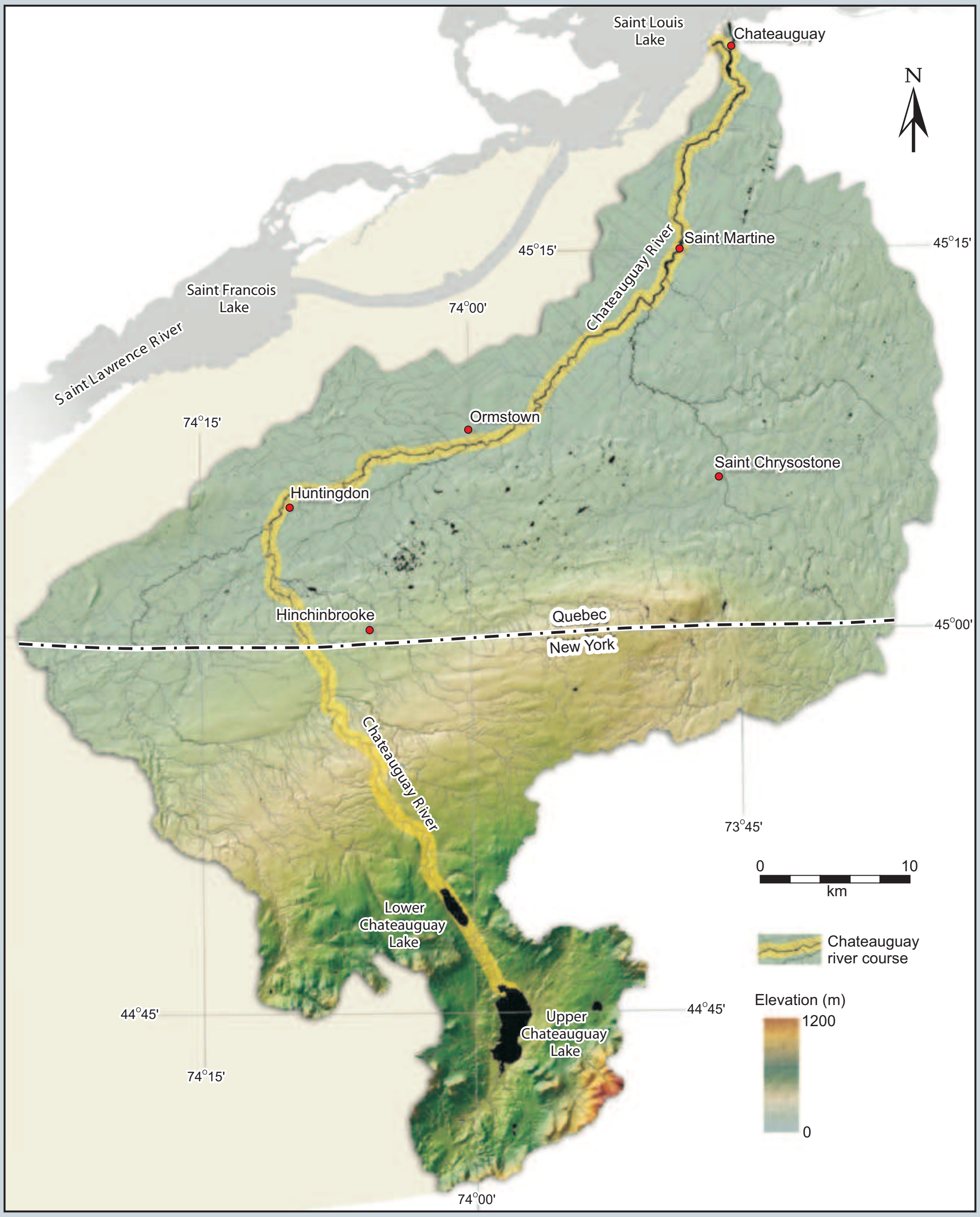


Figure 13.34 Location of Chateauguay River Watershed (from Côté et al., 2006).

Groundwater quality is typically good in the

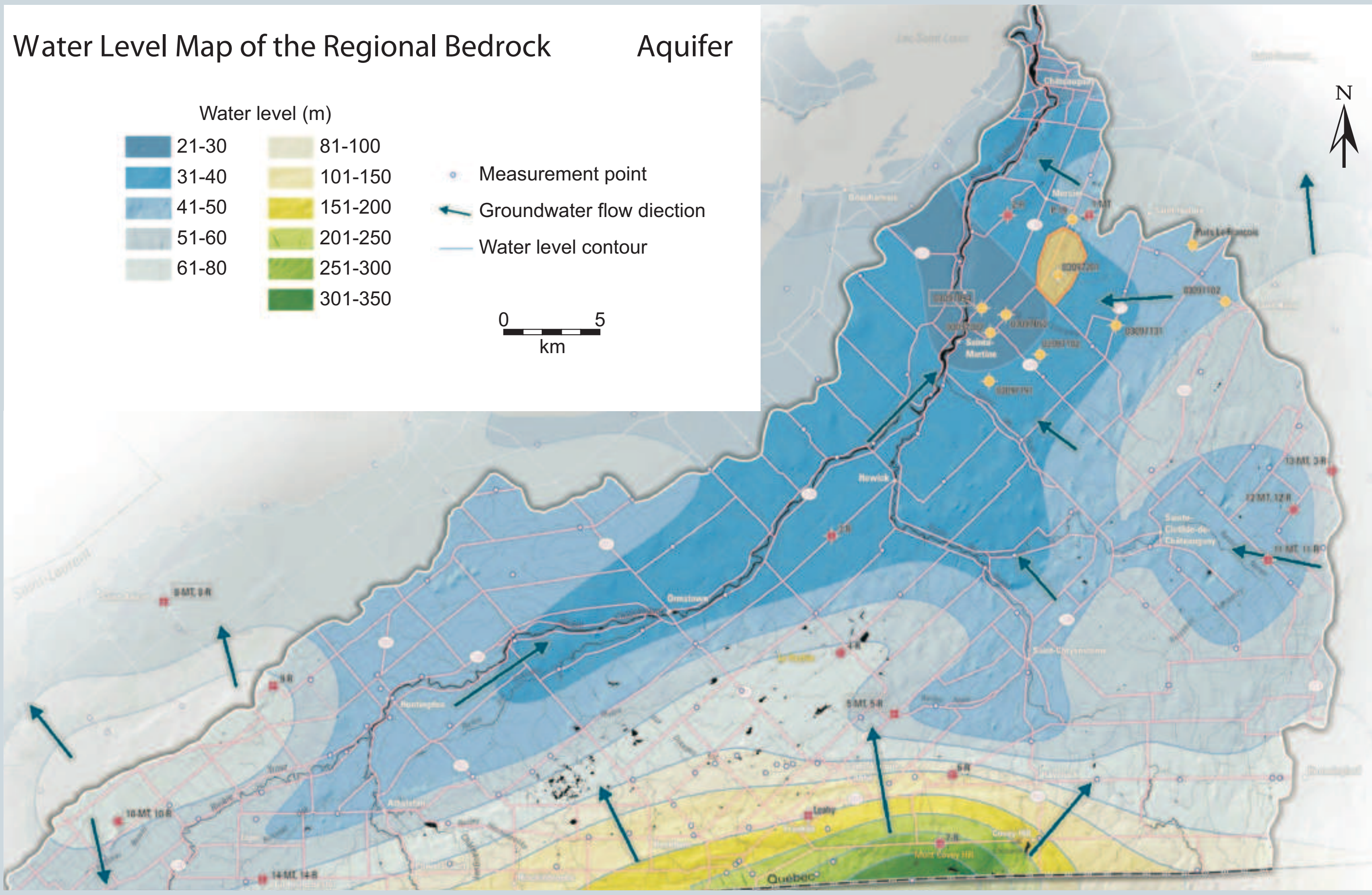
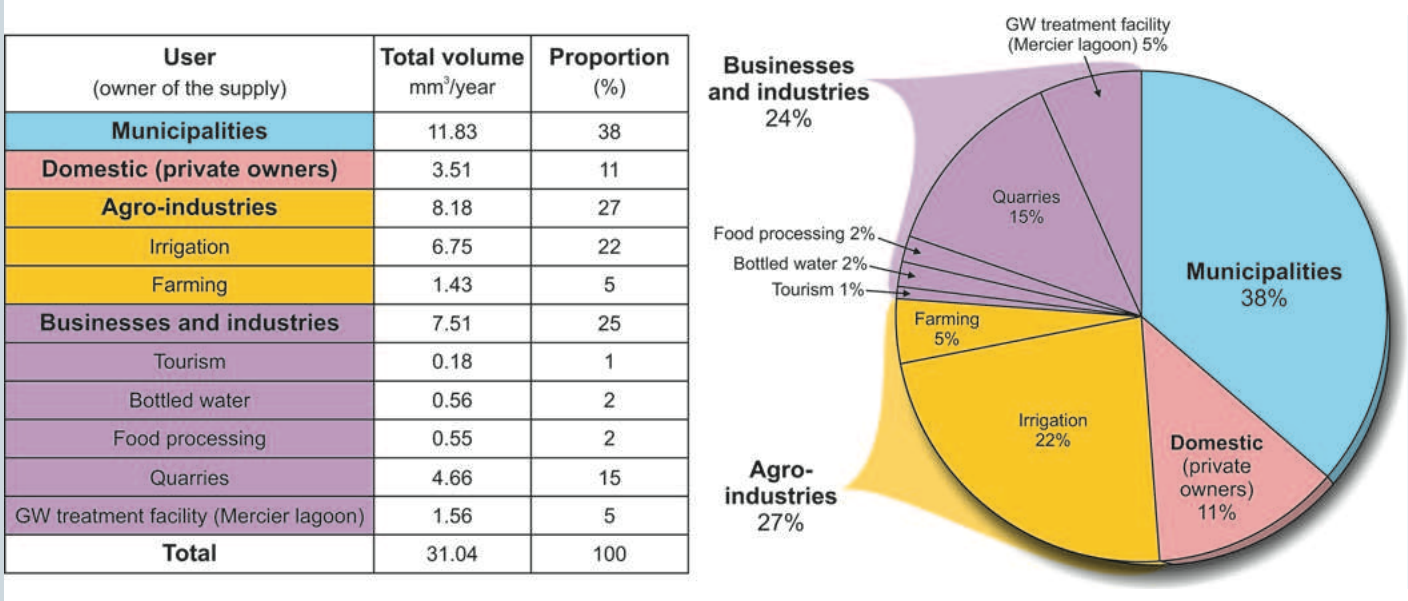


Figure 13.35 Water level map of the regional bedrock aquifer in the Chateauguay River Watershed.

bedrock aquifers of this study, because human activities are not a threat to the integrity of the resource. Except for very local problems with respect to fluoride and barium, which are of natural origin, all of the analysed samples meet Canadian drinking water quality standards. Aesthetic issues, however, arising from high concentrations of iron and manganese, hardness and dissolved solids are a factor in nearly the entire watershed and pose huge problems for private



User (owner of the supply)	Total volume mm³/year	Proportion (%)
Municipalities	11.83	38
Domestic (private owners)	3.51	11
Agro-industries	8.18	27
Irrigation	6.75	22
Farming	1.43	5
Businesses and industries	7.51	25
Tourism	0.18	1
Bottled water	0.56	2
Food processing	0.55	2
Quarries	4.66	15
GW treatment facility (Mercier lagoon)	1.56	5
Total	31.04	100

Figure 13.36 Groundwater use.

well owners. High sodium and chloride content has been also reported in a few wells along the Chateauguay River, where there are larger amounts of marine clays.

Surficial granular deposits are not used for major consumption, but are used instead for private shallow wells, as well as spring catchment.

BOX 13-3 MERCIER LAGOONS

The geological characterization of Mercier Lagoons' site, notes that these water bodies are located just west of a valley filled with a very permeable sand and gravel unit (esker), more than 30 metres thick, in the middle of a glacial till depression till that plays a key role in the recharge of the regional bedrock aquifer. The till is absent at the centre of this valley, such that the granular unit is directly in contact with the underlying fractured Beekmantown dolomite formation. These openings allow groundwater to flow from the esker to the bedrock, and explain the contamination of those wells which tap the rock formation for their water needs. Figure 13.37 depicts the developed conceptual model of the lagoon sites and the location of the groundwater treatment unit downgradient from the lagoons.

Groundwater sampling campaigns for the area began in 1974, but, because phenol was the main chemical indicator used in this type of pollution and since it is now known that natural hydrocarbons are found in the underlying bedrock, the area of the site plume was overestimated. Since those initial samplings, and with this new knowledge

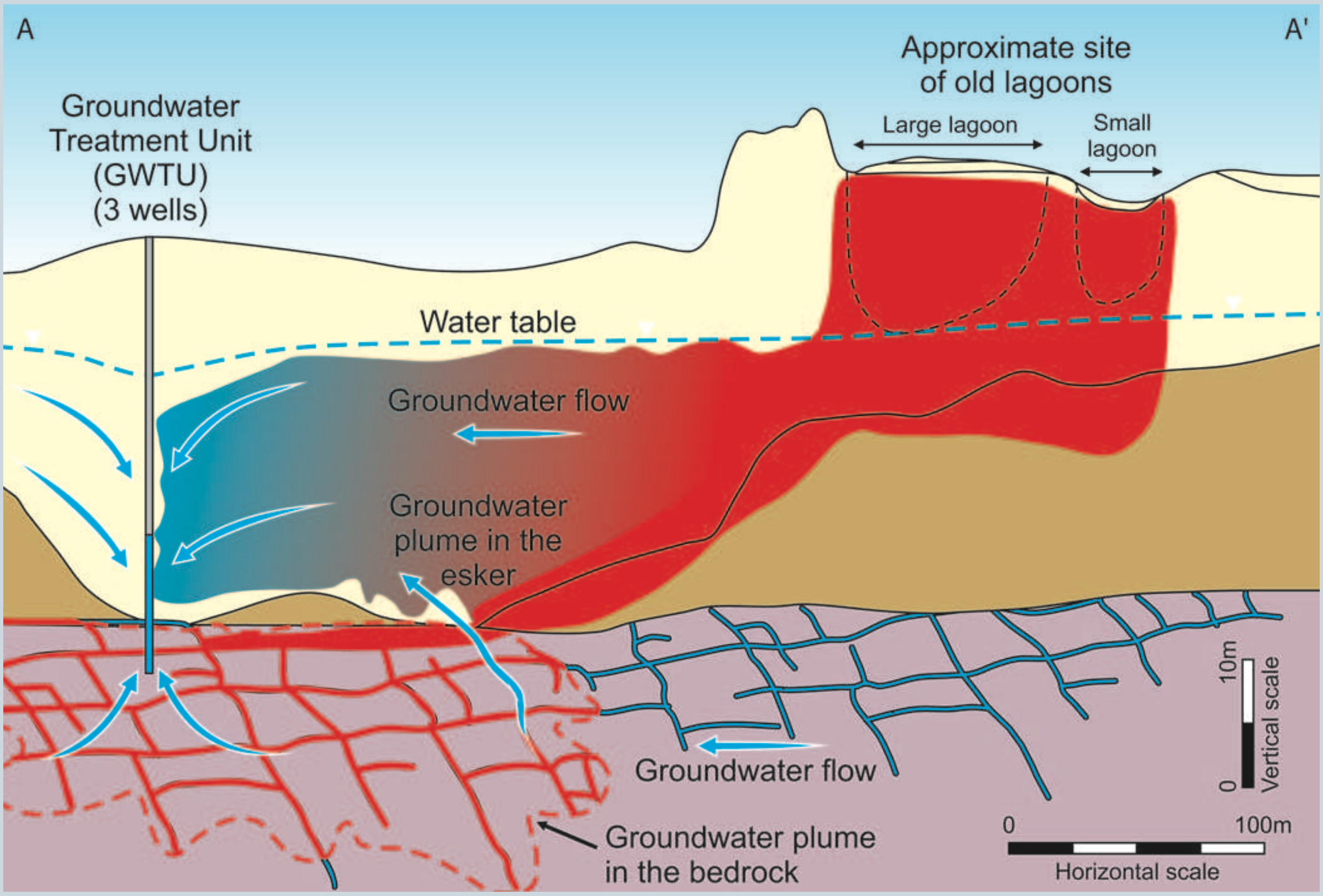


Figure 13.37 Conceptual model of the City of Mercier lagoons site showing dissolved contaminants plume and the GWTU.

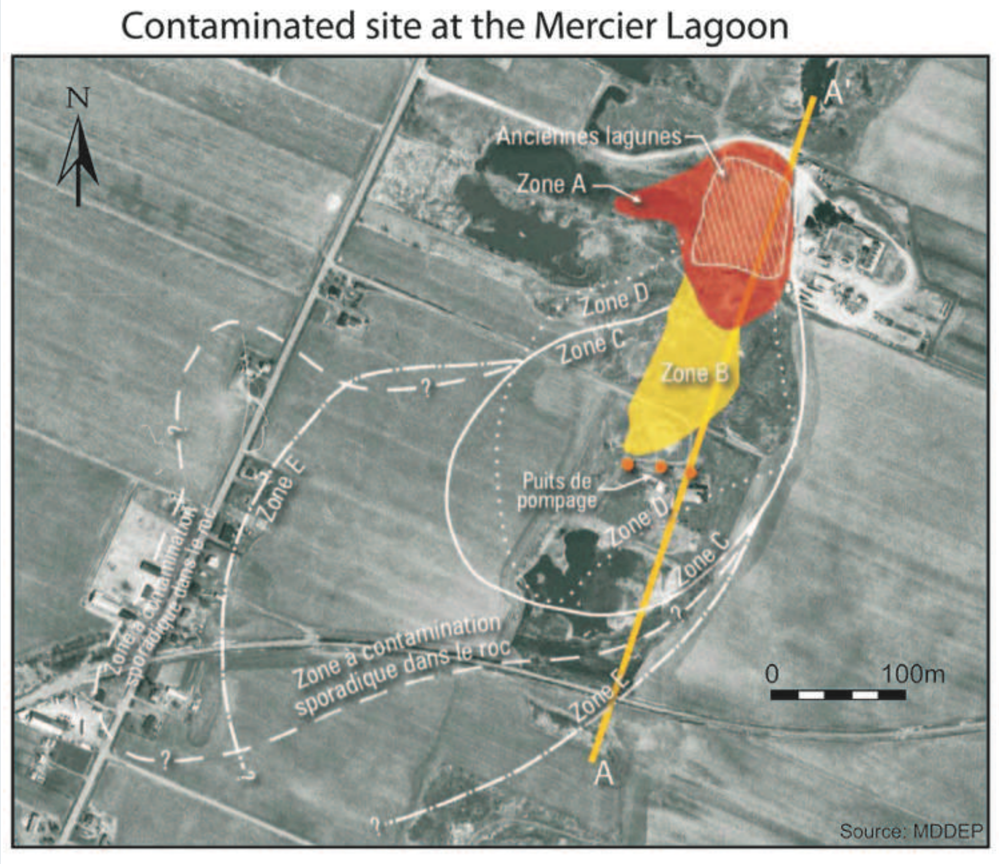


Figure 13.38 Plan view of the contaminated plume in the Mercier Lagoons (Source: Côté et al., 2006).

and the improvement of laboratory analytical methods, other chemical indicators have been used. The monitoring methodology was modified to become systematic collecting of groundwater samples from 15 observation wells comprising the Mercier groundwater-sampling network. This contamination has been monitored twice a year (May and October) since 1995 to check the efficiency of the GWTU. Figure 13.38 shows the extent of the contaminated plume in the area investigated.

BOX 13-4 MIRABEL AREA

This study was carried out between 1999 and 2002 in an area of about 1,500 km^2 northwest of Montreal to obtain a better understanding of groundwater behaviour in the fractured bedrock system aquifers of southwestern Quebec. Figure 13.39 (Savard et al., 2002) locates the study area.

The mean monthly temperature recorded in 15 meteorological stations during a 30-year period (1979–2000) ranged between –11.4°C (January) and 20.9°C (July). During the same period, the area recorded 1,047 mm of precipitation ranging from 929 mm to 1,129 mm.

Bedrock aquifers in the area are located in the Potsdam, Beekmantown, Chazy, Black River and Trenton Groups. Regional groundwater flow was found to occur in two main hydrostratigraphic units within the first 40 metres below the ground surface. The first, and most permeable, is a sand-gravel unit mixed with highly fractured and altered rocks within the first 10 to 20 metres directly beneath the ground surface. Although the distribution of that unit is not uniform throughout the area, large volumes of water can be obtained where the unit is present. The second unit, located beneath this mixed unit is associated with the fractured zones (bedding planes, solution channels) of various types of rock, extending to a depth of some 40 metres. Field tests carried out below that level revealed a substantial decrease in permeability, which would prevent easy extraction of large groundwater volume.

Figure 13.40 illustrates the regional groundwater flow regimes in the bedrock aquifers of the study area.

The volume of groundwater extracted from the aquifer annually to meet various requirements in the study area can be as high as 15 Mm^3, while the estimated recharge volume is 75 Mm^3/year (Paradis et al., 2002). Figure 13.41 shows the distribution of groundwater used in the area. On a regional scale, and assuming a mean regional porosity between 1% and 5%, the estimated volume of the total groundwater reserve across the area is between 1,220 Mm^3 and 6,100 Mm^3; consequently, groundwater use corresponds to 0.2% to 1.6% of groundwater in storage.

As Figure 13.41 (Nastev et al., 2002) illustrates, there is substantial groundwater pumping in quarries; this accounts for a larger volume of water than the amount used for drinking water (37% vs. 27%). In the Saint-Eustache quarry (Beekmantown Group), the pumping of groundwater generates a drawdown of 40 metres. Nevertheless, this study indicated that the average drawdown generated by groundwater pumping across the area is 0.8 metre, while the annual fluctuation of the aquifer is in the order of 1.6 metres. This data indicates that the bedrock aquifers of the study area are currently in

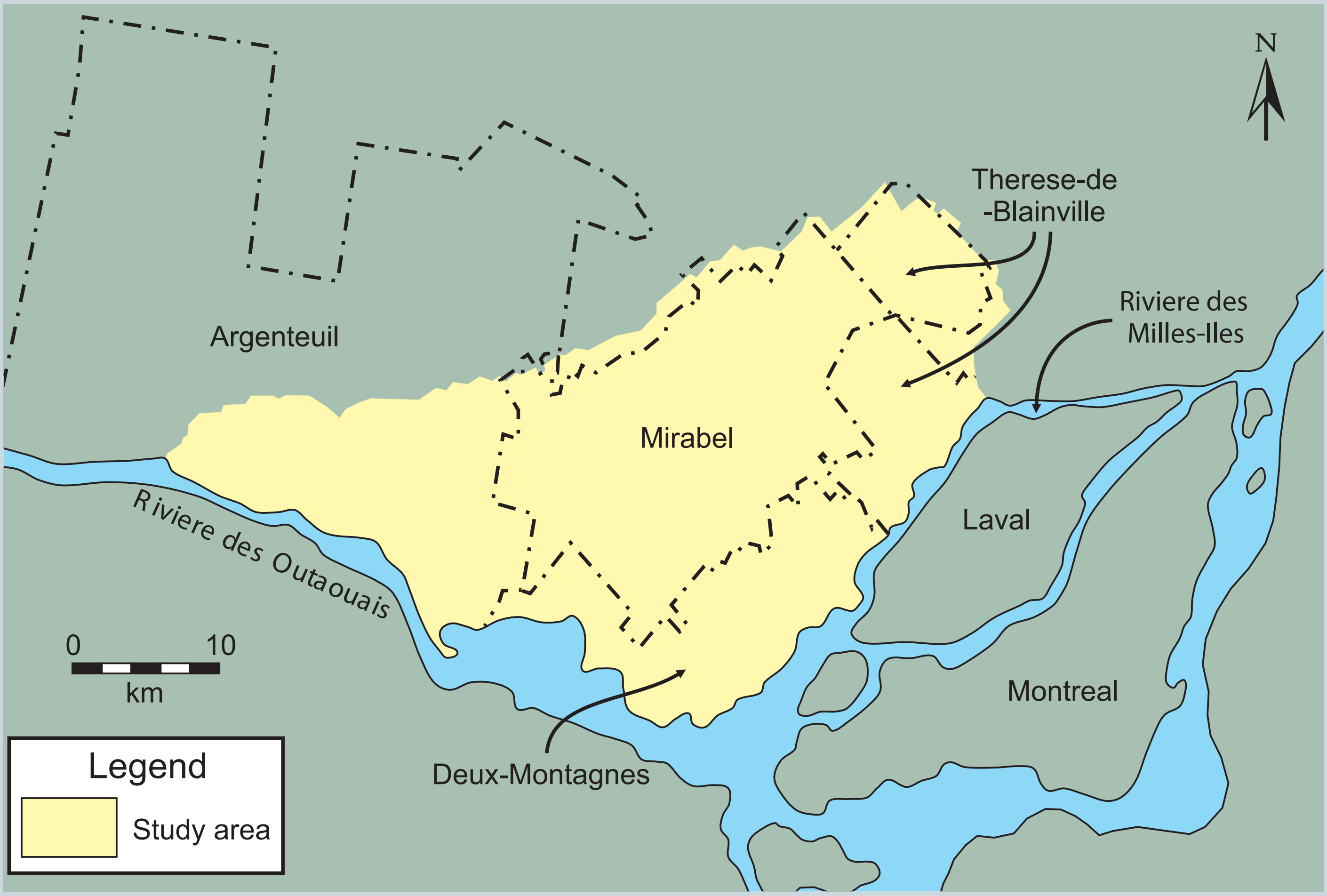


Figure 13.39 Location of study area at Mirabel (from Savard et al., 2002).

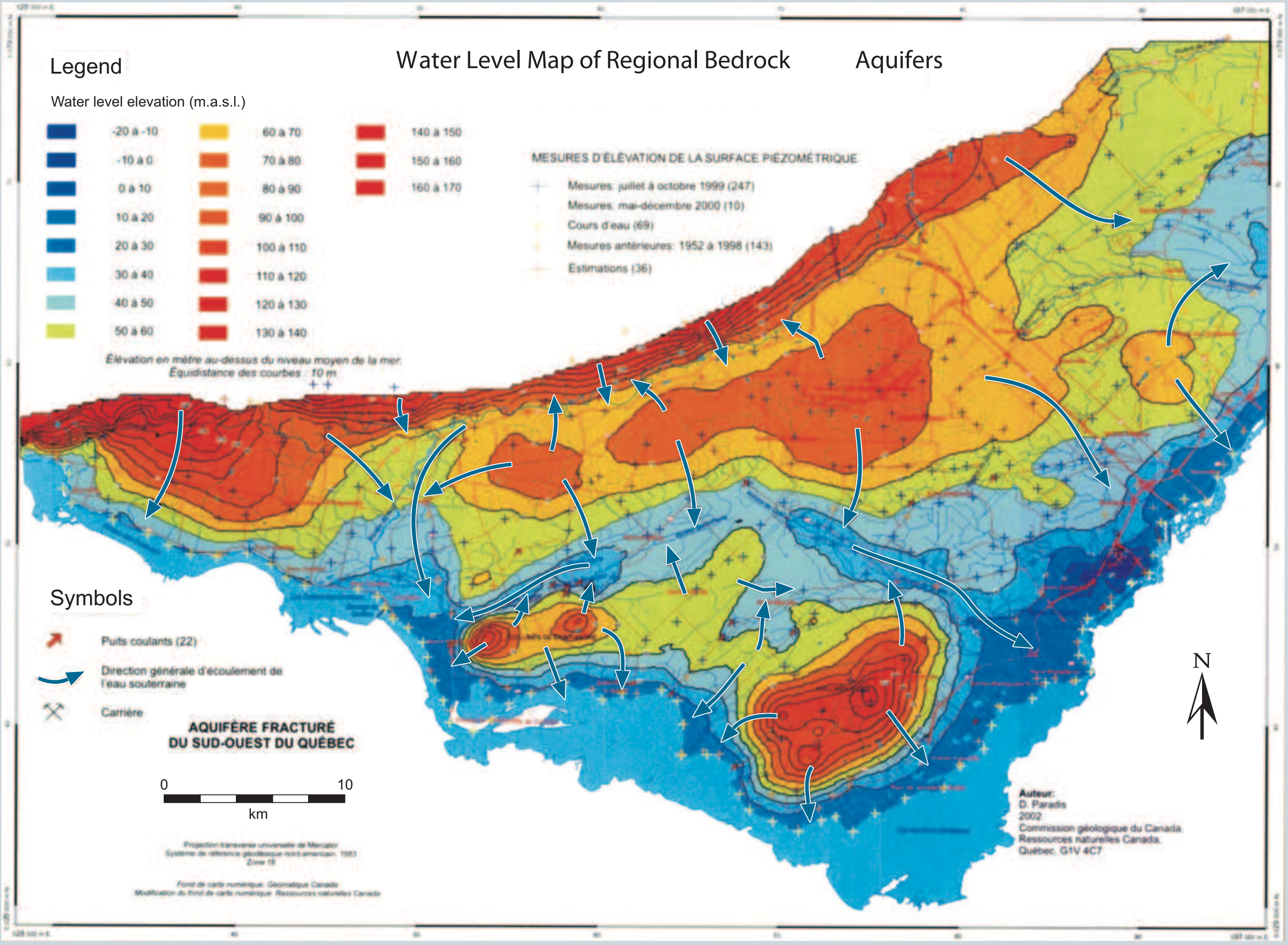


Figure 13.40 Water level map of regional bedrock aquifers (adapted from Paradis et al., 2002) .

User	Groundwater withdrawal			
	Volume m³/year	(%)	Total volume m³/year	(%)
Municipalities (aqueducts)	3,923,249	26.5	6,143,419	41.5
Domestic (private owners)	2,220,170	15		
Irrigation	1,217,475	8.2	2,529,833	17.1
Farming	1,312,358	8.9		
Golf fields	84,999	0.6	6,121,279	41.4
Bottled water	504,576	3.4		
Quarries	5,531,704	37.4		
Total	14,794,531	100	14,794,531	100

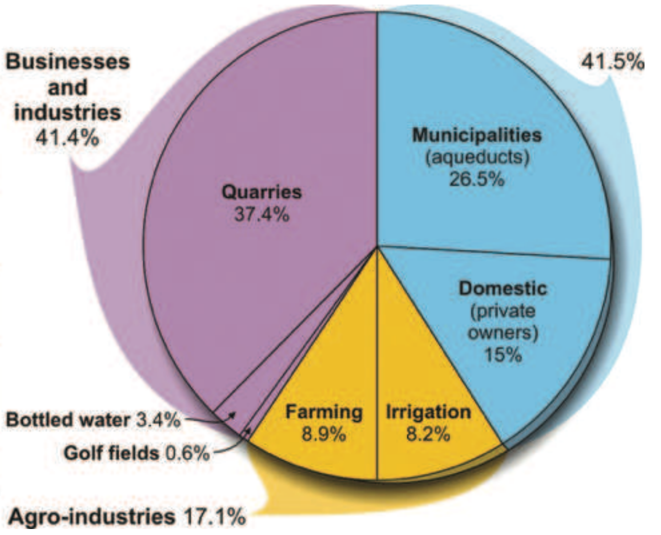


Figure 13.41 Groundwater use (Nastev et al., 2002).

safe condition, and that there is no over-pumping which might jeopardize their sustainability. Again, as above, a situation of groundwater overuse may occur locally, should a community of groundwater users pump large volumes for its individual needs.

Groundwater quality is usually good in these aquifers because human activities do not pose a threat (except for a case of nitrates which exceeds the limit of 10 mg/L N at one site only). Barring the very local problems associated with high fluoride and barium of natural origin and associated with the Potsdam, Beekmantown, Chazy and Trenton Groups (fluoride) and the Beekmantown and Chazy Groups (barium), all of the analysed samples within this study meet Canadian drinking water quality standards. Aesthetic issues arising from high concentrations of iron and manganese, hardness, sulphides and dissolved solids remain a factor across most of the study area, posing huge problems for private well owners. High sodium and chloride content has also been reported here and there in the study area: this is related to the presence of marine clays of the Champlain Sea.

CHAPTER 14

APPALACHIANS

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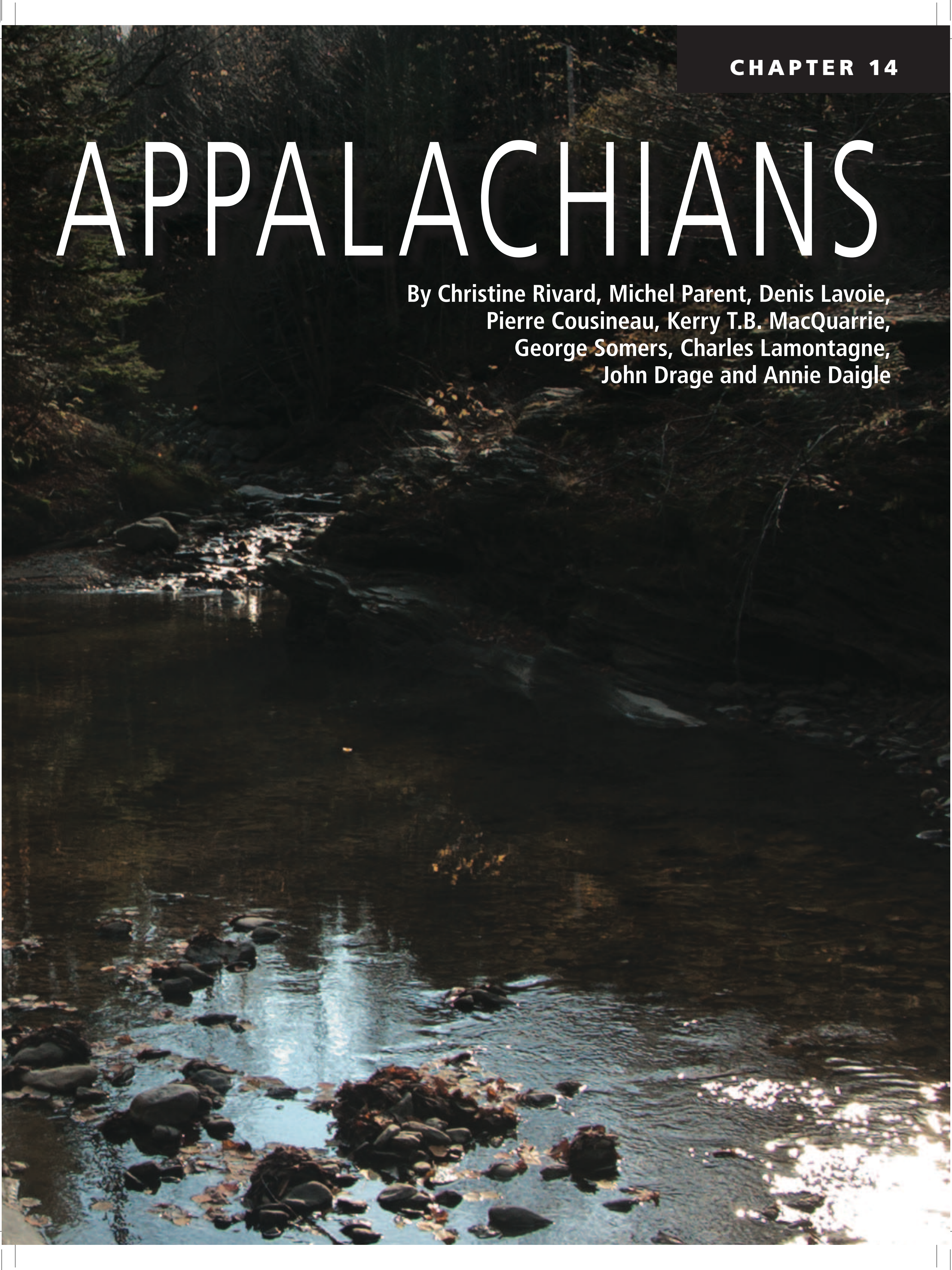

14.1 DESCRIPTION OF THE APPALACHIAN REGION

The Appalachian physiographic region consists of a system of mountains and intervening uplands and lowlands, 160 to 480 km wide, extending from Newfoundland to Alabama (United States) 2,400 km to the southwest. The Canadian Appalachians comprise the three Maritime provinces (New Brunswick, Nova Scotia, and Prince Edward Island), most of the Island of Newfoundland, as well as the southeastern part of Quebec (Figure 14.1). The Quebec portion includes the south shore of the St. Lawrence River (including Estrie, Chaudière-Appalaches, Bas St-Laurent, and Gaspésie regions) and Îles-de-la-Madeleine.

The Canadian Appalachians cover a land area of 309,000 km^2. They are an ancient and eroded mountain range with rocks ranging in age from Neo-Proterozoic (Late Precambrian, 1,000 to 540 Ma; Lavoie, 2008) to Cretaceous (144 to 66 Ma; Pe-Piper and Jansa, 1987). Metamorphism is typically low grade and concentrated in the central domain of the chain. The Appalachians generally consist of elongated belts of folded and faulted, continental to shallow and deep marine sedimentary rocks, with locally intercalated tectonic slivers of ancient ocean floor, accessory plutons and volcanic rocks. The surficial sediment cover consists largely of transported sediments formed during Quaternary (2.6 Ma to modern) glacial/deglacial episodes. As a result, glacial sediments, mainly tills, are ubiquitous. The stratigraphy and architecture of these Quaternary sediments are often very complex, due to repeated erosional and depositional phases that

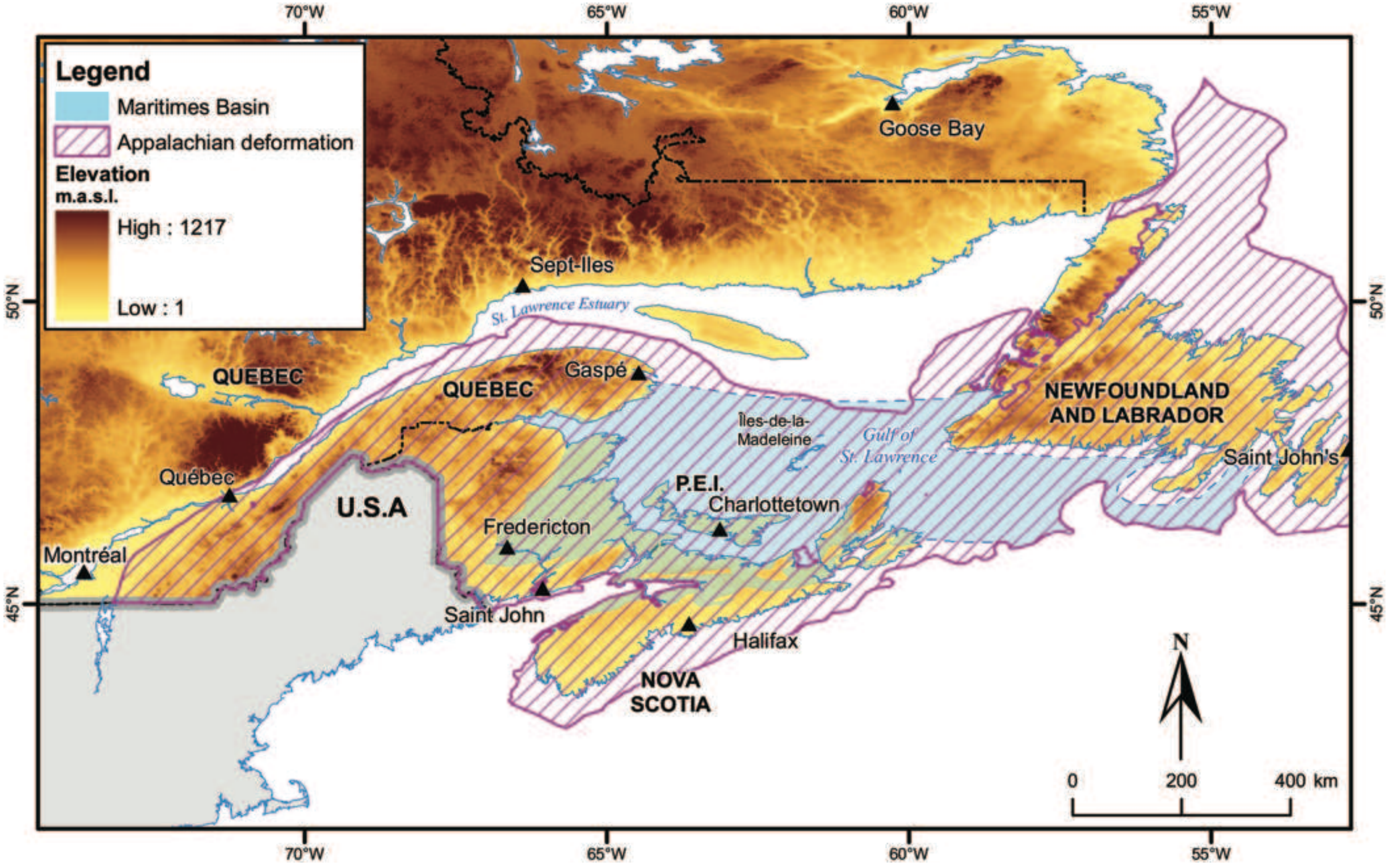

Figure 14.1 Location of the Canadian Appalachians and Maritimes Basin regions showing topography. Hatching lines illustrate the Appalachians deformed domain.

occurred during glacial advances and retreats, and also to the topographic context.

14.1.1 Physiography and hydrography

The Appalachian Mountains consist of ancient folded rock formations eroded into low, rounded mountains, dissected by valleys, and interrupted by lowland areas developed on weaker rock formations (Britannica, 2006). Much of the land in the Canadian Appalachians consists of hilly uplands with intervening, locally steep-sided valleys. Major highland areas include the Shick-shock Mountains (elevation 1,200 m) and Notre Dame Mountains (elevation 1,070 m) in Quebec, and the Long Range Mountains (elevation 800 m), as well as a dissected plateau in Newfoundland. The uplands in New Brunswick and Nova Scotia are in general lower in elevation, while Prince Edward Island is essentially a lowland area. The highest elevations for New Brunswick, Nova Scotia and Prince Edward Island are, respectively, 817 m (Mount Carleton), 532 m (Cape Breton Highlands), and 142 m (Queens County). The region's lowland areas extend mainly along the seacoast and the major rivers. The topography of the Canadian Appalachians could be described as undulating to relatively flat, with most (approximately 75%) of the region lying between sea level and 300 m (see Figure 14.1). Elevations above 600 m represent only 1% of the land area, and are mainly located in Quebec and Newfoundland.

The Canadian Appalachians are generally drained by a hydrographic network comprised of branching watercourses with a dendritic drainage pattern, common in environments characterized by uniform erosion. These inherited Tertiary networks were greatly "deranged", throughout most of the region, by successive episodes of glacial erosion and deposition. Some of the area's major rivers include the Saint John and Miramichi in New Brunswick; Saint-François, Chaudière, Temiscouata and Matapedia in Quebec; the Cornwallis, Annapolis, St. Mary's, Shubenacadie and Margaree in Nova Scotia; and the Main in Newfoundland. Major rivers in Prince Edward Island are tidal along a significant portion of their lengths, representing drowned river valleys: freshwater portions of these systems are usually relatively short and shallow. Newfoundland has a significant percentage of wetlands, covering 18% of the island, while almost 7% of New Brunswick is wetlands. It has been estimated that since Europeans began to settle here in the early 17th century (KCEDA, 2000), some 80% of the original salt marshes in the Annapolis Valley, Nova Scotia, and have been reclaimed to create agricultural land.

14.1.2 Climate

The four Atlantic Provinces have a humid continental climate and are subjected to the influence of both continental and oceanic air masses. Because of the region's relatively low relief, distance to the sea is often the major influence on local weather. Coastal areas are cooled in the summer and warmed in the winter by the ocean; typically, the warmest and coldest months are August and February, respectively. Winter ice cover in the Gulf of St. Lawrence, however, may reduce the ocean's warming influence to some degree, especially in Prince Edward Island. Proximity to the ocean generates a fairly mild and humid climate, with sudden temperature changes, high humidity (often >85%), and frequent freeze-thaw cycles during winter. Snowfalls are often heavy, with accumulations in excess of 50 cm during a single storm not uncommon. Inland parts of this region are shut

TABLE 14.1 CLIMATIC CONDITIONS IN THE APPALACHIAN REGION

PROVINCE	No. OF STATIONS	MEAN TOTAL PRECIPITATION (MIN/MAX)	MEAN ANNUAL TEMPERATURE (MONTHLY MIN/MAX)
New Brunswick	18	1172 mm/yr (1033/1531)	4.8ºC (–10.2/18.6)
Newfoundland	18	1188 mm/yr (852/1584)	3.1ºC (–9.8/15.7)
Nova Scotia	25	1398 mm/yr (1054/1700)	6.3ºC (–5.7/18.3)
Prince Edward Island	8	1143 mm/yr (1046/1241)	5.4ºC (–7.9/18.6)
Quebec (incl. 4 regions)	16	1112 mm/yr (963/1267)	4.5ºC (–11.7/18.9)

Source: http://climate.weatheroffice.ec.gc.ca/index.html

off from the ocean's tempering influence (Brown, 1967). Thus, a humid continental climate prevails, characterized by variable weather patterns, coupled with a fairly large annual range of mean monthly temperatures (about 25°C).

The Appalachian region is one of the wettest in Canada; here, the warm moisture-laden air masses, moving in from southern latitudes, are constantly meeting cold air masses descending from the northern interior (Brown, 1967). Annual total precipitation (rain and snow) varies between 850 and 1,700 mm, with an average, over the study area, of 1,150 mm, except for Nova Scotia, where the average is around 1,400 mm. A substantial amount (20%–30%) of precipitation occurs as snowfall. Mean monthly air temperatures vary between 16ºC and 19ºC in the warmest months and between –12ºC and –6ºC during the coldest months. Table 14.1 summarises the climatic conditions, by province, of several representative weather stations within the Appalachian region. Newfoundland has the coolest weather, and Nova Scotia the warmest, with the most precipitation.

14.1.3 Population and groundwater use

The total population in the Canadian Appalachian region is 3.3 million (i.e., 11% of the total Canadian population): about half the population lives in urban areas. The population density is, on average, 18/km^2. Residents are mainly concentrated along the coastline, and in inland valleys close to major rivers. Large portions of the Appalachians (mainly inland) are forested; agricultural lands generally represent less than 7% of the total land area. These agricultural percentages are highly variable, however, being much higher (46%) in Prince Edward Island, and much lower in Newfoundland and Labrador (0.1%[1]). Farms are relatively well distributed over the land area, except in certain areas such as Prince Edward Island and in Nova Scotia's Annapolis Valley, which have significant concentrations of agricultural activity.

Groundwater is an important source of water supply within the Appalachian region. Indeed, on a provincial basis, between 34% and 100% of the population relies on this resource for potable water, either from municipal or private wells (see Table 14.2). In rural areas, these percentages are higher. In Kings County, Nova Scotia, for example, 99% of the residents draw their drinking water from groundwater (KCEDA, 2000). In Prince Edward Island and Îles-de-la-Madeleine, 100% of the population relies on groundwater. However, 90% of the population of Îles-de-la-Madeleine is supplied by municipal systems. In Prince Edward Island, which has 12 municipal supplies, this

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[1] The percentage is unknown for the island of Newfoundland.

TABLE 14.2 PERCENTAGE OF THE POPULATION SUPPLIED BY GROUNDWATER

PROVINCE	% OF THE POPULATION
New Brunswick	67%
Nova Scotia	46%
Prince Edward Island	100%
Newfoundland	34%
Quebec (Bas St-Laurent=48%; Estrie=40.7%; Gaspésie=48%; Îles-de-la-Madeleine=100%; Chaudière-Appalaches=52.8%)	≈ 48%*

Source: Groundwater use in Canada, West Coast Environmental Law, November 2004, http://www.wcel.org/sites/default/files/publications/Groundwater%20Use%20in%20Canada.pdf and http://www.mddep.gouv.qc.ca/eau/regions/.
* As a comparison, the percentage is 28% for the entire province of Quebec.

percentage drops to 45%. In New Brunswick, 56 out of 70 (80%) municipal water supply systems use groundwater in some form and 32 additional municipalities rely on groundwater from private wells. In Newfoundland, most groundwater systems are small, serving 5–40 houses.

Some of the larger municipal groundwater supplies within the study area include Sydney, Oxford, Amherst, Kentville, and Wolfville in Nova Scotia; Lac-Mégantic, St-Gédéon-de-Beauce, and Rivière-du-Loup in Quebec; Fredericton, Miramichi, Sackville, and Sussex in New Brunswick; Charlottetown and Summerside in Prince Edward Island; and Saint John's and Stephenville in Newfoundland. Several municipalities use a combination of surface water and groundwater.

14.2 GEOLOGICAL CONTEXT

14.2.1 Bedrock

14.2.1.1 Geological and structural settings

Rock units of the Appalachian geological province have been classified according to Williams' work (1979). His proposal includes zones, belts, and basins defined on the basis of rock unit ages and orogenic phases (see Figure 14.2). Rock units of Cambrian and Ordovician age are grouped into zones formed during continental rift and drift, coupled with an initial oceanic closure which produced the Taconic Orogen. Rocks of Silurian and Devonian ages are grouped into belts formed initially as successor basins following the Late Ordovician Taconic Orogeny. The Devonian period was a time of major accretion events, with the Early Devonian Acadian Orogeny (accretion of Avalonia to Laurentia) and the Late Devonian Neo-Acadian Orogeny (accretion of Meguma to Laurentia). Rocks units of Carboniferous and Permian ages are grouped into basins which originated as successor basins, later evolving into tectonically active basins, formed between the Neo-Acadian Orogeny and the Alleghenian Orogeny (this latter resulting in the assembly of the supercontinent Pangea).

Cambrian and Ordovician tectono-stratigraphic zones are believed to represent five distinct former paleogeographic areas that evolved during those geological periods. These zones, from northwest to southeast, are (1) Humber zone, relict of the former rift-passive-convergent margins of Laurentia (e.g., ancestral North America), (2) Dunnage zone, relict of the Iapetus oceanic basin, (3) Gander zone, which contains sediments partly similar to those of the Humber zone, and interpreted as the continental margin of a far travelled terrane, (4) Avalon zone, a collage of smaller blocks originating from the other side of Iapetus Ocean, and (5) Meguma zone, a fragment of the continent Gondwana (Figure 14.2).

The Taconic and Acadian Orogenies resulted from mostly orthogonal collisions producing both external and internal zones that differ in the degree

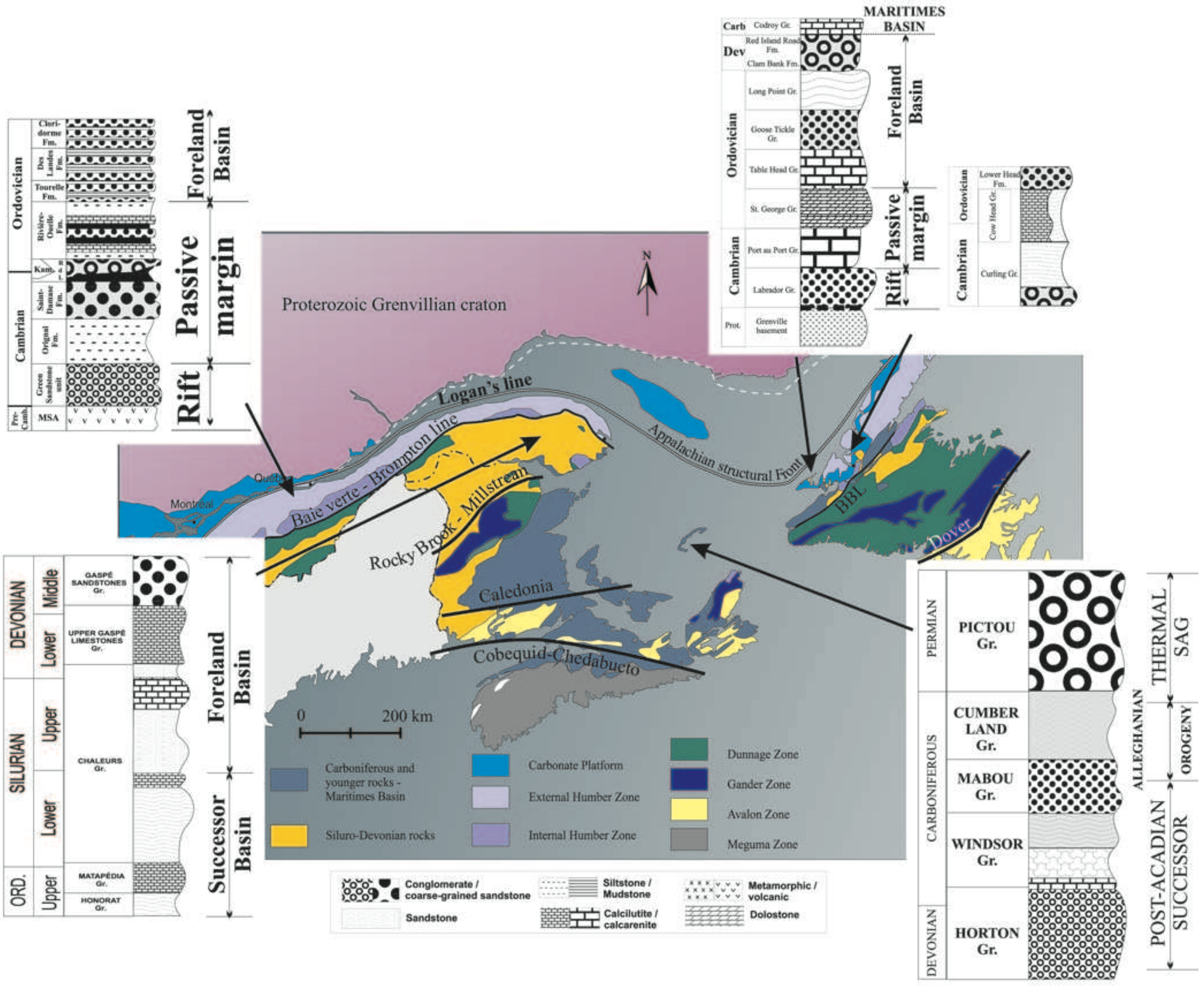


Figure 14.2 Bedrock geology showing tectono-stratigraphic zones and representative stratigraphic columns (adapted from Williams, 1979). The white dashed line marks the offshore limit between the Proterozoic Grenvillian craton to the west and northwest, and the Cambrian-Ordovician St. Lawrence platform to the east and southeast.

of deformation and metamorphism. The Acadian Orogeny was intense and its effects are generally superimposed on previously deformed rocks. There is usually a decrease in deformation from the more central zones (Dunnage and Gander) to the more peripheral Humber and Avalon (and Meguma) zones. Given the geometry of these continental collisions, most of the tectonic fabric was generated by compression or low-angle thrusting; in those areas where major faults are strike-slip in nature, deformation is largely limited to rocks adjacent to the faults. Major strike-slip faulting after the Devonian Orogeny favoured the formation of pull-apart basins in the Maritimes. The Neo-Acadian and Alleghenian Orogenies were not as intense as previous orogenies, consequently. Carboniferous and Permian rocks may be significantly less deformed and are generally found resting unconformably on older, more deformed rocks. Mesozoic rocks in the Canadian Appalachians are rare and related to the opening of the current Atlantic Ocean. Outcropping younger rocks include the Minas Basin (including the Annapolis Valley) in Nova Scotia, and the Monteregian Cretaceous alkaline intrusions which form a series of aligned plutons from Montreal to the coast of Maine.

14.2.1.2 General bedrock porosity and permeability

Aquifer classifications consider both primary and secondary porosities (Roy et al., 2006). As a first-order approximation, the younger the sedimentary rock, the better its primary (pore) porosity and, to some extent, its permeability. Secondary porosity is controlled by diagenetic and tectonic features. These include cross, longitudinal, and bedding joints in undeformed to deformed competent rocks, whether sedimentary, igneous or metamorphic. Most igneous and metamorphic rocks deformed by the Acadian and Taconic Orogenies do not appear to have developed the large interconnected fracture zones associated with good aquifers (Brown, 1967). However, synthetic and antithetic joints may be particularly well developed during brittle events occurring near minor to major fault zones (e.g., faults of the external Humber zone, see section 14.2.1.3.1). Secondary porosity in carbonate rocks may be significant, but is more difficult to predict. Secondary dolomitization and karst features, such as those related to dissolution along joint planes, may be locally important. High-relief areas are typically composed of low-porosity/low-permeability rocks that do not favour recharge. More information on bedrock porosity and permeability is available in Chapter 2.

Table 14.3 provides examples of effective porosities and estimates of maximum hydraulic conductivities for rocks (drawn mainly from Quebec samples) of a given type and age; although the samples were collected at surface, results are in the same order of magnitude as those obtained from core samples (Hu and Lavoie, 2008). Porosity values were obtained using a pressure chamber. Hydraulic conductivities (K) were estimated using water injection on 2 to 4 cm diameter samples collected from drill cores or field samples (Kmax represents the addition of the horizontal and vertical components of K). These values are theoretical, but they do provide a good picture of the prospective hydraulic conductivity and aquifer potential of these formations. From Table 14.3, we can see that sandstones have generally increasing permeability from older to younger rocks, being close to 10^{-4} m/s in Carboniferous rocks. Sandstone effective porosities vary widely from less than 1% to 11.3%.

14.2.1.3 Bedrock stratigraphy

14.2.1.3.1 Cambrian and Ordovician rocks

Humber zone

The external Humber zone forms a continuous belt extending throughout the Canadian Appalachians. This zone consists of two distinct tectono-sedimentary assemblages, the parautochthonous and the allochthonous, separated by a major fault known as Logan's Line in Quebec. The more westerly external Humber zone is moderately deformed and regional metamorphism is low, the more easterly internal Humber zone forms a nearly continuous belt in southern Quebec (and extends into the adjacent United States), but crops out sparingly as slivers or inliers elsewhere. Deformation is intense and metamorphism of higher grade. Internal stratigraphy for the latter is difficult to establish.

The parautochthonous assemblage consists of tectonic slices of shallow to deeper marine Cambrian-Ordovician St. Lawrence platform rocks (see Chapter 13 on the St. Lawrence Lowlands for detailed tectono-stratigraphic descriptions). Even

TABLE 14.3 ESTIMATES OF EFFECTIVE POROSITY (N) AND HYDRAULIC CONDUCTIVITY (K) OF DIFFERENT TYPES OF ROCKS FROM VARIOUS PERIODS (FROM LAVOIE, 2009)

PERIOD		ROCK TYPE	FORMATION OR GROUP	NO. OF SAMPLES	N (%)	K_{max} (M/S)
Carboniferous		Sandstone	Bonaventure Fm.	2	11.3	8.5E-05
Devonian	Lower-Middle	Sandstone	Battery Point Fm.	5	0.4	1.2E-05
	Lower	Sandstone	York River Fm.	5	6.3	3.5E-07
	Lower	Sandstone	Fortin Gp.	1	0.8	1.2E-07
	Lower	Limestone	Indian Cove Fm.	2	1.1	1.2E-07
	Lower	Limestone	Forillon Fm.	2	0.6	1.2E-07
Silurian - Devonian	Upper S–Lower D	Sandstone	Indian Point Fm.	1	1.9	6.9E-07
Silurian	Upper	Carbonate	West Point Fm.	13	1.7	2.6E-06
	Upper	Sandstone	Saint-Léon–Gascon Fms.	4	2.1	4.6E-07
	Lower	Carbonate	Sayabec–La Vieille Fms	24	1.7	3.5E-06
	Lower	Quartzite	Val Brillant Fm.	3	2	2.3E-06
	Lower	Sandstone	Anse Cascon Fm.	6	1.8	3.5E-07
	Lower	Sandstone	Weir Fm.	4	3.4	3.5E-07
	Lower	Sandstone	Cabano Fm.	2	1.7	3.5E-06
Ordovician - Silurian	Upper O–Lower S	Limestone	White Head Fm.	2	0.9	1.2E-07
Ordovician	Upper	Sandstone	Garin Fm.	2	0.9	1.2E-06
	Middle	Sandstone	Tourelle Fm.	2	0.5	1.2E-07
	Lower	Sandstone and limestone	Rivière-Ouelle Fm.	3	0.7	1.2E-07
Cambrian	Upper	Quartzite	Kamouraska Fm.	13	1.8	1.2E-07
	Upper	Sandstone	St. Damase Fm.	12	1.1	1.2E-07
	Lower-Middle	Sandstone	St. Roch Group	10	1.7	1.2E-07
	Lower	Sandstone		8	1.2	2.3E-07

though approximately 50 of these slices were identified in the subsurface from Montreal to Quebec City, only three of them are present at the surface (near Philipsburg, Saint-Hyacinthe, and in the Acton Vale–Upton areas). These slices commonly form small hills in a dominantly low-lying area, and are limited by faults and related joints. They represent good potential recharge areas and aquifers, given the high potential for subaerial karst dissolution of their predominantly carbonate lithologies.

The Humber zone's allochthonous assemblage is made up of weakly to moderately metamorphosed sedimentary rocks, consisting of (1) a thick Lower-Middle Cambrian succession of mudstones and green sandstones, with some basalt flows; (2) a more diversified Upper Cambrian–Lower Ordovician succession including mainly mudstones, sandstones, conglomerates with subordinate limestones; and (3) a flysch and melanges succession derived from the erosion of the westward-migrating Middle Ordovician to Late Ordovician Taconian wedge (Lavoie et al., 2003). Porosity and hydraulic conductivity values of representative Humber zone samples are found in Table 14.3 (Cambrian to Middle Ordovician samples).

The allochthonous assemblage can be subdivided into external and internal thrust sheets. Deformation and metamorphism increase from west to east, typically grading from (1) open folds affected by lower greenschist metamorphism and low-angle thrust sheets, to (2) recumbent or upright tight folds affected by upper greenschist metamorphism, and high-angle thrust, normal, or strike-slip faults. Rocks of the Humber zone are cut by numerous faults of various ages which tectonically juxtapose variably sized slivers of rocks of different composition and age. Stratigraphic units are fairly continuous laterally but may change along-strike (Cousineau and Longuépée, 2003). Rare plutons (e.g., the Devonian McGerrigle Pluton, and Cretaceous Mounts Shefford and Brome in Quebec) intrude the Humber rocks. Primary porosity and permeability in these rocks are generally very low to nonexistent. Fracture porosity is best developed near faults and expressed by synthetic and antithetic fracture networks. The local importance of this type of permeability is variable and directly related to the abundance and thickness of folded and faulted competent units present within the less competent rocks (McCormack, 1978; 1982).

Dunnage Zone

The Dunnage zone, present in Quebec, northern New Brunswick, and central Newfoundland, is a composite terrain consisting of laterally discontinuous segments that have been thrusted to the northwest. The boundary between the Humber and Dunnage zones is known as the Baie Verte–Brompton Line (BBL, see Figure 14.2), and extends throughout the Canadian Appalachians. To the east, the boundary with the Gander zone is less well established and relationships between both zones are subject to different interpretations. Most rocks of the Dunnage zone are Ordovician in age.

Structure and metamorphism in the Dunnage zone are generally less intense, but stratigraphic units are more discontinuous than in the adjacent internal Humber zone. Generally, rocks of the Dunnage zone may be grouped into four assemblages: (1) ophiolite complexes composed of mafic to ultramafic intrusive and extrusive rocks representing ancient sea-floor material thrusted over the continent; (2) shale-rich melanges of tectonic as well as sedimentary origin that contain blocks of various size, age, abundance, and composition; (3) volcaniclastic to epiclastic flysch sediments with some siliceous ("chert") and minor marine carbonate; and (4) volcanic, volcaniclastic and intrusive rocks of magmatic arc provenance. Primary porosity within these rocks is almost nonexistent and, as in the adjacent Humber zone, permeability is variable (but typically poor), being related to local abundance of fractures in fold hinges and regional faults in competent rocks. The city of Thetford Mines, Quebec, is located on these rocks (ophiolites).

Gander zone

The Gander zone consists of laterally discontinuous segments in New Brunswick, Nova Scotia (western Cape Breton Island) and central Newfoundland. The most typical sedimentary rocks of this zone are passive margin-type, Ordovician, quartz-rich sandstone and black shale. These were variously deformed and metamorphosed from greenschist to amphibolite grade during multiple phases of deformation that extended from the Cambrian to the Silurian (van Staal, 2005). Silurian and Devonian granitic intrusions may constitute about half the zone. Ordovician and Silurian volcanic rocks are locally present, especially in some parts of northeastern New Brunswick (Miramichi Highlands) and Nova Scotia (Cape Breton Highlands). The intensity in deformation and metamorphic grade of these fine-grained sedimentary rocks does not allow for significant porosity or permeability, other than fracture conduits.

Avalon zone

The Avalon zone crops out primarily in Newfoundland, where it represents the easternmost one third of the island. Numerous other disjunct segments are found, however, throughout the Appalachian Orogen, in eastern Nova Scotia (Cape Breton Island, Antigonish Highlands, Cobequid Mountains) and southern New Brunswick (Caledonian Highlands). The Avalon zone is bounded on both sides by major faults, characterized by steep ductile shears and brittle deformation zones (see Figure 14.2). There is no uniform stratigraphy throughout the zone, in part because it was an active margin for at least 100 million years (van Staal, 2005). This suggests that a substantial part of the Avalon zone is in fact a collage of smaller terranes made up of different rock types. Metamorphism is low, especially when compared to that in the Gander zone.

Stratigraphy of Newfoundland's Avalon zone is distinct from that elsewhere in the Maritimes. The upper unit is composed of terrestrial sedimentary and volcanic rocks. The youngest rocks are Cambrian and Ordovician shale and sandstone, exposed locally. In Nova Scotia and New Brunswick, the zone's younger, often more widespread rocks, consist of Upper Precambrian volcanic and volcaniclastic, and sedimentary rocks. Porosity and permeability values are expected to be low.

Meguma zone

The Meguma zone is restricted to the area of Nova Scotia south of the Cobequid-Chedabucto Fault. The Meguma "Supergroup" (excluding the overlying Annapolis Supergroup of Silurian and Devonian age) is Late Cambrian to Early Ordovician. Sedimentary rocks of the Meguma Supergroup are of marine origin. Quartzitic and feldspathic sandstones occur in the lowermost succession while the rest of the Supergroup is dominated by greyish muds to black shales (White et al., 2007). These rocks were mildly to moderately deformed and metamorphosed during a Devonian tectonic event. Their permeability is typically low.

14.2.1.3.2 Silurian and Devonian belts

Silurian and Devonian rocks of the Appalachians are often mildly to intensely deformed, especially in the vicinity of major faults. The stratigraphic description of the Upper Ordovician to Middle Devonian succession within the Gaspé Belt (*sensu* Bourque et al., 1995) is based on the synthesis of Bourque et al. (1995, 2001), and Lavoie (2008). The Gaspé Belt extends from southern Quebec (and northern US) to western Newfoundland; the succession is preserved in three major lithotectonic domains which are best exposed in the Gaspé Peninsula. From north to south, these are: (1) the Connecticut Valley-Gaspé synclinorium (Upper Ordovician to Middle Devonian rocks), (2) the Aroostook-Percé anticlinorium (Upper Ordovician to Lower Silurian rocks), and (3) the Chaleurs Bay synclinorium (Upper Ordovician to Upper Silurian rocks).

The stratigraphy within these major structural elements can be divided into four broad temporal and lithological assemblages (see above-cited literature for details). Main lithologic assemblages include marine clastic assemblages of mudstones, sandstones, conglomerates and limestones. Most units are characterized by low porosity and permeability, except for sandstones. (see Table 14.3). Aerial studies of these sandstone facies' distribution (not shown) reveals that they form the topmost rock unit of close to 25% of the Gaspé Peninsula's modern landscape. Fracturing and subaerial karst dissolution for carbonates can increase permeability locally, favouring groundwater circulation.

14.2.1.3.3 Carboniferous and younger rocks of the Maritimes Basin

During the Late Devonian, small fault-bounded basins opened following the Devonian Acadian and Neo-Acadian Orogenies. These individual basins are known collectively as the Maritimes Basin. With time, these small continental basins increased in size, with evidence of one major marine incursion. Sedimentation, was largely continental to marginal marine.

At the base of the statigraphic succession, the Upper Devonian to Lower Mississippian Horton Group is a thick succession dominated by coarse-grained sandstone and conglomerate near the faulted margins of individual half-graben basins (Hamblin and Rust, 1989). These sandstones have low permeability and porosity. Permeability is usually related to bedding and orthogonal joint sets, and improves where carbonate cement is dissolved. The Horton Group is abruptly and unconformably overlain by the Lower Mississippian carbonates of the Windsor Group (Giles, 1981) with major beds of deep-marine sulphates (gypsum and anhydrite) and salt (halite). Hundreds of metres of mafic volcanic flows and intrusive gabbros are found within the Windsor Group, in the central part of the Maritimes Basin and outcroppings on Îles-de-la-Madeleine. The Windsor Group is overlain by upper Lower Mississippian fine-grained clastics of the Mabou Group, and by the Pennsylvanian continental deposits, which contain abundant coal seams of the Cumberland Group.

Lower Permian clastics and aeolian sandstones of the Pictou Group occur at the top of the stratigraphic pile. These aeolian sandstones are well exposed on Prince Edward Island and on the Îles-de-la-Madeleine. Sandstones of the Mabou, Cumberland, and Pictou (and correlative units in small areas in western Newfoundland, e.g., Deer Lake and Stephenville areas) are characterized by variable porosity and permeability values. However, several of these formations can be considered good aquifers (see section 14.4). These units blanket large areas of New Brunswick, Nova Scotia, Prince Edward Island, and the Îles-de-la-Madeleine, Quebec: all are widely exploited for water supply.

14.2.2 Surficial sediments

14.2.2.1 Quaternary events and stratigraphy — A brief overview

Although the northern Appalachian region was repeatedly covered by ice sheets and ice caps during the Quaternary period, its surficial sediment cover is rather discontinuous and consists of sediments, most of which were deposited during the last glacial-deglacial cycle, the Late Wisconsinan substage (Grant, 1989). The Late Wisconsinan glacial advances, those associated with the Last Glacial Maximum (LGM), largely obliterated or buried the sedimentary record of Early to Middle Wisconsinan and earlier (Illinoian) glacial advances and/or retreats. Although these older Quaternary sediments were once regionally extensive, today they are only partially preserved in a few regions of Nova Scotia (Stea et al., 1998), New Brunswick (Rampton et.al., 1984; Lamothe et al., 1992) and southeastern Quebec (McDonald and Shilts, 1971; Shilts, 1981; Lamothe et al., 1992).

Surficial sediments in uplands and high tablelands of the region are generally thin and discontinuous, consisting primarily of glacial sediments and minor glaciofluvial sediments. The Quaternary sediment cover in lowlands, such as the Maritime Basin, is significantly thicker and more continuous. Valleys, which are locally the locus of thick Quaternary sediment fill, generally contain the best and most extensive granular aquifers of the region. Depending on the local Quaternary context, the nature and stratigraphic architecture of these sediments may range from relatively simple, terraced alluvial sediments, to quite complex assemblages, where glaciomarine or glaciolacustrine silt units may be overlain or underlain, or both, by fluvial or glaciofluvial sediments. Somewhat exceptionally, such as along parts of the Saint John, Chaudière, Nicolet or St-François Rivers (Lamothe, 1992; Shilts, 1981; Parent, 1987), these valleys may contain older Quaternary sediments buried below those deposited during the last glacial-deglacial cycle. The study of buried valleys, particularly preglacial valleys, is an important part of hydrogeological research in several glaciated terrains as these valleys generally present good hydraulic potential (Simard, 1970). Modern postglacial streams usually occupy broad valleys formed in pre-Quaternary time, although some valley segments are now located some distance from their former courses. One fairly well-known example of this phenomenon is the Saint-François River valley at East-Angus near Sherbrooke, where successive glacial advances have considerably disturbed the pre-Quaternary hydrographic pattern and clay-rich surface till and glaciolacustrine silts (McDonald, 1968) conceal a high-yield aquifer in the buried valley (Simard, 1970). The presence of rock-entrenched valley segments often indicates the nearby presence of buried preglacial valleys.

There has been extensive debate concerning the nature, timing, and extent of glaciation throughout the northern Appalachian region (Grant, 1977; Rampton et al., 1984; Dyke and Prest, 1987; Stea et al., 1998). It should be noted, however, that issues such as ice-flow patterns or glacial limits have only limited implications for hydrogeological conditions in the region (largely due to the fact that most of the contentious issues are associated to regions now lying below sea level). As in most other regions of Canada, tills are by far the most common surficial material of the Applachian region, covering about 90% of the surface area as calculated from the Surficial Materials Map of Canada (Fulton, 1995). The texture of tills, ranging from silty clay to sandy to stony is controlled by depositional processes, as well as by the lithological nature of their source rocks. Till texture has considerable relevance for regional hydrogeological conditions, and particularly for aquifer recharge. Usually, basal or lodgement tills in any given region are significantly finer grained, more compact, and less permeable than their ablation or melt-out counterparts. Those basal tills derived from Cambro-Ordovician and Siluro-Devonian rock assemblages in the Appalachians are typically rather stony with silty sand to sandy silt matrices, whereas tills overlying or derived from the Maritime Basin red beds have silty to silty sand matrices, and are relatively clast-poor.

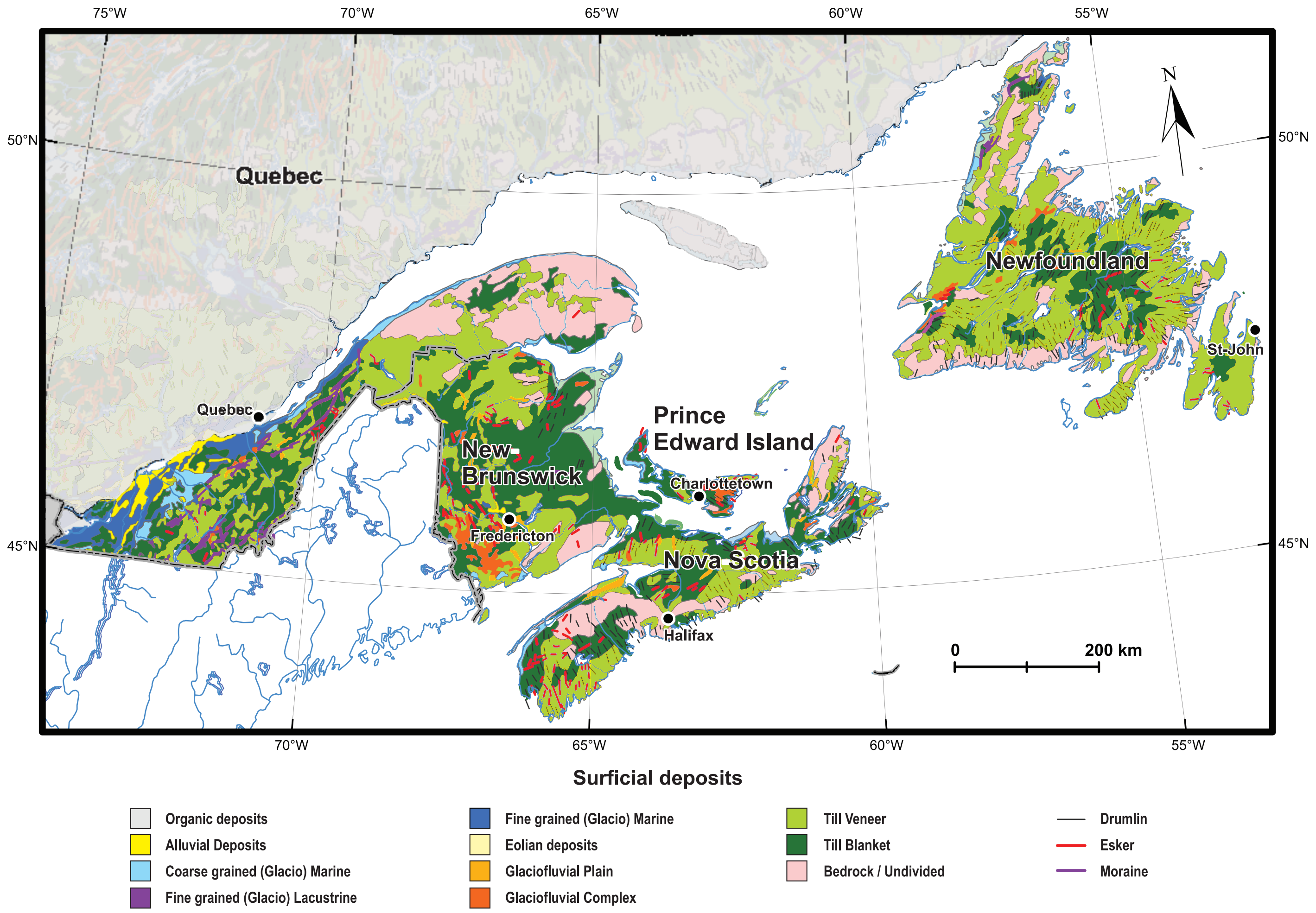


Figure 14.3 Surficial geology map of the Canadian Appalachians and Maritimes Basin region (adapted from Fulton, 1995).

The surficial geology map depicted in Figure 14.3 has been patterned after the Surficial Materials Map of Canada (Fulton, 1995). Figure 14.3 also locates those landforms, such as moraines and eskers, which often make good aquifers. Most of the eskers in this region are located in the western part of both New Brunswick and Nova Scotia, whereas moraines are usually found in the southwestern half of the Quebec Appalachians.

Coarse-grained glaciofluvial sediments, moraines and eskers constitute only a small part of the regional surface area (< 10%). Nevertheless, they provide, along with alluvial sediments, the most significant groundwater resources and some of the best aquifers of the region. Glaciofluvial sediments, mainly ice-contact sand and gravel, occur as discontinuous patches in all parts of the Appalachian region, although they are notably scarce in the lowlands of eastern New Brunswick, in Prince Edward Island, in Cape Breton Island, in Newfoundland and on the high plateaus of the Gaspé peninsula. Glaciofluvial valley trains are not a typical feature of the region, except for parts of southwestern New Brunswick. Morainal sediments, mainly end moraines consisting of ice-contact gravels, occur mostly in southern Quebec where, locally, they constitute high-yield aquifers for municipal water supply: Rivière-du-Loup (population ~ 20,000) which draws its water from an array of horizontal wells connected to a large diameter (4.9 m) production well dug into glaciofluvial sandy gravel associated with the

Saint-Antonin Moraine, a prominent regional feature (Lee, 1962), is a prime example.

Glaciolacustrine sediments are fairly uncommon in the northern Appalachians and, as a result, their role on local or regional hydrogeological conditions is often very limited. In Quebec, these sediments occur almost exclusively as rather discontinuous silty or sandy units in northward-sloping Appalachian valleys where proglacial lakes were locally impounded against the ice margin as it retreated toward the central St. Lawrence Lowlands (McDonald, 1968; Parent and Occhietti, 1988, 1999). In New Brunswick, however, glaciolacustrine sediments rarely constitute large surface units, although they do occur as subsurface units along the Saint John River valley, particularly between Grand Falls and Edmunston where they consist of silty to sandy sediments deposited in proglacial Lake Madawaska (Rampton et al., 1984).

14.2.2.2 Emergence-submergence zones and resulting stratigraphy

As the continental crust was unloaded from its glacial cover during of deglaciation, glacioisostatic recovery lagged behind global sea level rise: many coastal regions were temporarily invaded by North Atlantic marine waters. This short-lived, diachronous marine incursion left discontinuous blankets of marine sediments in many coastal regions, particularly along the estuary and northwestern Gulf of St. Lawrence. As shown in Figure 14.4, the maximum elevation reached by these postglacial seas (locally named Goldthwait, Champlain and De Geer) ranges from 0 m a. s. l. in the central regions of the Gulf of St. Lawrence (Grant, 1989) to as much as 185 m a. s. l. on the northern Appalachian front in southern Quebec (Parent and Occhietti, 1988).

The marine limit isopleths depicted in Figure 14.4 can be used to define the maximum local elevation at which coarse-grained marine sediments may be found. Fine-grained marine sediments generally occur at elevations well below the local marine limit, up to 50 m below marine limit in wave-exposed coastal areas, and less in sheltered embayments and reentrants. The 0 isopleth defines the region (zone A) where no marine sediments exist above the present-day coastline (Grant, 1989). Figure 14.4 also presents an alternate limit between zone A and zone A-B south of Îles-de-la-Madeleine; this alternate is based on unpublished findings (Parent and Dubois, unpublished data, 2007) showing post-LGM littoral sediments at elevations up to 50 m.a.s.l. Marine sediments exert a considerable role on hydrogeological conditions, in the fairly restricted (but densely inhabited) regions where they occur (zones A-B and B).

Beach, nearshore sediments, and thick, sandy marine deltas formed at the mouth of rivers entering postglacial seas, constitute extensive high-yield aquifers. On the other hand, locally extensive blankets of marine silt and clay constitute aquicludes (impermeable layers) that provide confining conditions for underlying Quaternary sediment and/or fractured bedrock aquifers. The occurrence of these fine-grained marine sediments is common along the Chaleur Bay coast in Gaspésie and New Brunswick, and in valley fills along the Saint John, Petitcodiac and Northwest Miramichi Rivers (Rampton et al., 1984; Violette, 1990; Daigle, 2005). Clayey marine sediments can also be found in valley reentrants and along a fairly narrow strip of land along the northern Appalachian front in southern Quebec.

Alluvial sediments occupy a small surface area within the Appalachian region. However, they are

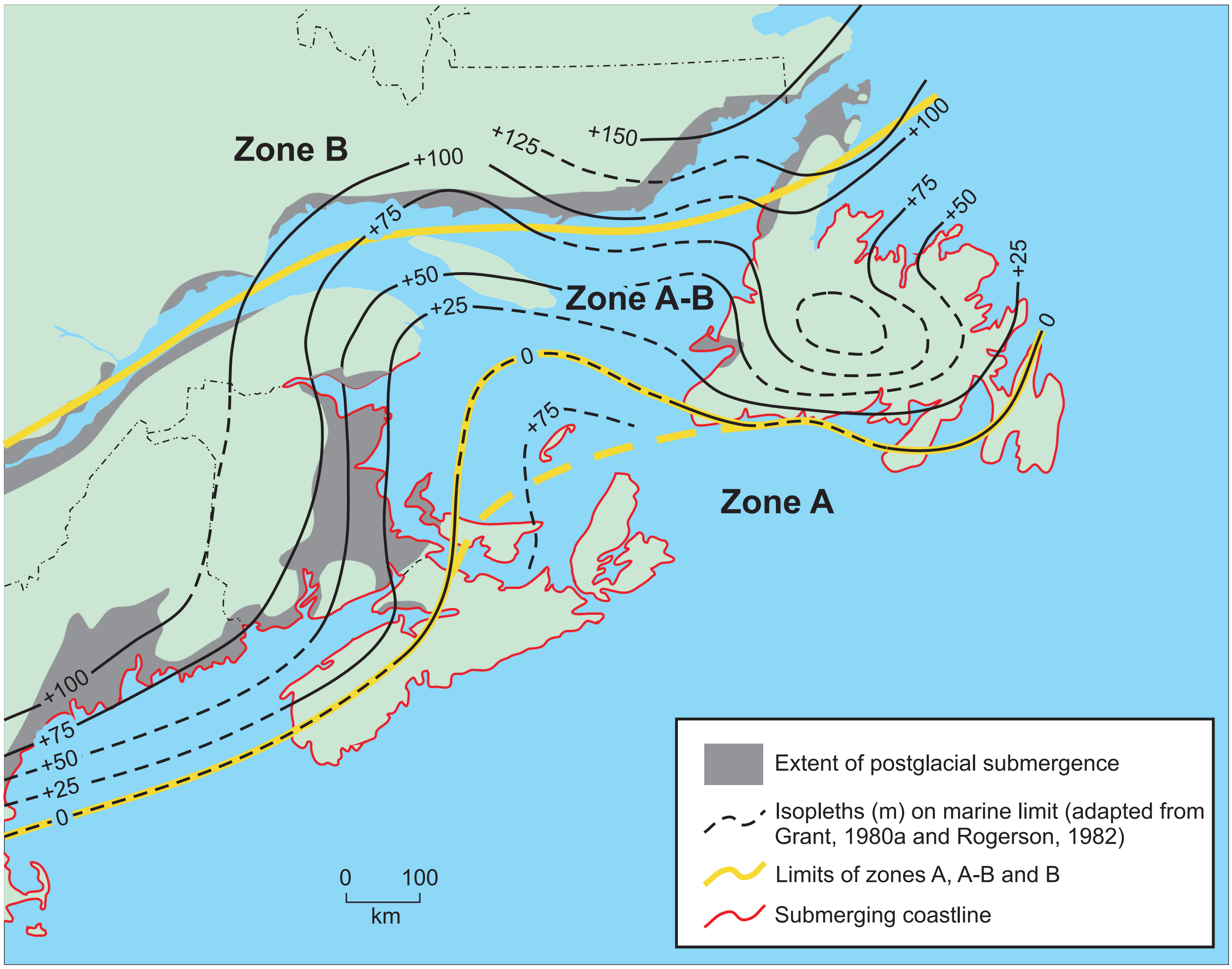


Figure 14.4 Regional distribution of Late Quaternary emergence-submergence zones (zones A, A-B and B) in Atlantic Canada and marine limit isopleths in metres (adapted from Grant, 1989).

present throughout the region and they constitute many of the best aquifers. The coarser facies, pebbly or cobbly gravels and sands, are the most interesting not only because of their high transmissivity, but also because they occur in valleys where main population centres are located. Large deposits of alluvial gravels underlie floodplains or fluvial terraces along intermediate- to low-gradient reaches of most major rivers. In the lower reaches next to the coast, alluvial sediments are commonly interstratified with finer-grained marine sediments, or overlain by silty floodplain sediments.

The Late Quaternary relative sea level history varies across the region; likewise stratigraphic and architectural relationships between alluvial and marine sediments along the coastline also vary (Figure 14.5). In zone A valleys, where relative sea level has been below present since time of deglaciation, alluvial sediments were deposited during marine lowstands and covered by intertidal muds deposited during subsequent highstands, particularly in macrotidal settings such as the St. Lawrence Estuary. In microtidal or mesotidal settings, such as along Nova Scotia's Atlantic coast, or in eastern Prince Edward Island, these valleys are generally drowned by the ongoing submergence.

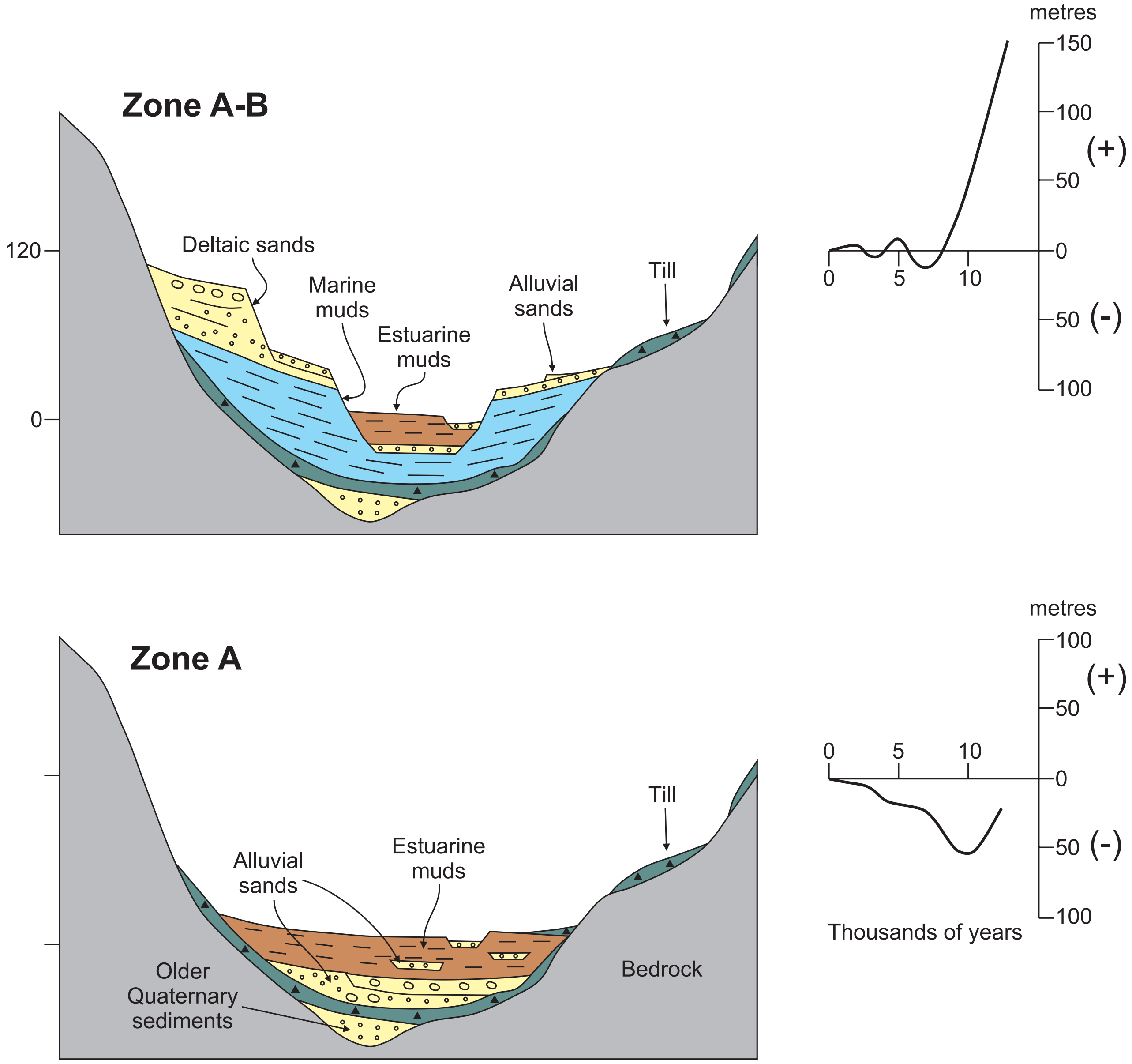


Figure 14.5 Late Quaternary relative sea level changes and resulting schematic stratigraphy in the lower reaches of valleys in zones A and A-B.

Aquifers consisting of alluvial sediments in coastal regions of zone A are commonly confined under intertidal muds; yet, because they lie below modern sea level, they are vulnerable to saltwater intrusion (Figure 14.5). Boisvert (2004) documented an aquifer confined below thick intertidal muds and containing brackish water (TDS = 5,800 mg/L) in the Memramcook valley of southeastern New Brunswick, a region of shallow postglacial submergence, where conditions are almost identical to those of zone A. In valleys of zone A-B (between isopleths 0 and 100 m) where postglacial land emergence was followed by one or several phases of submergence (continuing today), glaciomarine muds deposited earlier were incised down to below present sea level. They were subsequently covered by alluvial sediments, which were in turn overlain by intertidal muds, particularly in macrotidal settings such as in the Bay of Fundy or the St. Lawrence River estuary. Emerged coarse-grained marine sediments in zone A-B regions commonly constitute large, productive unconfined aquifers. These regions may also host various confined aquifers, either below fine-grained marine sediments

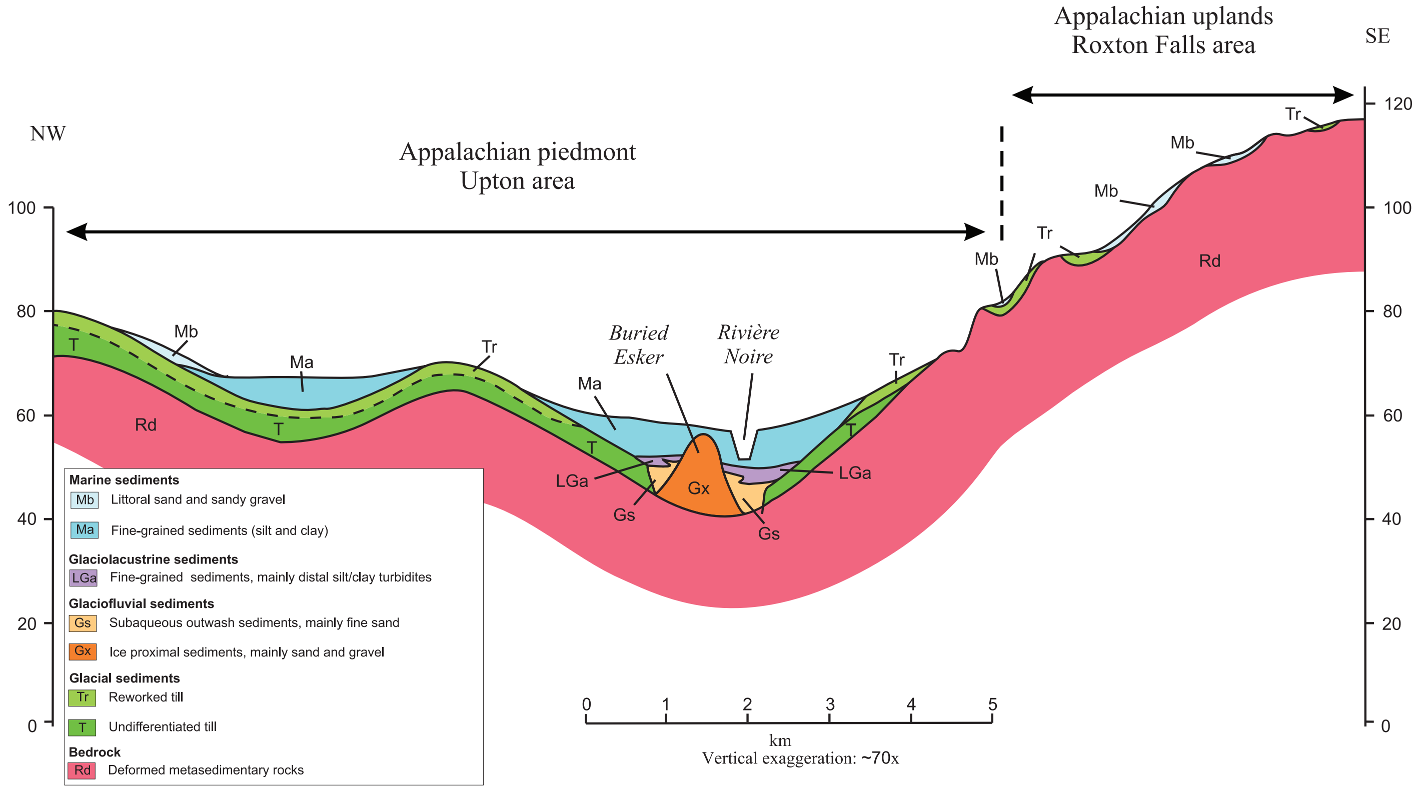


Figure 14.6 Schematic cross section of the Appalachain piedmont and uplands in southeastern Quebec.

or below intertidal muds such as in Quebec City (Lamarche et al., 2008). Large valleys, such as the York River near Gaspé, located in microtidal settings of the central Gulf of St. Lawrence, are being infilled by a prograding wedge of sandy alluvial sediments, whereas small valleys such as those on Prince Edward Island are being drowned by ongoing submergence.

14.2.2.3 Typical cross section for the Appalachian piedmont and uplands

Figure 14.6 presents a schematic cross section of the Appalachian piedmont and uplands of southeastern Quebec by illustrating the stratigraphic architecture of a typical deglacial sediment succession in the Upton-Roxton Falls region. The piedmont was invaded successively at time of glaciation by an ice-dammed lake (Glacial Lake Candona, LGa unit) and by the Champlain Sea (Ma and Mb units). The fine-grained sediments are locally underlain by discontinuous eskers (Gx unit) which often rest directly on bedrock, as the underlying till was eroded by meltwater in subglacial conduits prior to esker deposition. Such ice-contact sediment bodies, composed of sand and gravel, and the associated subaqueous outwash sands (Gs unit) usually have excellent aquifer potential. These glaciofluvial sediments may also benefit from complete or partial confinement by clayey marine sediments which provide them protection from surface contamination. Assemblages of reworked till and littoral sand are one of the main characteristics of the piedmont, where their sandy-gravelly texture and widespread occurrence favours infiltration. The compact, dense till which commonly underlies these sediments, however, has low permeability, with the result that a large part of the infiltrated water may not reach the bedrock regional aquifer below. On the other hand, infiltrated water may migrate under the silty-clay cover via sandy till, reworked till, or even bedrock subcrops, thus forming good aquifers that may supply small rural municipalities.

The common sequence of surficial sediments found in the Appalachian piedmont and uplands, as illustrated in Figure 14.6 includes, from bottom to top: 1) glacial tills which usually cover bedrock; 2) discontinuous glaciofluvial sediment bodies (e.g., eskers) found locally in Appalachian valleys; and 3) glaciolacustrine and glaciomarine silts and/or clays related to Lake Candona and the Champlain Sea, both of which covered the piedmont and valleys of the western Appalachian uplands (Parent and Occhietti, 1988; Lefebvre et al., 2011). Marine sediments are not present in the Appalachians beyond the limit of the Champlain Sea, nor are they found on the larger Monteregian hills, which formed islands.

14.3 HYDROGEOLOGICAL CONTEXTS

Three main hydrogeological contexts have been generalized to provide a framework for a more detailed description of the most important aquifer systems of the Canadian Appalachians. These contexts are based on distinctive bedrock and/or surficial geology, major tectonic episodes, and physiographic divisions. The schematic figures illustrate simplified tectono-stratigraphic zones, and geological features, in order to show differences in bedrock deformation intensity, characteristic surficial sediment-landform assemblages, and associated stratigraphic architecture. The result indicates those areas where potential aquifers and their typical extent can be found. Although the schematics depict representative geological settings from the study area, they do not correspond to a specific "real" area.

14.3.1 Context 1: Appalachian uplands with sparse glaciofluvial sediments and localized glaciolacustrine submergence

The Appalachian uplands are most commonly underlain by fractured non-porous bedrock, in which the connectivity of joints or fractures controls hydraulic conductivity. Rocks of this context are largely Cambrian to Devonian sedimentary, with some volcanic and plutonic rocks that have been metamorphosed at low grade, and more or less deformed and fractured. Many major high tablelands can be found within this context, including the Notre-Dame and Shick-shock Mountains in Quebec (which broadly coincide with the internal Humber zone), the Cobequid Mountains and Cape Breton highlands in Nova Scotia, the Newfoundland highlands (Long Range Mountains), and more localized plutonic rocks such as the Monteregians hills in Quebec, or thrust sheets with thick competent rock units (e.g., the Kamouraska quartzite in the Lower St. Lawrence Valley, Shick-shock volcanics in Gaspésie). Bedrock aquifers with good hydraulic properties are largely localized and can be expected along regional fault zones and folds in the more competent and brittle rock units. Some of these aquifers can also be found in carbonate rocks where dissolution has increased fracture porosity. The complex geology of Newfoundland and Cape Breton cannot be adequately represented in this simplified sketch, because these two areas evidence significant tectonic overprint by the Acadian and Alleghenian Orogenies.

The Quaternary sediment cover consists most commonly of thin and discontinuous till blankets, particularly on interfluves. The silty sand and sandy silt texture of this till blanket controls infiltration, allowing for significant recharge (see section 14.4.4) to the underlying bedrock aquifers.

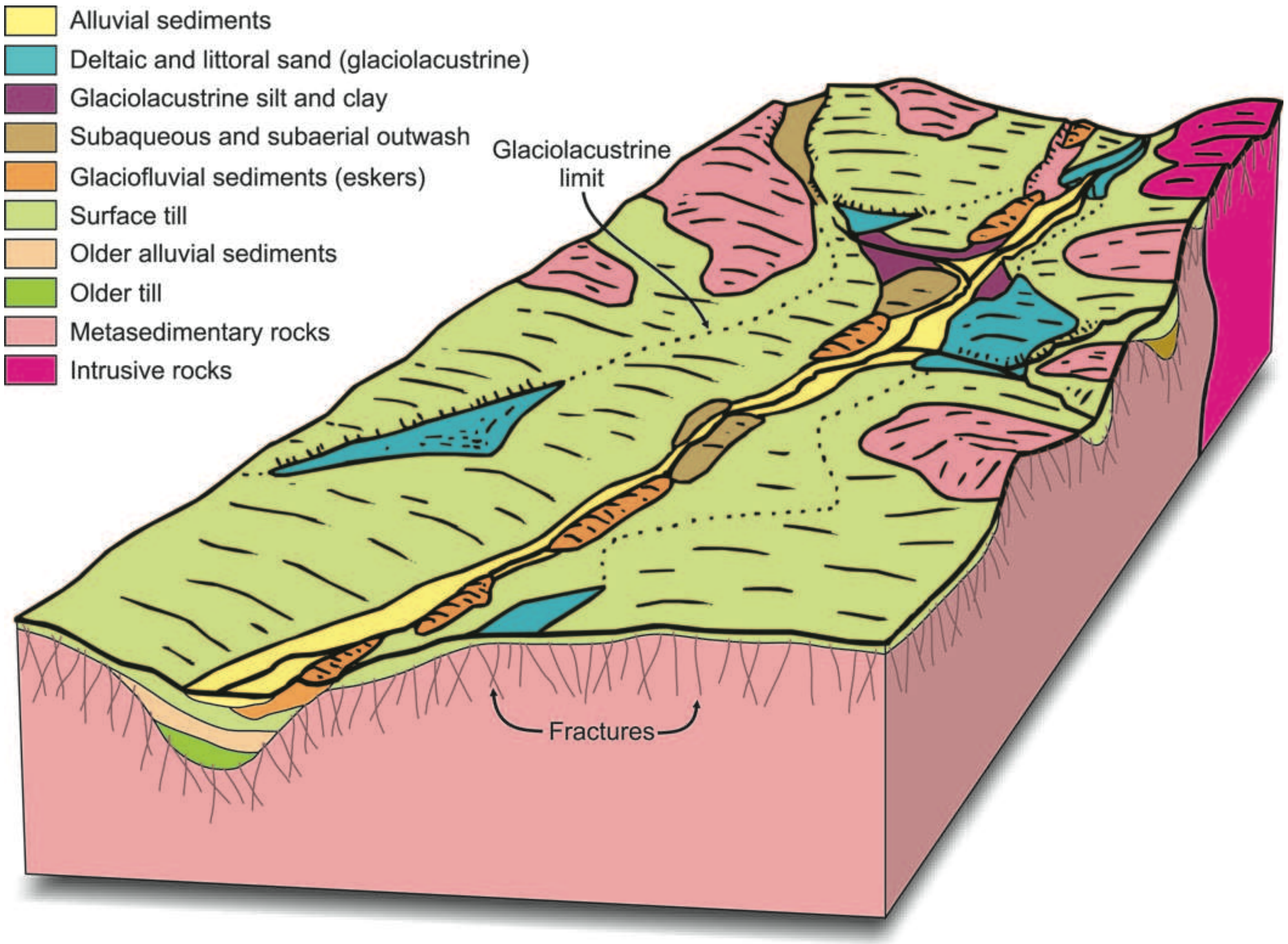


Figure 14.7 Context 1—Schematic depicting the Appalachian uplands with sparse glaciofluvial sediments and localized glaciolacustrine submergence.

Surficial aquifers are largely concentrated in valleys where the topmost Quaternary sediments consist of sandy to gravelly alluvial plains and terraces. As shown in Figures 14.4 and 14.7, eskers and other glaciofluvial sediment bodies occupy rather limited surface areas in the Appalachian uplands, particularly in north-central New Brunswick, in central Newfoundland and in the Gaspé Peninsula. Not only are glaciofluvial sediments scarce in these upland regions, they also tend to be "dry," as groundwater is generally not retained within these highly permeable sediments. Hence the most commonly used aquifers in the uplands are unconfined or semi-confined bedrock aquifers, while in valleys, alluvial sediments provide excellent, generally unconfined surficial aquifers.

The occurrence of fine-grained glaciolacustrine sediments in some Appalachian valleys provides local confining conditions for underlying unconsolidated sediments or bedrock. Silty clay sediments were deposited in glacial lakes impounded by retreating ice margins within many Appalachian valleys, particularly those of southern Quebec (McDonald, 1968; Parent and Occhietti, 1988, 1999), but also in other regions such as Nova Scotia's Annapolis Valley (Rivard et al., 2012). Valley shoulders and slopes are locally overlain by sandy littoral and deltaic sediments deposited at or near the former glacial lake shorelines: these may constitute interesting surface aquifers. The bottom

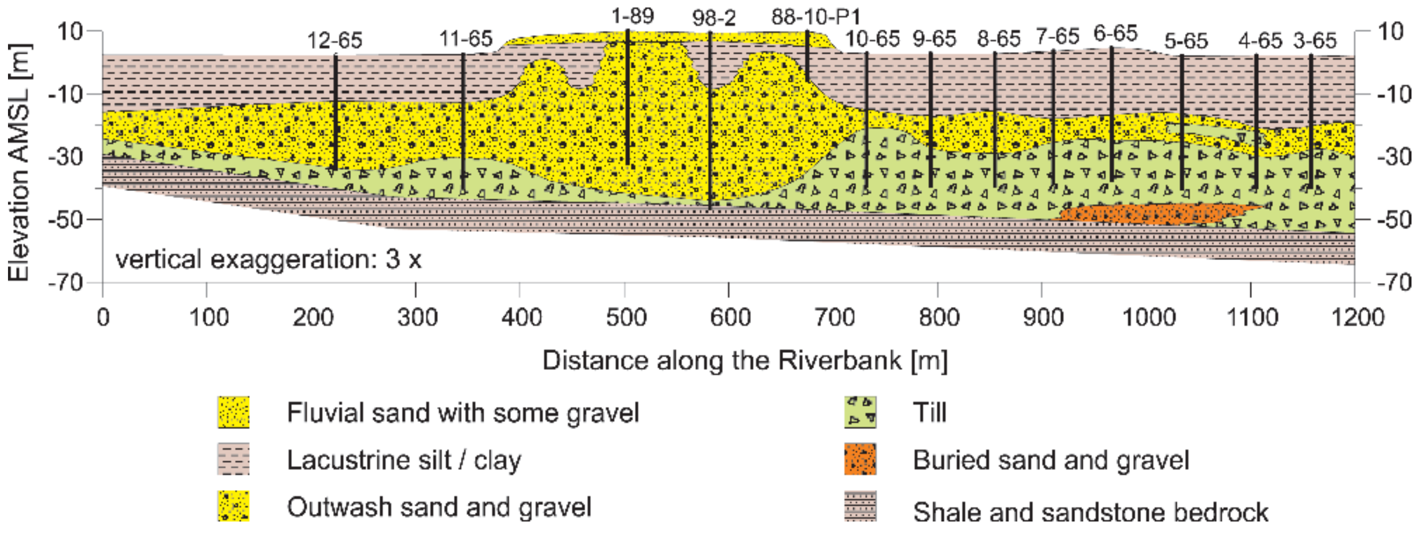


Figure 14.8 Representative cross section taken along the south shore of the Saint John River, and passing obliquely through the aquifer (outwash sand and gravel) near the Wilmot Park well field, Fredericton, New Brunswick (source: Butler et al., 2004).

of these valleys, however, is locally underlain by fine-grained sediments which commonly form discontinuous sheets as a result of subsequent fluvial incision or simply as a result of non-deposition. These confined or semi-confined valley bottom sediments may locally constitute excellent aquifers, depending on permeability, thickness and groundwater quality.

One excellent example of this phenomenon occurs in the Saint John River valley where glaciofluvial outwash sediments, partially buried by glaciolacustrine silt and clay, constitute a high-yield aquifer exploited by Fredericton for municipal water supply (Figure 14.8). Near Fredericton, the Saint John River lies in a broad bedrock valley partially filled with up to 65 m of coarse-grained Quaternary sediments. The sediments that make up the main aquifer have the morphology of a buried esker-like ridge which runs along the valley floor underneath the City of Fredericton and the Saint John River valley. The deposit thins as it spreads toward the north and south valley walls (Figure 14.8). The ridge is up to 30 m thick, and contains a wide variety of particle sizes, including sands, gravels, cobbles, and boulders (Violette, 1990; Daigle, 2005). A clay/silt aquitard, which overlies most of the aquifer, has been eroded at several locations along the crest of the ridge. These features, locally termed "windows", allow for relatively direct recharge of the aquifer.

Elsewhere in the Appalachian uplands, coarse-grained glaciofluvial sediments can constitute good aquifers, although their surface area is very limited. Moreover, these aquifers are commonly very thin because of topographic position, and, in many cases, have been compromised as a result of aggregate resource exploitation.

14.3.2 Context 2: Appalachian piedmont with localized Late Quaternary marine sediment cover

The Appalachian piedmont in much of southern Quebec was invaded by a postglacial marine incursion (Champlain and Goldthwait seas), which produced hydrogeological conditions partly shared by the adjacent St. Lawrence Lowlands, as well as by the southern edge of the Canadian Shield. The bedrock units underlying the Quaternary sequence correspond predominantly to the external Humber zone. Their permeability is primarily controlled by

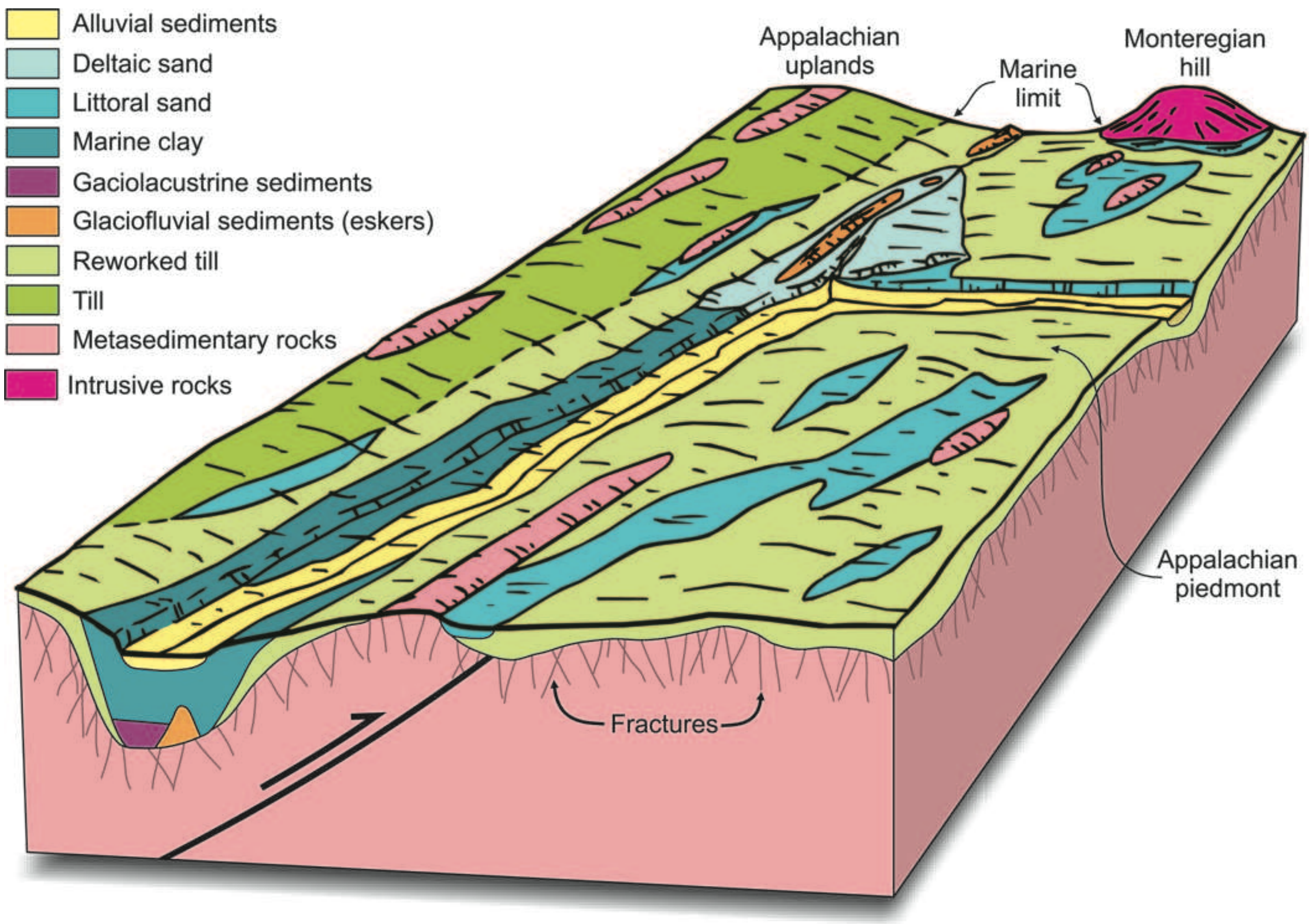


Figure 14.9 Context 2—Schematic illustrating the Appalachian piedmont with localized Late Quaternary marine sediment cover.

fracture porosity, much like those of the internal Humber zone of context 1 (Figure 14.7). However, key components of the marine incursion context (Figure 14.9) are related to (1) surface occurrence of fairly thick (5–10 m) fine-grained deposits which form widespread aquitards and produce confining conditions in the underlying sediment or rock units; (2) occurrence of large sheets of prograding sandy deltaic and offlap littoral sediments that may constitute large unconfined aquifers; (3) widespread wave action and current related winnowing and reworking of glacial sediments which increase the rate of infiltration in these sediments over vast areas below the marine limit. Towns such as Upton (Qc) and Sainte-Hélène-de-Bagot (Qc), as well as small cities such as Rimouski (Qc) are only a few examples of municipal water supply in granular or bedrock aquifers underlying marine clays.

Although the sedimentary platform of the Maritimes Basin could, in theory, be included in this context of marine incursion, it seems best to exclude it because the marine limit was generally too low or too short-lived to allow widespread deposition of fine-grained marine sediments. For instance, detailed investigations in the Moncton region (Boisvert et al., 2002; Boisvert, 2004), as in much of eastern New Brunswick (Rampton et al., 1984), have provided no evidence for fine-grained marine sedimentation nor for significant wave-washing or winnowing of tills.

14.3.3 Context 3: Maritimes Basin

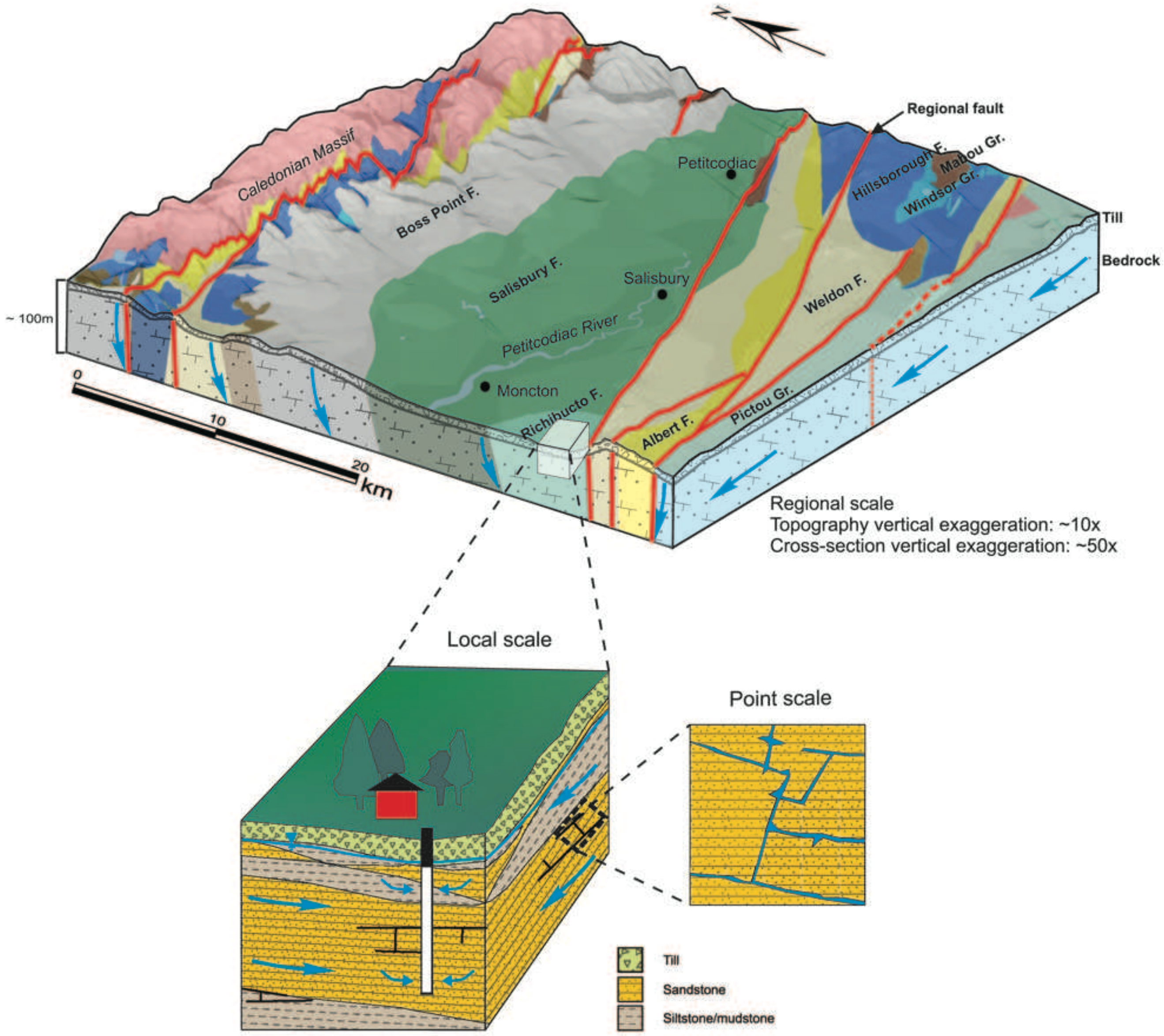
The Maritimes Basin represents one of the main regional aquifer systems in Canada. It includes Prince Edward Island, the northern part of Nova Scotia (including a portion of Cape Breton Island), the eastern part of New Brunswick, Îles-de-la-Madeleine, as well as two small areas east and south of the Long Range Mountains in Newfoundland (see Figure 14.1). In total, this basin covers 46,000 km^2. It is composed largely of Carboniferous and younger sedimentary rocks, consisting mostly of sequences of lenticular bodies of sandstone, shale, siltstone, and conglomerate, in varying proportions, in different lithostratigraphic units. There are also some volcanic rocks (basalts) present in Îles-de-la-Madeleine and along the Bay of Fundy in Nova Scotia (North Mountain). A thin layer of glacial till (mostly 4–8 m, but reaching locally up to 20 m in thickness) usually covers these formations. The main till properties strongly reflect the lithology and colour of the underlying bedrock units.

This basin is characterized by significant and rapid lateral and vertical facies changes, as in most continental to marginal marine successions. These weakly consolidated rocks constitute a vast regional aquifer with modest to significant yields. Good aquifers can also be found in the glaciofluvial sand and gravel units, as well as in fluvial valley fills, but these are notably scarce in the Maritimes Basin. Bedrock aquifers are often confined, mainly depending on the bedrock composition, layering, and fracturing. Although the porosity of these Carboniferous, Permian and Triassic rocks is usually much higher than that of older rock units elsewhere in the Appalachian region, groundwater still circulates, largely through fractures. Almost all residential wells are shallow, open holes (about 20 m), cased only through surficial sediments. Preferential groundwater recharge occurs where bedrock is overlain by sandy till.

Figure 14.10 provides a schematic representation for the particular geological context near Moncton, New Brunswick. Three scales (regional, local, and point) were used in Rivard et al. (2007; 2008) to describe the main hydrogeological characteristics of the surficial sediments and sedimentary rock units of the basin. At the region scale, each formation can be considered as only one hydrostratigraphic unit with uniform properties, although generally anisotropic. Anisotropy may indeed have a significant impact on flow system behaviour, as laterally extensive and sometimes thick impermeable strata are present. At the regional scale, however, fractures are often probably sufficiently connected to provide an equivalent porous media. Faults are interpreted to play a key role in the regional flow, based on results of numerical flow modelling.

At the local scale, each hydrostratigraphic unit has its own set of characteristic structural and hydrogeologic properties. Layering of the various strata with contrasting hydraulic properties leads to an aquifer/aquitard sequence for many geological formations. Due to this layering, and also to fracturing, these porous fractured aquifers are locally heterogeneous and anisotropic. Nevertheless, based on pumping test results, they appear to behave as equivalent porous media.

Work performed at the point scale indicated that most fractures consist of shallow-dipping joint sets generally oriented in a northeasterly direction, in agreement with regional structures. More specifically, water-bearing fractures are commonly related to bedding planes and lithological changes.



14.4 CURRENT KNOWLEDGE OF HYDROGEOLOGY

14.4.1 Most important aquifer systems

Bedrock aquifers are frequently exploited in the Canadian Appalachians. As discussed in Chapter 2, water in bedrock aquifers, may come from fractures alone (referred to as secondary porosity) such as in igneous rocks (e.g., basalts, granite), or it can be stored and circulated through pores (referred to as primary porosity) and fractures, as is often the case with sedimentary rocks such as sandstones. Fractured porous media (mainly sandstone and conglomerate) usually provide better yields and aquifer potential than strictly fractured aquifers because the latter have no primary porosity. Nevertheless, strictly fractured aquifers can supply significant yields locally, when sufficient interconnected fractures or a thick cover of saturated Quaternary sediments is present. Bedrock, in most places in the Appalachian region, is overlain by a thin layer of glacial sediments (generally till less than 10 m thick) that does not yield large quantities of water. Sand and gravel units, which have very good hydraulic potential, are present only over a limited area (<10% of the land area).

Recently, two regional hydrogeologic studies have been carried out over formations of the Maritimes Basin: the Maritimes Groundwater Initiative (Rivard et al., 2005, 2008) and the Annapolis-Cornwallis Aquifer Study (Rivard et al., 2007, 2012). The Maritimes Groundwater Initiative (MGWI) project covered a land surface of 10,500 km^2, of which 9,400 km^2 is underlain by Carboniferous and younger rocks, including the southeastern part of New Brunswick, the western part of Prince Edward Island and the northern part of Nova Scotia. The Annapolis-Cornwallis Aquifer Study (hereafter called "Annapolis") covered 2,100 km^2, including the Annapolis Valley proper and parts of North and South Mountains in Nova Scotia. The MGWI project mainly focused on permeable formations of the Pictou, Cumberland and Prince Edward Island Groups, whereas formations of the Triassic-Jurassic Fundy Group were of main interest in the Annapolis project (i.e., the Wolfville Formation underlying the valley floor and the Blomidon and North Mountain formations constituting North Mountain).

In Nova Scotia, 14 published regional groundwater resource studies characterizing different counties were carried out between 1968 and 1986 (they are available at the Nova Scotia Environment website http://www.gov.ns.ca/nse/groundwater/groundwaterresources.asp). Agriculture and Agri-Food Canada (AAFC) recently conducted a few studies in the Annapolis Valley (e.g., AAFC-PFRA, 2003). Several theses were also devoted to more or less local areas in all provinces (e.g., Carr, 1969; Trescott, 1968; Brown, 1971). Numerous local hydrogeological studies have also been undertaken throughout the Canadian Appalachians with results generally available through provincial databases.

14.4.1.1 Bedrock aquifers

The most important bedrock aquifers of the Canadian Appalachians are hosted by Carboniferous or younger rocks (Figure 14.2), located in the Maritimes Basin (Context 3, Figure 14.10). Formations in this basin consist of discontinuous layers of sedimentary rocks, forming an inter-layered suite of permeable, and almost impermeable, strata with a shallow northeastern dip (see section 14.3.3). Individual beds range in thickness from a few centimetres to several metres: their lateral extent is variable.

Most bedrock formations outside the Maritimes Basin cannot supply high-yield wells. Rocks of Contexts 1 and 2 (Figures 14.7 and 14.9), since they mainly depend on fracture porosity (very poor primary or intrinsic porosity), commonly only provide yields sufficient to supply one to a few houses. Therefore, several wells may need to be drilled to provide sufficient water to supply an industry or a community, as is the case throughout much of Newfoundland. Some igneous (e.g., granites) and sedimentary rocks, however, can provide good yields on a local basis. For instance, in the Gaspé Peninsula and in the southern part of Quebec, some Silurian and Devonian sandstones and carbonates have high hydraulic conductivities (see section 14.2.1.3.2), although the region underlain by these rocks (Figure 14.2) is rather sparsely populated, and few wells other than residential have been drilled; as a result, aquifer properties are not well known. Quartzites in other parts of the Silurian and Devonian belt, may offer some aquifer potential due to the fact that they can be quite fractured, as opposed to more ductile and finer-grained sedimentary rocks, even when the latter have been subjected to folding and fracturing. Bedrock in the Chaudière watershed (6,682 km^2), located south of Quebec City, consists mainly of schist, slate, mudstone, and sandstone, with local volcanic or intrusive rocks belonging to the Humber zone, and is thus not very permeable. The most intensely fractured and folded rocks in this area can only provide yields varying from 0.8 to 1.5 L/s (i.e., sufficient for average household use or for a (very) small central system or some commercial uses), unless they have been overlain by sufficiently thick, permeable surficial sediments.

Surficial sediments in many areas of this region are too thin or too impermeable to provide adequate yields. This fact, coupled with the prohibitive costs of construction and operation of filtration plants necessary for surface water treatment, means that groundwater from poorly permeable rocks often represents the only economically viable solution for many small municipalities, even if several wells or combined systems must be developed.

14.4.1.2 Surficial aquifers

The Appalachian region's surficial geology is usually very complex, largely because this area has been subjected to several glaciation/deglaciation cycles. As a result, the region is characterized by the presence of different landform-sediment assemblages, including rare, locally preserved sequences of interglacial/interstadial sediments (see section 14.2.2). Each glacial/deglacial cycle in the Appalachian region tended to erode surficial sediments deposited during previous cycles; hence Quaternary sediments are generally thin throughout the region, in contrast to other regions such as the Prairies where each glacial/deglacial cycle generally added to the total thickness of the Quaternary sediment pile.

There are exceptions, where Quaternary sediments can be quite thick locally, reaching up to about 100 m near Lac-Mégantic in the Upper Chaudière valley, and near Saint-Antonin in the Bas-St-Laurent region, Quebec; and 50 m in a few areas of New Brunswick (e.g., Fredericton) and Nova Scotia (e.g., Kentville).

Surficial units, with yields > 1.5 L/s, capable of supplying the needs of municipalities, industries or institutions are typically isolated sand and gravel deposits of diverse origin. These units often constitute excellent aquifers, and in the Appalachians, they consist mainly of alluvial or glaciofluvial sediments (see section 14.2.2), which provide potable water supplies for a number of fair-sized municipalities throughout the region (Fredericton, Wolfville, Parrsboro, Lac-Mégantic and most of the municipalities along the St. Lawrence estuary, as well as Stephenville in Newfoundland). Sand and gravel deposits usually occur (1) along river valleys, (2) in buried or partly buried valleys, or (3) as glaciofluvial sediment bodies (e.g., deltas, moraines, eskers), which also tend to be concentrated in valleys.

The main valleys hosting sand and gravel aquifers within the region are: the Saint John and Kennebecasis Rivers in New Brunswick, the Chaudière, Matapedia, and Bonaventure Rivers in Quebec, and the Cornwallis and Musquodoboit Rivers in Nova Scotia. Some deltas, moraines, and eskers are also exploited for water supply (the esker ridge near Sussex, New Brunswick, the St-Antonin moraine ridge in Rivière-du-Loup, and the Saint-Césaire esker in Quebec). Buried or partly-buried valleys can be found in various areas of the five provinces (in the Moncton area, and near

Lac-Mégantic and East-Angus, Quebec). These valleys have the advantages of (1) being commonly confined and thus, naturally protected from surface contamination, and (2) containing usually better-sorted, coarser-grained sediments than their overlying units, which usually consist of glacial sediments. However, buried valley aquifers are often not exploited for a variety of reasons, including poor water quality (mainly excessive iron and manganese content) and/or distance from populated areas.

Sand and gravel units sometime provide remarkably high groundwater yields, despite having only a few metres of saturated thickness. One good example of this is in Quebec's Saint-Hubert-de-Rivière-du-Loup. This municipality exploits a sand and gravel unit, 4 m thick and extending over 0.19 km^2, to supply more than a thousand people. This exploited glaciofluvial unit is assumed to belong to the Saint-Antonin Moraine, which is also present at Rivière-du-Loup. The Moraine constitutes a small enclave surrounded by till, and underlain by a clayey gravel, considered to be the base of the aquifer (Arrakis Consultants Inc., 1991). Monitoring of water levels has shown large variations between the minimum and maximum levels relative to aquifer thickness (min=1.2 m and max=2.9 m based on six observation wells). The extraction system consists of a very shallow dug well with four horizontal radial collector drains. Several similar systems are also in use within the region.

Aquifer potential of surficial sediments in the Appalachian piedmont of Quebec is currently under investigation (Lefebvre et al., 2011), particularly in valleys, where fairly thick (~5 to 10 m) permeable sediments underlie low-permeability (protective) glaciolacustrine or glaciomarine sediments (as illustrated in Figure 14.6). Scientists are paying particular attention to the extent and aquifer potential of eskers concealed under the Champlain Sea clay cover. Aquifer potential of the coarse-grained littoral sediments surrounding the Monteregian Hills is also being documented (Lefebvre et al., 2011).

14.4.2 Hydraulic properties and aquifer potential

The quantity of water yielded by any given well depends on the type of geological material, the thickness of the saturated zone, the number of transmissive fractures and/or the porosity and thickness of permeable layers encountered, well depth, recharge available, and storage capacity. The location of the well with respect to boundary conditions (proximity to a river that can feed the well, or to a less permeable boundary, as, for example, a valley wall limiting the extent of the aquifer) is also important. Hydraulic conductivity (K) is a critical parameter in hydrogeologic investigation because it provides a quantitative estimate of the ability of the formation to convey water to the well. Most commonly, however, K values are not directly available and must be derived from transmissivity values (T). These are an integration of K over the saturated thickness (b) of the assessed aquifer (T=K*b), and are commonly provided in provincial databases and reports. Transmissivities are best estimated from observed water level drawdown/recovery rates during long-duration pumping tests. Most jurisdictions only require long-term pump tests for relatively high capacity wells, or for multiple user wells. More details on these hydraulic properties are provided in Chapter 2.

1,600 transmissivity values (1,300 for bedrock and 300 for surficial aquifers) were used in the Appalachian region to depict hydraulic properties of the formations. Transmissivity values were collected from provincial databases (for New Brunswick, Prince Edward Island, and Nova Scotia), and from reports (for Quebec). No data was available for Newfoundland. Transmissivities, rather than hydraulic conductivities, have been presented here, because, as noted above, this parameter is usually the one provided in databases, and the screen and/or casing length required to estimate saturated thickness is not always provided to estimate K values. Wells often have approximate locations, as they were either located using a provincial grid system (with a precision of approximately 1 km^2) or by using the centroid of the municipality, when no other information was available. Several wells are often located in clusters and thus, cannot be distinguished at the scale of the Appalachians.

14.4.2.1 Bedrock aquifers

Transmissivity and porosity in bedrock aquifers varies according to the type of rocks, their age, and their tectonic history (see section 14.2.1). Carboniferous and younger sedimentary rocks of the Maritimes Basin (Context 3) often have moderate to high (>10^{-4} m^2/s) transmissivities, especially where sandstone and conglomerate are present. Because of aquifer and aquitard layering, many formations have variable aquifer potential[2], showing poor to moderate hydraulic conditions in those areas where shale and siltstone predominate. As a general rule, the greater the presence of sandstone and conglomerate, the more permeable the bedrock will be (although this does depend on the matrix characteristics). Wide ranges in hydraulic properties are due both to the presence or absence of fractures, and to layering. Carbonate rocks (e.g., limestones in the Gaspé peninsula, Quebec; the Scots Bay Formation, at the top of the Fundy Group succession, Nova Scotia), evaporites (those of the Windsor Group near Windsor, Nova Scotia); Salt Springs evaporite (deposits near Sussex, New Brunswick), and finer-grained strata (e.g., shale and siltstone) can also yield water, mainly from fractures, bedding planes, and cavities. Their aquifer potential is typically poor to moderate, except for water-soluble rocks such as evaporites or carbonates, where large fractures or karstic features caused by dissolution can significantly increase potential, although the groundwater quality within soluble rocks can be affected (e.g., brackish water from evaporites, enhanced hardness from carbonates).

Igneous rocks such as granites, basalts, gneiss, and gabbro typically have a relatively poor aquifer potential (with T<10^{-5} m^2/s), but these rocks can locally provide good yields if fractures are well interconnected. One of the municipal wells of Lawrencetown, Nova Scotia, constructed in granite, has a transmissivity on the order of 5×10^{-5} m^2/s. Highly fractured basalts of the North Mountain in Nova Scotia may also supply moderate to significant yields in some areas. Metamorphic rocks, such as slates of the Meguma Group in Nova Scotia, and schists of the Humber zone in Quebec, also commonly have a poor aquifer potential with transmissivities in the order of 10^{-6} to 10^{-7} m^2/s; typically, they can only provide water for a single house.

Figure 14.11a presents the minimum, maximum, and median bedrock transmissivity values obtained for each province. Figure 14.11b presents the same data, but using tectono-stratigraphic zones to illustrate ranges of values. Transmissivities mainly

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[2] The classification “variable aquifer” means that good hydraulic potential can be found in certain areas, while poor transmissivities (or low yields) are observed in other parts of the formation, likely where fractures and sandstone layers are less abundant.

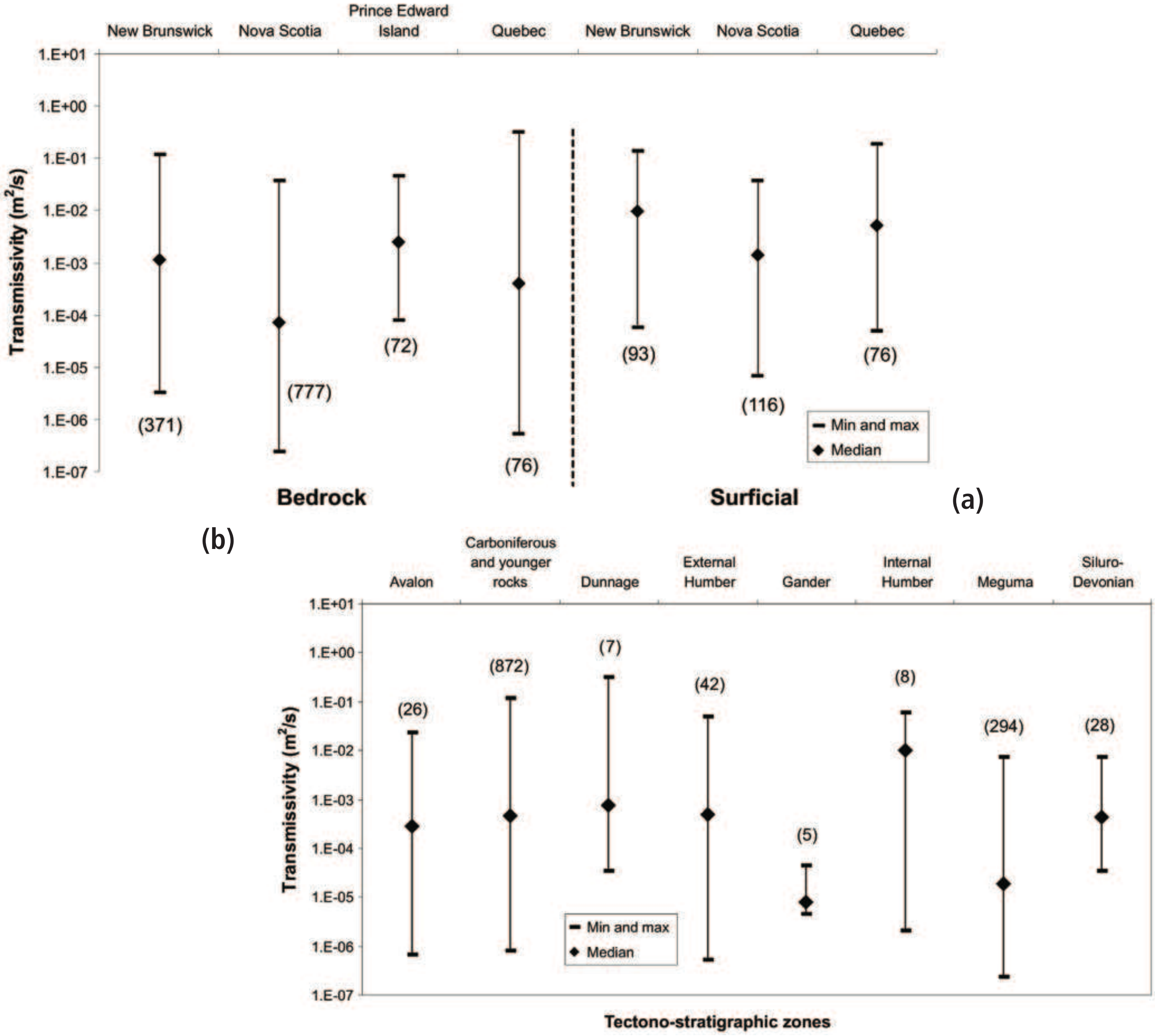


Figure 14.11 Minimum, median, and maximum values of transmissivity (m^2/s): (a) by province for bedrock and surficial sediments and (b) by tectono-stratigraphic zones. Note that there are no major high-yield wells in surficial sediments on Prince Edward Island.

range between 10^{-6} and 10^{-1} m^2/s, with most values varying between 10^{-5} and 10^{-2} m^2/s based on statistical distributions (not shown). This indicates that a relatively good hydraulic capacity is available throughout the Appalachian region. It must be kept in mind, however, that these reported values are probably positively biased, especially for less permeable bedrock formations, because only relatively productive wells are tested, and often several wells must be drilled and abandoned before finding the required yield; these "failed" wells are not included in databases. As a result, reported values likely tend to overestimate the median transmissivity of the formations. Nevertheless, figure 14.11 demonstrates that moderate to good transmissivities may, perhaps surprisingly, be found in all bedrock formations, mainly due to local fracturing.

Figure 14.12 illustrates the spatial distribution of bedrock permeability using three transmissivity (T) classes. The diagram shows that

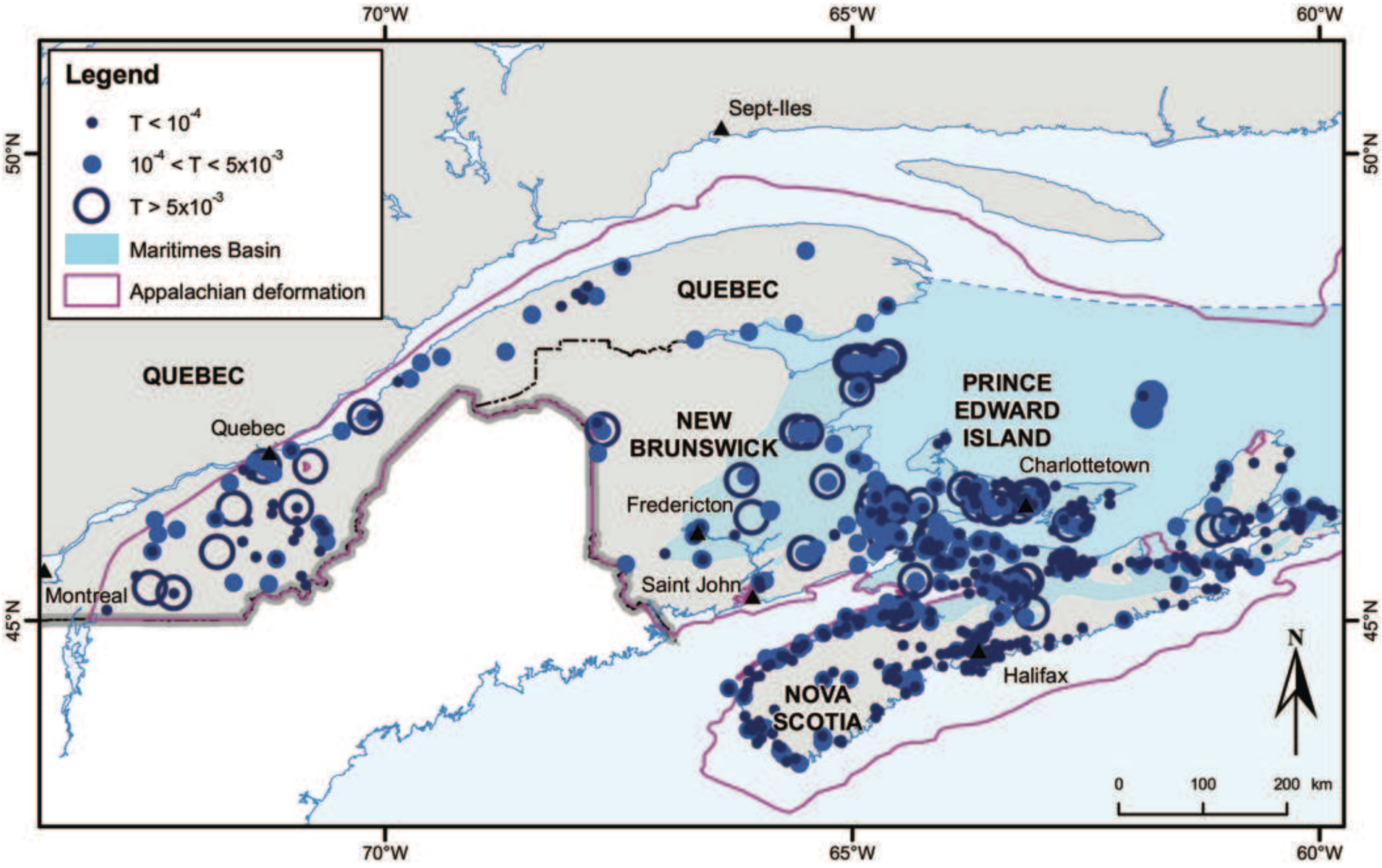


Figure 14.12 Spatial distributions of transmissivities (in m^2/s) in bedrock aquifers (data taken from provincial databases and reports).

moderate- to high-transmissivity values ($T>10^{-4}$ m^2/s) can be found in almost any municipality of the Appalachian region. Several sedimentary formations of the Maritimes Basin, including those of Prince Edward Island, Îles-de-la-Madeleine, the eastern Annapolis Valley and the Acadian littoral of New Brunswick show large values ($>10^{-3}$ m^2/s), typical of high-capacity formations. Other high values may be found on the south shore of the St. Lawrence River in Quebec, probably associated with local tectonic features. Large variations between geological formations of the same group and even within each individual stratum in sedimentary rocks have been observed. This variability attests to the important heterogeneity of bedrock aquifers and asserts the strong influence of both fracturing and layering (Rivard et al., 2008).

Areas where no data are available do not necessarily correspond to regions with poor aquifer potential; rather they usually relate to sparsely populated areas, or to areas where surface water, not groundwater, is the main water source. Long-term pump tests are required only for multi-user wells (for industrial, municipal, and institutional supplies): information for areas where demand is small is thus limited. Nonetheless, Figure 14.12 provides a good indication of where high transmissivities may be found.

Storage coefficient values, which provide an indication of the degree of confinement of an aquifer, are rarely available. This is largely because pumping tests are often performed without using observation wells. Moreover, the storage coefficient value is often questionable, as the tests do not extend over a sufficient time period. Reported storage coefficients have an overall average of

4×10^{-4}. Values typically range between 5×10^{-5} and 5×10^{-2}, showing a relatively high variability due to surficial sediment composition, bedrock layering and fracturing heterogeneity. Despite the uncertainty, these figures provide yet another indication that several bedrock formations are under confined conditions (under pressure) due to overlying fine-grained strata or to the absence of well-interconnected fractures. Such aquifers may therefore be better protected against surface contamination (see section 14.4.7 on vulnerability).

Field measurements from bedrock aquifers in the Maritimes Basin have shown that the movement of groundwater is predominantly controlled by fractures/bedding planes, although some sandstones and conglomerates may have preserved significant primary porosity (Rivard et al., 2012). The pattern, strike, dip and frequency of the fractures vary widely in the various geological formations due to differing primary lithologies and later tectonic stresses. In major aquifers of the area, fractures and bedding planes have been found to be mostly gently northeasterly dipping (toward the Northumberland Strait or the Bay of Fundy), and striking of 45º, in agreement with regional structures. Conversely, wells located in basalts or granites indicate the fact that water seems to be supplied predominantly by sub-vertical fractures, again preferentially striking in a northeastern direction.

Rocks in the Taconian zones and the Acadian Gaspé Belt (i.e., most rocks outside the Maritimes Basin) have been subjected to multiple phases of deformation associated with the Ordovician and Devonian orogenic events. These rocks are commonly folded and thrust-faulted over significant distances (see section 14.2.1) with younger rocks being tectonically overlain by older ones. The main hydrogeological differences between the internal and external domains of the Humber zone are that, within the internal domain, fractures and faults are often sub-vertical, folds are generally tight, and primary porosity is rather low to inexistent, whereas, in the external domain, fractures can be horizontal to vertical, and folds are relatively open. Deformation in external domains is less extensive, rocks are less crystallized and both primary and secondary porosities can be locally preserved, although in lower percentage and absolute values when compared to Carboniferous and younger rocks. General observations indicate that topographic highs often correspond to rocks of the internal domain.

According to water-well drillers, provincial hydrogeologists, and some reports (e.g., Francis and Gale, 1988; Chi et al., 2003), fractures in the Maritimes Basin appear to decrease with depth, both in number and in aperture. As a result, the permeability of these aquifers should generally decrease with depth. Many wells, in recharge areas drilled deeper than 100 m, yielded little or no water beneath this depth (Carr, 1969). This suggests that fractures, which account for a large part of the aquifer permeability, tend to be less frequent, less interconnected and/or have progressively smaller aperture with depth, presumably due to increasing lithostatic pressures.

In addition to the influence of fracturing, the total porosity of each rock type also varies widely, mainly due to the presence of calcite or other cements within pores, to dissolution and to diagenetic processes. The MGWI and Annapolis projects compiled estimated total porosities for the Maritime Basin formations, mainly through thin sections, coming up with values ranging between 0% and 28%. Total porosity was also evaluated by Hu and Dietrich (2008) through detailed analyses of geophysical well logs and core data in six deep wells within Carboniferous rocks (onshore and offshore) of the basin. They reported similar porosity values in the upper levels (~0–400 m), generally ranging from 3% to 25% and averaging 15% to 20%: the highest values typically corresponded to the highest percentage of sandstone in the rock. Kinematic (effective) porosity, however, may be smaller than 10%. Chi et al. (2003) showed that the total porosity of Prince Edward Island formations decreases significantly with depth, from some 20% at surface to about 12% at depths of about 1 km. This finding compares well with results obtained by Hu and Dietrich (2008) who discovered average porosity values of 15% to 20% at shallow depths (above 1,000 m), with a decrease to 10% or less below depths of about 2,000 m.

These relatively high porosity values (mainly due to the matrix, but sometimes including significant fracturing) could lead one to expect that the Maritimes Basin flow system would react hydraulically like a double-porosity medium. Typically, relatively short-term (72 h and less) well tests do not exhibit such a double-porosity behaviour, but rather demonstrate drawdown curves representative of equivalent porous media (Rivard et al., 2012). This may be caused by the presence of very well developed fracture networks (at least in the vicinity of tested wells), having themselves enough storage to act as equivalent porous media at a scale relevant to such investigations. However, longer-term pumping tests (where available) frequently reveal delayed drainage effects associated with dual porosity aquifers. Little literature on this topic is found for the region. Scientists also suspect that anisotropy has a significant impact on flow system behaviour at both local and regional scales, due to the strike of main fractures (north-east) and/or the predominance of shallow-dipping bedding plane fractures, coupled with aquifer/aquitard layering of some geological formations (Francis, 1989; Paradis et al., 2006; Rivard et al., 2012). Effective porosities of rock samples obtained in fractured rocks of Quebec are generally lower, varying between 0.4% and 11.3%, with a median of 1.7% (Table 14.3).

14.4.2.2 Surficial deposits

A solid knowledge of hydraulic properties of surficial sediments is key information for studies of the Appalachian region, and is required to identify areas with both high and low hydraulic conductivities. Areas with high hydraulic conductivities correspond to preferential recharge zones and potential aquifers, unfortunately with little protection against potential pathways for surface contaminants. In those areas with low hydraulic conductvities, or low permeability, the deposits have limited (or no) water supply potential, but offer good protection to underlying aquifers, and contaminants are unlikely to enter the hydrogeological system.

Fine-grained sediments such as glaciomarine and intertidal sediments can often play a role in the confinement of bedrock aquifers. One good example of this interplay can be found in the vicinity of Fredericton's municipal well field, where McGuigan (2005) obtained vertical hydraulic conductivity values for the overlying clay/silt aquitard (Figure 14.8) on the order of 2×10^{-9} m/s, using conventional consolidation tests, flexible wall permeameter tests, and a piezocone test. At the other end of the spectrum, sand and gravel units often have very high permeabilities ($K>10^{-4}$ m/s or $T > 5\times10^{-3}$ m²/s, see Figure 14.13). Pumping tests conducted in the Fredericton municipal well field have yielded transmissivity values as high as 10^{-2} to 10^{-1} m²/s (Violette, 1990; GEMTEC, 1989,

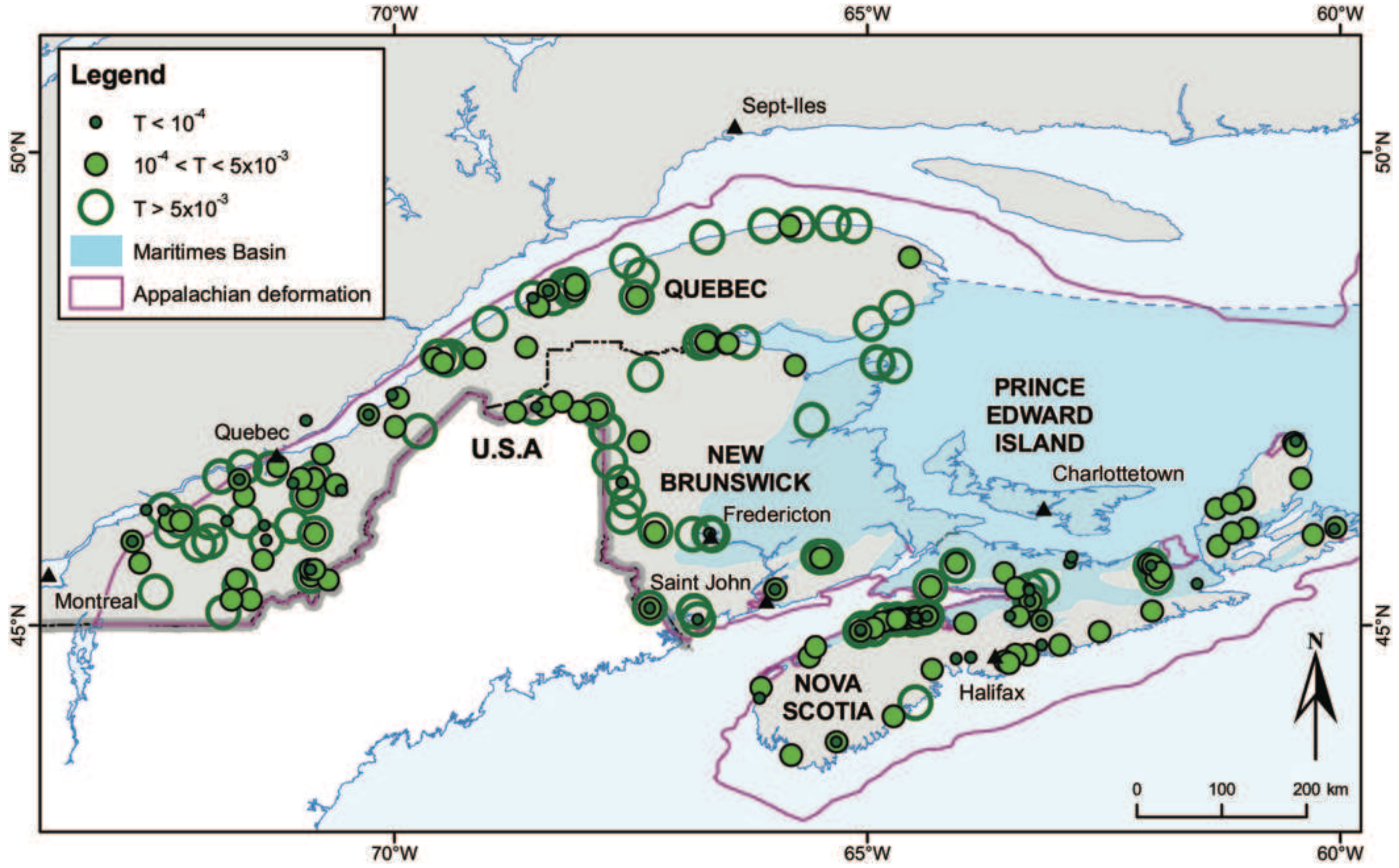


Figure 14.13 Spatial distributions of transmissivities (in m^2/s) in surficial deposits (values classified into three ranges).

1992, 1999; unpublished data, University of New Brunswick, 2005).

Figure 14.13 shows that the high-permeability surficial deposits (sand and gravel) generally have T values higher than bedrock units for a given province, with medians varying between 10^{-3} and 10^{-2} m^2/s (see Figure 14.11a). Reported storage coefficients are typically higher than those for bedrock wells, with an overall average of 1×10^{-2}. This suggests that surficial aquifers may often be unconfined. Values are still quite variable, ranging usually between 10^{-4} and 0.5.

Tills are the most widespread surficial sediments within the Appalachian region, but they cannot provide high yields, mainly because of the broad grain-size distribution of their matrix, relatively high silt and clay content, and limited saturated thickness. Numerous permeameter tests (testing the first metre of soil) in the MGWI and Annapolis projects, have confirmed that these tills have a wide range of hydraulic conductivities, varying from 10^{-9} to 5×10^{-5} m/s (Boisvert, 2004; Rivard et al., 2012). Despite their poor capacity to deliver water to a well, tills play a major role in aquifer recharge, due to their ubiquitous presence, and to the fact that they generally act as a storage reservoir for bedrock aquifers. Indeed sandy tills have been shown to act as preferential paths for infiltration in the MGWI project (see section 14.4.4 for recharge values). Widespread expanses of till in Quebec's Appalachian piedmont are also believed to constitute significant regional groundwater recharge areas, particularly when they occur in low-relief regions and were reworked by wave action during the marine episode. Significant recharge is also inferred to occur locally in valleys of the Appalachian uplands (Lefebvre et al., 2011).

Till cover, because of its prevalent occurrence throughout the Appalachians, is thought to provide the main recharge pathways to bedrock aquifers. It is well known that tills exert considerable control over recharge rates, with sandier tills allowing higher recharge rates and silty/clayey tills significantly limiting recharge. Moreover, since storage capacity of many bedrock units (containing little or no primary porosity) is low, sustainable yields of some bedrock wells should decrease sharply when the water table lies below the till layer (Randall et al., 1988).

Based on these considerations, areas that could be regionally mapped as good potential aquifers are: the Maritimes Basin and areas located along major fault zones for bedrock (Figure 14.2) and alluvial, glaciofluvial, and coarse-grained marine deposits for surficial sediments (Figure 14.3). Other formations can be used for significant water supply, but their extent is limited and these do not appear as major features at the current Canadian Appalachian scale.

14.4.3 Groundwater levels and flow, well depths and yields

Most residential bedrock wells are 150 mm in diameter and average 30 m in depth; they are typically cased only through the surficial sediments and are of open hole construction except where friable wall-rock conditions, or known contamination problems, dictate greater casing lengths. Dug wells are usually less than 10 m deep and most often are made from 90 cm diameter precast concrete rings (referred to as crocks) that can store large amounts of water. Municipal and other high capacity, multi-user wells are typically in the order of 50 to 100 m deep for bedrock wells and, on average, less than 26 m deep for surficial wells (see Table 14.4 for provincial averages).

Average yields are highly variable for each province, varying from 0.25 L/s in Newfoundland to 11.4 L/s in New Brunswick for bedrock wells, and from 0.8 to 9.8 L/s for surficial wells. Values in Table 14.4 only include multi-user wells (thus excluding residential wells). From this table, both bedrock and surficial formations of Newfoundland appear

TABLE 14.4 SUMMARY OF MULTI-USER WELL CHARACTERISTICS FOR EACH PROVINCE

PROVINCE	NO. OF WELLS AVAILABLE	AVERAGE WELL DEPTH (M)	AVERAGE STATIC WATER LEVEL (M)	AVERAGE WELL YIELD (L/S)
BEDROCK				
New Brunswick	371	88.4	7.2	11.36
Newfoundland*	809	50.1	–	0.25
Nova Scotia	777	71.6	5.8	1.21
Prince Edward Island	72	70.4	7.2	13.3
Quebec	76	53	7.1	2.73
SURFICIAL **				
New Brunswick	93	21.3	4.0	1.64
Newfoundland*	8*	–	–	0.76
Nova Scotia	116	15.2	2.7	4.55
Quebec	95	26	3.2	9.83

* Values for Newfoundland correspond to averages obtained for a group of wells for a given municipality. "-" means that the value was not available.
** No high-capacity well taps surficial deposits in Prince Edward Island.

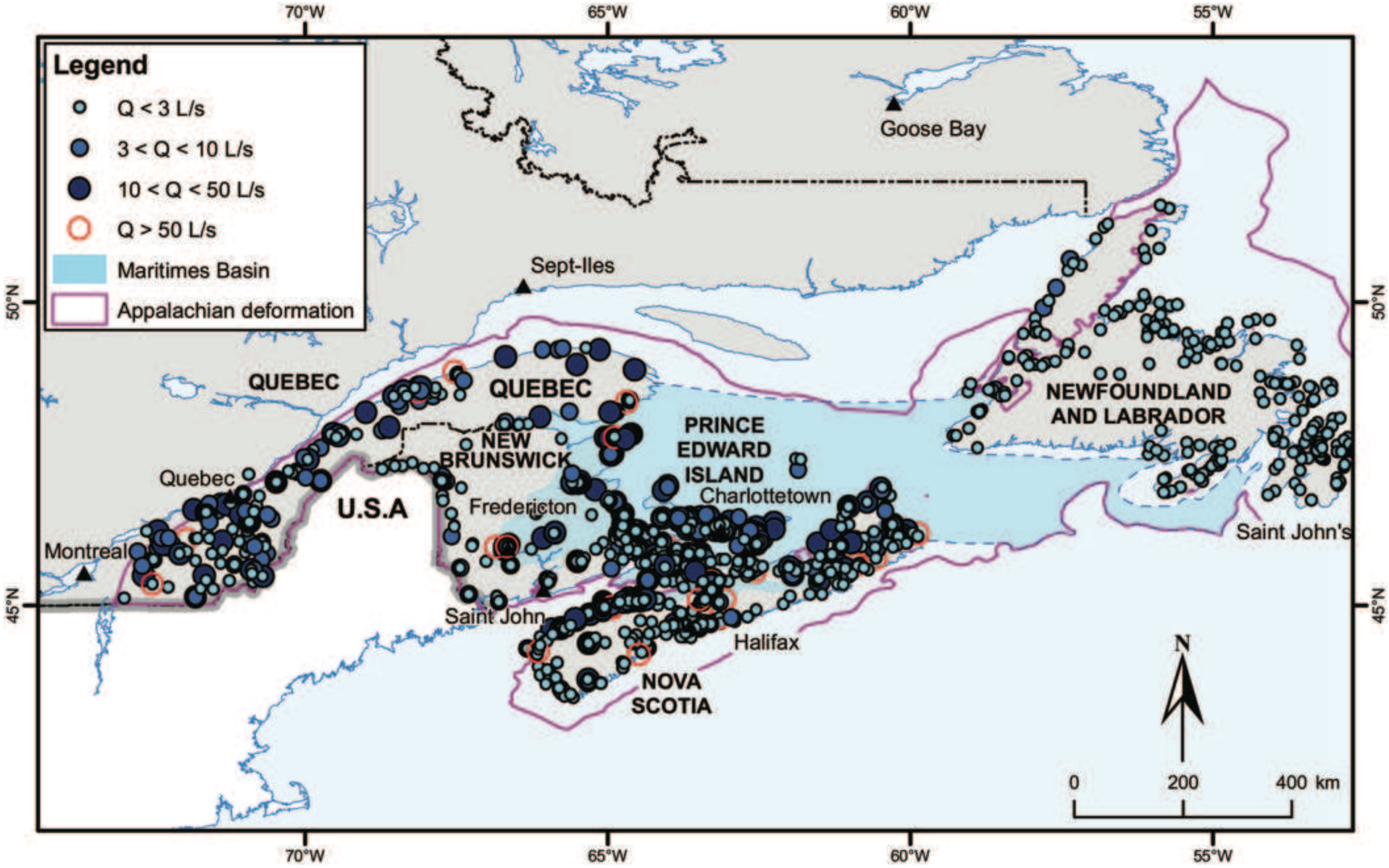


Figure14.14 Well yields from high-capacity (multi-user) wells, including both bedrock and surficial aquifers.

to be the least productive. Very few wells in this province have a yield larger than 3 L/s and very few tap surficial deposits (<1%).

Figure 14.14 presents well yields of high-capacity (i.e., multi-user) wells, from both bedrock and surficial aquifers. Therfore, the available information on well yields provides an approximate picture of groundwater withdrawals only for populated areas (where high yields are required). The yields used for Figure 14.14 were classified into four categories, according to their values. Most wells (63%) have a yield less than 3 L/s; only 21% have a yield higher than 10 L/s, and 2.7% above 50 L/s. In Newfoundland, typical yields are very small (less than 0.5 L/s), with slightly higher yields located in the Long Range Mountains.

Groundwater levels in the Appalachian region vary from flowing artesian conditions, to depths reaching as much as 50 m below the ground surface. Because of the fracturing and/or lenticular arrangement of beds, wells in fractured aquifers can show significant water level differences over a very short distance (revealing high vertical hydraulic gradients). In spite of this wide range of conditions, the water table is most often found within about 7 m from the surface, although usually deeper in high-relief areas.

Figure 14.15 presents the bedrock piezometric map produced by the MGWI project. Piezometric maps provide estimates of the spatial distribution of hydraulic heads and groundwater flow direction, based on water level measurements. They are key pieces of information and are typically one of the first outputs to be produced. Hydraulic heads are estimated by subtracting groundwater levels (depths) from ground surface elevations.

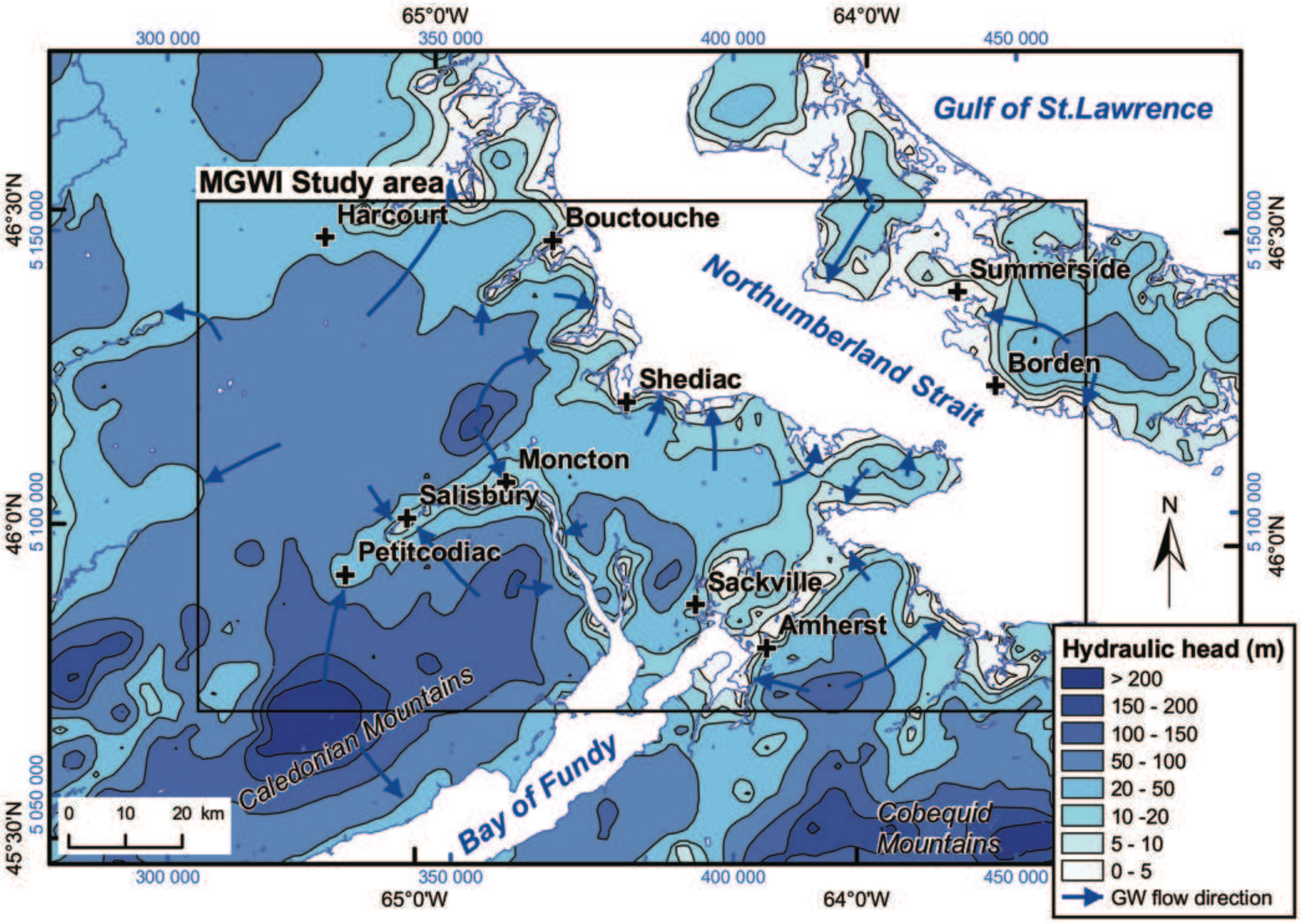


Figure 14.15 Piezometric map of the bedrock aquifers in the MGWI Project area of the Maritimes Basin (arrows indicate general flow directions) (adapted from Rivard et al., 2008).

Groundwater levels used for Figure 14.15 were collected from various sources, such as provincial databases, field campaigns and reports. Maps developed in the MGWI and Annapolis projects show that groundwater flow in bedrock aquifers is mainly regional and topographically driven (i.e., that water follows the topography), generally flowing toward the main river of a given watershed or to the ocean. Boundaries of individual groundwater flow systems essentially mimic surface watershed boundaries. These observations could likely be extended to a large part of the Maritimes Basin. Groundwater flow in the Appalachian piedmont is assumed to be mainly regional, and more local in the uplands; however, more work is necessary to confirm the role of valleys in the piedmont (Lefebvre et al., 2011).

The proportion of groundwater discharge to rivers may be quantified from river hydrograph separation. It is estimated that groundwater discharge in the Appalachian region accounts for about 60%, and maybe even up to 70%, of annual stream flow (Randall et al., 1988; Benson et al., 2007; Rivard et al., 2012). Many municipal wells are, or used to be, located in close proximity to streams and rivers to ensure that enough water was available for well recharge, and also because granular formations are often present along such water courses. Recharge to the Saint John River valley aquifers, for example, is often dominated by pumping-induced influx of river water, contrary to more regionally-extensive aquifers. This is the case for Fredericton, the largest municipality within the Canadian Appalachian region to use groundwater from surficial deposits exclusively. Hodder and MacQuarrie (2004) have noted that this form of recharge is also likely dominant for the Grand Falls, Edmundston, Perth/Andover and Woodstock municipal aquifers of New Brunswick. It has been estimated that 66% to 70% of recharge to the aquifer supplying the Fredericton well field was derived from the Saint John River (Violette, 1990; Thomas et al., 1994).

It is a known fact that microbial pathogens can travel from surface water to a nearby pumping well. Some provinces (notably New Brunswick, Nova Scotia and Quebec) have established detailed investigation procedures to evaluate any potential hydraulic connection and to test whether particulates or bacteria which might be present in the well water would be indicative of surface water influences (called "GUDI" conditions, i.e., Groundwater Under the Direct Influence of Surface Water). Such conditions may affect the design or construction of a treatment plant.

14.4.4 Water budgets

A water budget reflects the relationship between input and output of water through a region. It is crucial information to have in order to support the development of a water management plan. Values for the individual parameters included in a water budget, however, can vary widely and may be difficult to estimate with accuracy, especially for recharge. Several methods are normally used to obtain ranges for each budget parameter. Precipitation is high in the Appalachian region, on the order of 1,150 mm/year (even more for Nova Scotia), and till at the surface usually allows a fair amount of this water to infiltrate. Therefore, it is often (erroneously) assumed, in initial estimates, that evapotranspiration, surface runoff, and infiltration each represent one third of available water. This fraction may not adequately reflect the infiltration rate, however, depending on parameters such as slope of the ground surface, soil texture, timing and intensity of precipitation, and land use. Furthermore, not all the infiltrated water reaches bedrock aquifers, which means that recharge to the regional aquifer is often much less than 33% of precipitation, except where permeable deposits overlie permeable rocks. In general, aquifers supply water to streams in eastern Canada, even during the summer. Figure 14.16 presents a summary of plausible value ranges for the Maritimes Basin water budget.

According to Peters (1981), the proportion of the total precipitation that infiltrates the Maritimes Basin varies from 1% to 50%, and as much as half of this infiltration is expected to occur during the spring period. The MGWI study estimated recharge to bedrock between 130 and 165 mm/year over the entire study area (varying from 300–400 mm/year over Prince Edward Island to ~22 mm/year over the basement Complex). This represents 13% of precipitation on average.

Estimated values of infiltration for the Annapolis study ranged from 73 to 430 mm/year, with a probable average bedrock recharge over the entire study area of 80–175 mm/year (Rivard et al., 2013a). Recharge to bedrock aquifers represented approximately 7%–15% of the precipitation, whereas recharge to sand and gravel aquifers (probably close to the upper limit, i.e., 350–400 mm/year), represented about one third of total precipitation. In both studies, recharge rates were

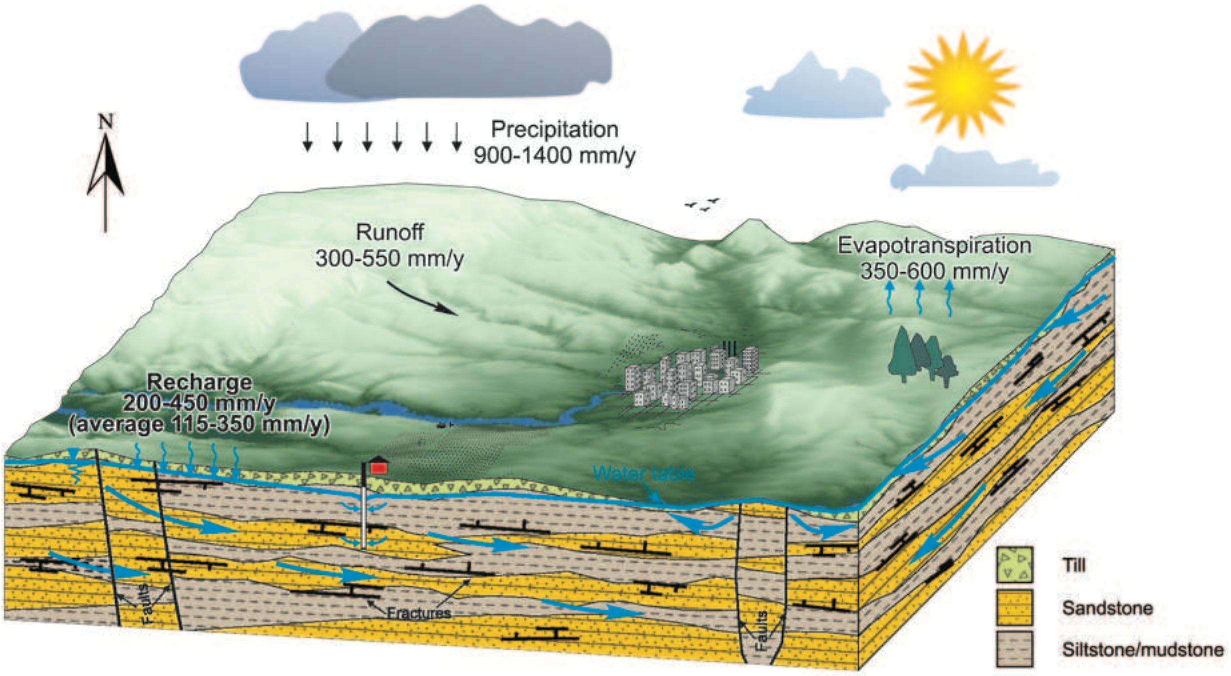


Figure 14.16 This schematic depicts representative ranges for water budget parameters of the Maritimes Basin. Recharge over large regions would be on the order of 115 to 250 mm/year, but can reach 300 to 400 mm/year on Prince Edward Island (adapted from Rivard et al., 2008).

evaluated using three approaches: hydrograph separation, water balance method, and modelling. The highest values were obtained using river hydrograph separation. However, recharge rates estimated by this method commonly reflect groundwater circulation through till and thus, may overestimate recharge to bedrock (Randall et al., 1988) when tills are saturated.

Local studies in New Brunswick have provided recharge values of 15% and 13% of precipitation for the town of Sussex and the Fredericton area, respectively (Jacques Whitford Environment Ltd., 1995; Gemtec Ltd. and FGA Ltd., 1994). Brown (1971) estimated the recharge rate near Shippagan (Taylor Island, in northern New Brunswick) to be 500 mm/year, where till is generally very thin (0.5 m) or absent, and rocks are highly fractured and weathered in the uppermost part. For Prince Edward Island, Francis (1989), using hydrograph separation, estimated that the recharge rate of the central portion of the island should be between 21% and 43% of annual precipitation, while Jacques Whitford and Associates Ltd. (1990) suggested 30% as a mean value for the entire island. On Îles-de-la-Madeleine, all reported values provided a recharge close to 230 mm/year (Groupe Madelin'Eau, 2004), also representing approximately 30% of precipitation. The minimum annual groundwater recharge in Nova Scotia was estimated between 125 mm to 150 mm over a watershed (the province being divided into 44 watersheds), or approximately 10% of the mean annual precipitation (Nova Scotia Museum of Natural History, 1996). Using the same 44 watersheds, Kennedy et al. (2010) have also recently presented recharge and groundwater use values for the province. Recharge values, illustrated in Figure 14.17, were based on baseflow estimates; they provided values ranging from 14% to 25% of total precipitation. Values reported in an NSE (Nova Scotia Environment) database, range from 8% to 30%, depending on the local context. All values are summarized in Table 14.5.

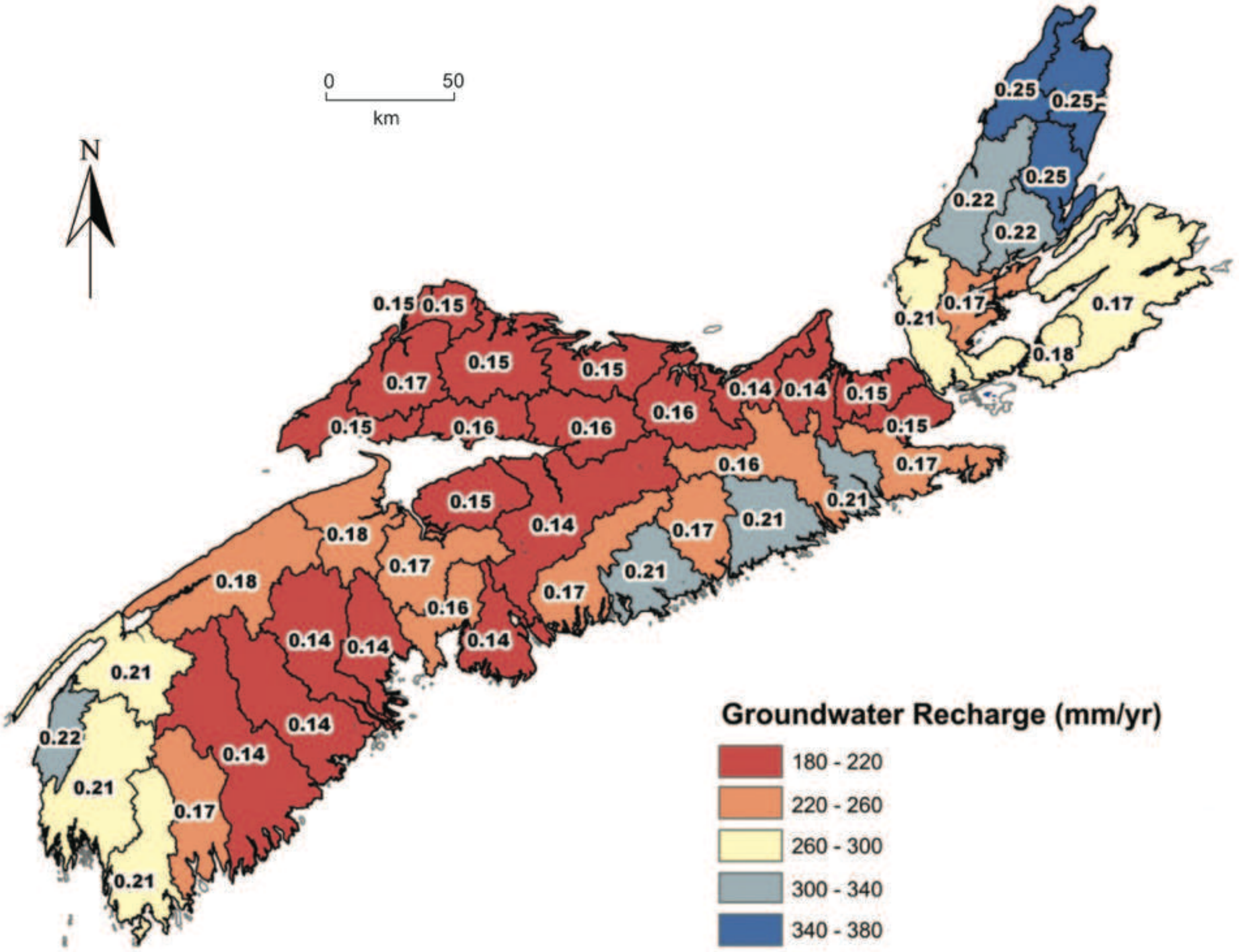


Figure 14.17 Estimated groundwater recharge across Nova Scotia (taken from Kennedy et al., 2010). Recharge ratios are also provided inside each watershed.

Recharge rates are important information for the management of groundwater resources, although, by themselves, are not sufficient to determine sustainability: the effects of changes in groundwater level on groundwater discharge rates, and aquifer storage, must also be considered (Healy, 2010). Sustainable yields must be estimated using ecological, demographical, economical, and cultural considerations. The percentage of groundwater demand (or use) as a fraction of recharge is an important parameter and is required in order to estimate the sustainability of any groundwater resource.

Although first-order estimates of groundwater use in each province are available, these values are usually less well known at the local scale, and little or no information is available on spatial distribution. Recently, Nova Scotia has made an effort (Kennedy et al., 2010) to estimate groundwater usage at the provincial scale using three major types of groundwater users (municipal, residential, and others) in 44 watersheds, based on methodology developed during a pilot study in the Annapolis Valley (CBCL Limited, 2009).

Results of the MGWI and Annapolis regional studies did not indicate overexploitation on a regional basis. Overall groundwater use in the MGWI study was estimated to be on the order of 5% of recharge. As a result, groundwater extraction in many regions could probably be increased

TABLE 14.5 SUMMARY OF REPORTED RECHARGE VALUES

LOCATION	RECHARGE RATE* (%)	SCALE	SOURCE
New Brunswick	1–50	Provincial	Peters, 1981
Nova Scotia	Min=10	Provincial	Nova Scotia Museum of Natural History, 1996
Nova Scotia	8–30	Provincial	NSE database
Nova Scotia	14–25	Provincial	Kennedy et al., 2010
Prince Edward Island	21–43	Provincial	Francis, 1989
Prince Edward Island	30	Regional	Jacques Whitford and Associates. Ltd., 1990
Maritimes Basin (MGWI study)	13	Regional (10,500 km^2)	Rivard et al., 2008
Annapolis Valley, NS	11–15	Regional (2,100 km^2)	Rivard et al., 2007; 2012; 2013a
Îles-de-la-Madeleine, QC	30	Regional	Groupe Madelin'Eau, 2004
Chaudière, QC	6	Regional (3,615 km^2)	Benoit et al., 2008
Sussex, NB	15	Local	Jacques Whitford Environment Ltd., 1995
Fredericton, NB	13	Local	Gemtec Ltd. and FGA Ltd., 1994
Shippagan, NB	50	Local	Brown, 1971

* In % of total precipitation. All values are for bedrock aquifers, except for Sussex and Fredericton, which are surficial aquifers.

significantly without jeopardizing other activities and natural habitats. Literature-based water use surveys for the Annapolis Valley, together with regional estimates, provided preliminary groundwater use estimates ranging from 3% to 42%, with an average at 21.5%, of the overall recharge to bedrock. These values were later refined in a consultant report carried out using questionnaires and existing data from the provincial database (CBCL Limited, 2009). Based on numbers provided in this report, groundwater use for the area represents about 7% of recharge, lying at the lower end of the range estimated by the Annapolis study. However, groundwater use, in the more populated and intensely farmed areas of the eastern part of the Valley, likely reaches more than 50%, a matter of some concern to local authorities because of the possible impacts of groundwater level lowering, including decreasing baseflow rates and altered aquatic habitats. Kennedy et al. (2010) found that groundwater use throughout Nova Scotia may range between 0.1% and 13% of recharge. As stated by these authors, although groundwater use seems to be significantly less than groundwater recharge on a regional scale, groundwater quantity issues are demonstrated in the province by the increasing number of water servicing requests and well modifications to improve yield.

Groundwater/surface water use should be known with a fair degree of confidence prior to developing an effective water management plan. Currently, this is an evident knowledge gap that must be addressed in the near future, especially in view of predicted population growth, economic development, and climate change that are expected to exert more pressure on groundwater resources, especially those in coastal areas in future years.

14.4.5 Monitoring wells and long-term behaviour

All Canadian provinces have numerous monitoring wells to observe groundwater level changes on

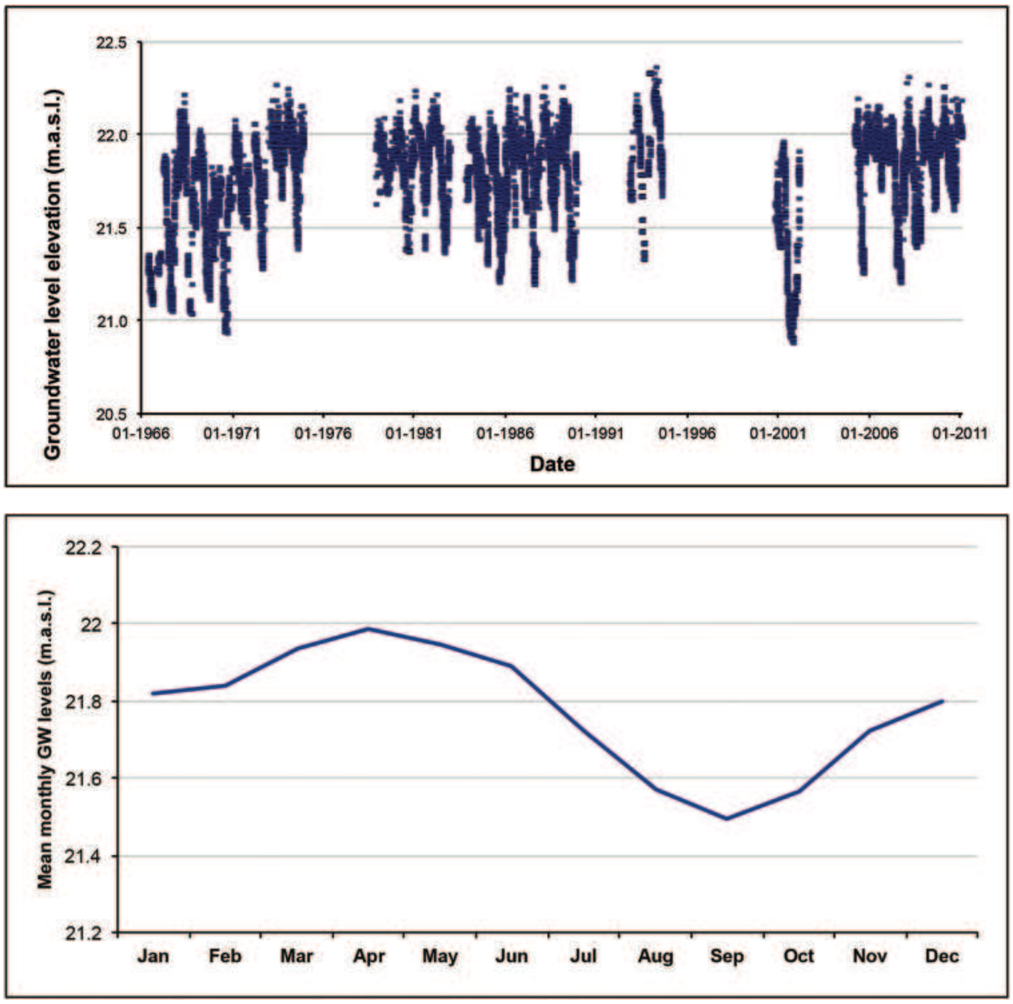


Figure 14.18 Historical data of groundwater levels from a provincial monitoring well in Greenwood, Nova Scotia a)on a daily basis; b) on a monthly basis, averaged over the entire record.

a long-term basis. The length of these records, and the number of short- and long-term data gaps, vary widely, and the specifications of these monitoring wells are not always fully documented. Several well monitoring programs were abandoned in the 1980s and 1990s due to budget constraints. In the Appalachian region, Quebec currently has 9 active monitoring wells (with 17 new wells soon be added, consult http://www.mddep.gouv.qc.ca/eau/piezo/index.htm), New Brunswick has 10, Nova Scotia has 38, Prince Edward Island has 13, and the island of Newfoundland has 10. Many of these monitoring wells are quite recent (installed after the year 2000) and most are now equipped with automated dataloggers. The number of observation wells appears to be low, at least in some areas, for such a diverse hydrogeologic region.

Mean annual water-level fluctuations typically range from 1 to 4 m (McIntosh, 1984; Francis, 1989; New Brunswick Department of the Environment, 1992). Well hydrographs usually show water-level responses to seasonal patterns: a major spring recharge event followed by a decline during the summer, a smaller recharge event during the fall, and, finally, a decline during the winter. Some recharge events, caused by winter thaws and rainfall, may take place during winter in coastal areas and areas with micro-climates (e.g., Annapolis Valley, Nova Scotia). Figure 14.18a charts an example of a daily hydrograph from a monitoring well located in a sand and gravel unit in Greenwood, Nova Scotia; Figure 14.18b shows monthly fluctuations estimated over a year, using the entire record (28 years).

A Canada-wide study by Rivard et al. (2009) employed trend statistical analysis of historical series of baseflow and groundwater levels as long-term recharge indicators, based on the commonly used non-parametric Mann-Kendall test. Series of 30, 40, and 50 years were selected. Although mixed trends were often observed across Canada, both baseflow and groundwater level data evidenced either no trend, or decreasing trends in

Atlantic Canada (and thus in the Appalachians), suggesting a recharge decrease within the region. Only six monitoring wells in the region had sufficiently long series, and four of those (two in PEI and two in NS) showed downward trends. Following this statistical study, a modelling exercise was carried out in the Annapolis Valley using the quasi-2D hydrological model HELP, and climate scenarios from a regional climate model, to define plausible projected ranges of both inter- and intra-annual variability (Rivard et al., 2013b). The model runs predicted an increase in annual recharge over the 2041–2070 period, contrary to the historical trend. However on a seasonal basis, a significant recharge decrease was observed during the summer, mainly due to a drop in precipitation, consistent with historical trends, while winter recharge increased over the same period in response to a temperature increase. These results are in general agreement with modelling studies such as those of Jyrkama and Sykes (2007) and Toews and Allen (2009) for other parts of Canada. Discrepancies in results based on the two approaches (statistical and modelling) may be due to the fact that historical series may not be representative of future climatic trends, or perhaps, to large uncertainties (both hydrological and climatic) within the models.

14.4.6 Groundwater quality

14.4.6.1 General groundwater quality and naturally occurring ions

Groundwater quality is generally excellent throughout most of the Canadian Appalachians. Natural groundwater quality used for water supply purposes usually meets Canadian drinking water guidelines (Health Canada, 2010), although concerns have been raised over the past few years regarding naturally occurring fluoride, arsenic, and uranium concentrations, and, to a lesser extent, iron and manganese concentrations. Most of these concerns are related to agricultural pollution, leaks from hydrocarbon-storage tanks, sewage and waste disposal, induced seawater intrusion, and road deicing activities. Several major and minor ions, trace metals, hardness, acidity (pH), and total dissolved solids (TDS) were mapped during the MGWI and the Annapolis projects. The results are available in atlases (Rivard et al., 2005, 2007). Hydrogeochemical data for these projects was provided largely from provincial databases. The New Brunswick Department of Environment has published a groundwater chemistry atlas depicting 28 general chemical parameters in private drinking water wells compiled from 1994 to 2007 data (New Brunswick Department of Environment, 2008). A geochemical study of the Montérégie Est area (Beaudry, 2013) that includes contexts 1 and 2 (see section 14.3 Hydrogeological contexts) defined different water types based on recently collected data, which helped better understanding groundwater flow.

Until recently, the occurrence of iron and manganese was not thought to be a threat to health, and most information collected about these metals was largely concerned with aesthetic limits. Contemporary studies, however, suggest a potential link between elevated Mn concentrations and the intellectual impairment of children (Wasserman et al., 2006; Bouchard et al., 2011). Aesthetically, elevated Mn concentrations give water a metallic taste, in addition to posing problems for laundry (black stains) and pipes (clogging). As a result, these concentrations must be lowered. Production wells in the Fredericton aquifer produce groundwater that may contain dissolved manganese concentrations

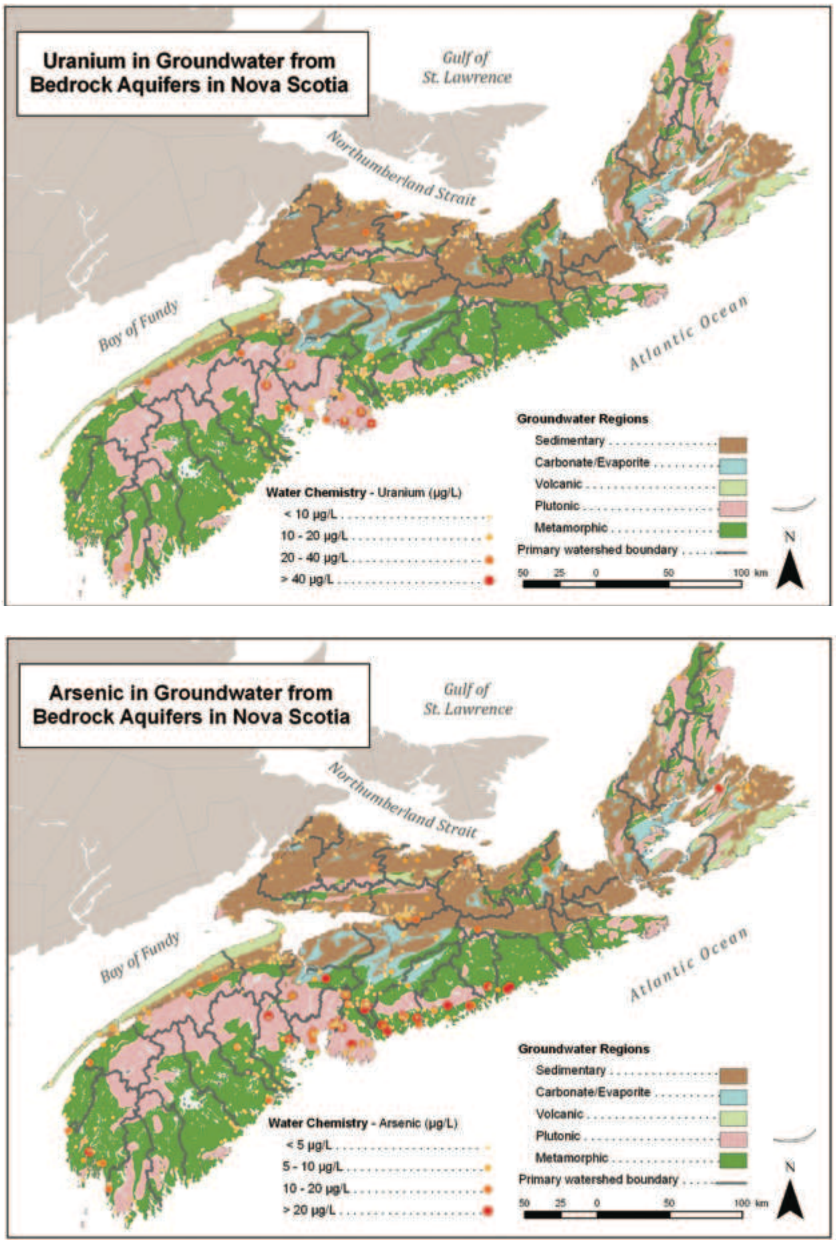


Figure 14.19 Natural occurrence of uranium and arsenic in Nova Scotia groundwater (taken from Kennedy and Finlayson-Bourque, 2011a, 2011b).

up to approximately 2 mg/L (Thomas et al., 1994), whereas the aesthetic objective is 0.05 mg/L (see Box 14-2). The water must be treated to remove manganese prior to distribution.

Elevated concentrations of fluoride, arsenic, and uranium are known to have impacts on human health. These elements are present in drinking water when groundwater dissolves the minerals that carry them. Fluoride, arsenic, and uranium are more likely to be found in drilled wells than in surficial wells, because they are present in different types of rocks and because the reducing conditions (low redox potential), more typical of bedrock groundwater, maintain them in solution (Fe^{2+}, Mn^{2+}). In sparsely located areas, such as in the municipality of Maria, in Gaspésie, and some municipalities east of Montreal, in Montérégie Est (Québec), fluoride concentrations exceed the acceptable drinking water limit of 1.5 mg/L; this is also true of areas along the Petitcodiac and Saint John Rivers, and the coast of Baie des Chaleurs in New Brunswick. Arsenic problems have been documented in a few areas of New Brunswick (on the Kingston Uplift) and Quebec (Saint-Gédéon in Beauce and Kingsbury in Estrie). Occurrences of slightly elevated arsenic and uranium concentrations in groundwater are relatively common in Nova Scotia, New Brunswick, and Newfoundland,. Nova Scotia has mapped the spatial distribution of these parameters (Figure 14.19), while Newfoundland has mapped areas of their potential occurrence (Figure 14.20). In Nova Scotia, arsenic concentrations most commonly exceed the drinking water guideline in metamorphic rock, whereas uranium concentrations most commonly exceed the guideline in plutonic rock.

When a well is constructed in New Brunswick, sending water samples to the Department of Environment is mandatory, whereas in Nova Scotia and Prince Edward Island, water analyses on private wells are provided to the government on a voluntary basis, except in the case of public

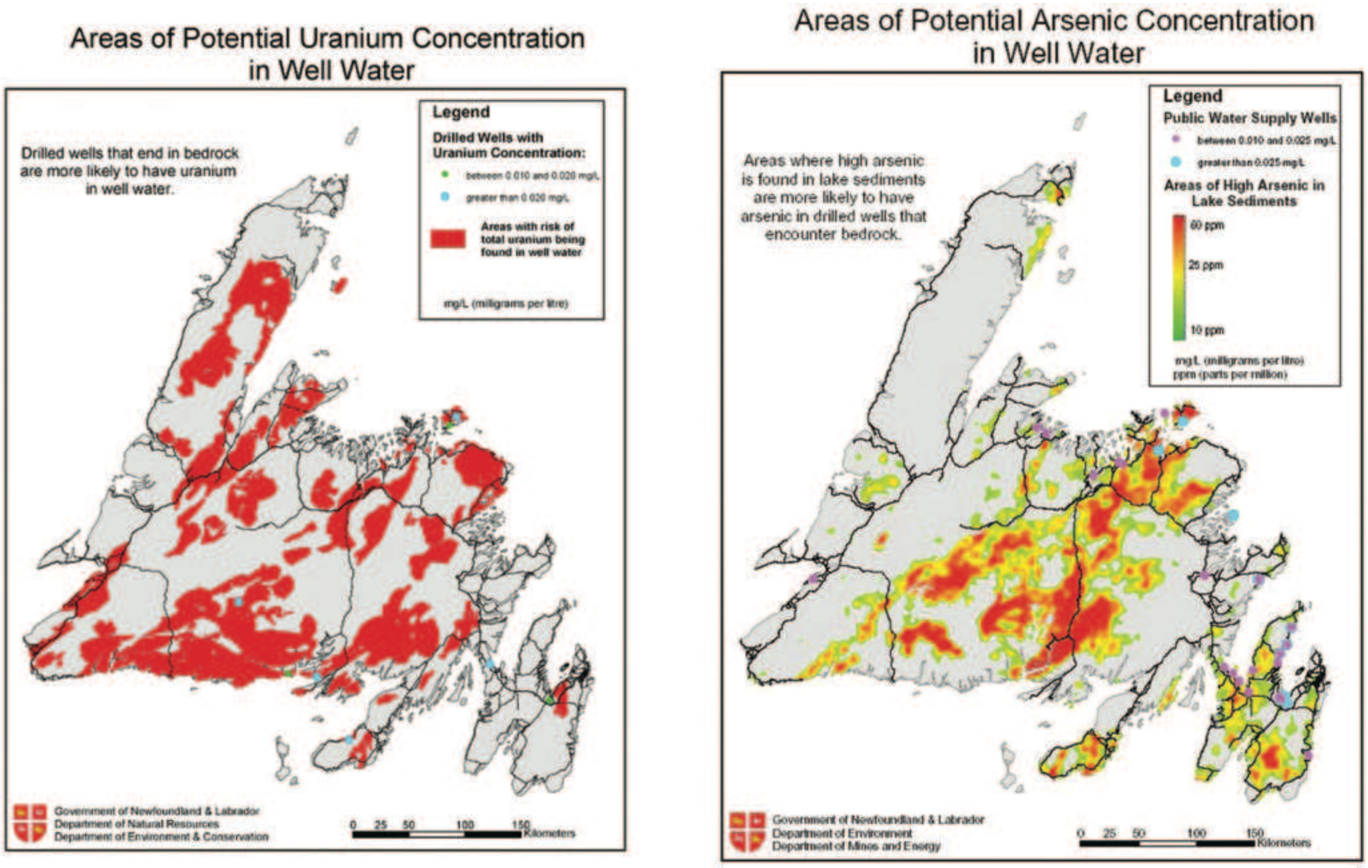


Figure 14.20 Areas of potential uranium and arsenic concentrations in well water (taken from NL Department of Environment and Conservation website http://www.env.gov.nl.ca/env/waterres/cycle/groundwater/well).

drinking water supplies where these analyses are mandatory. Some 5% of all drilled water wells in Newfoundland are randomly sampled during routine provincial inspections of new wells; this helps provide the province with a representative picture of groundwater quality. All municipal wells in Quebec are closely monitored and water analyses have been mandatory for all new wells since 2003.

Figure 14.21 presents a Piper plot of geochemical data compiled from public wells in four provinces (Nova Scotia, New Brunswick, Prince Edward Island, and Quebec). All analytical procedures available after the 1980s have been used to calculate medians, with the results classified according to exploited aquifer. Therfore several analyses are usually applicable for any given well.

Groundwater flowing in porous sedimentary bedrock typically has a higher total dissolved solids content, alkalinity, and hardness than water that flows through fractured rocks with low primary porosity, and water flowing through surficial sediments, mainly because of greater potential mineral dissolution, and longer residence times. In the Maritimes Basin, however, groundwater flowing through bedrock usually seems to be moderately to weakly mineralized, and thus, groundwater circulating in igneous and metamorphic rocks has a similar concentration of dissolved chemical species (Figure 14.21). This may be due to the fact that the siliciclastic rocks which constitute most aquifers are chemically stable and that most wells are supplied by relatively shallow, young water. Tritium dating results from Nova Scotia monitoring wells seem to corroborate the latter assumption, since only 5 of the 18 wells showed water older than 1954. Multi-level tritium dating in a 85 m deep well near

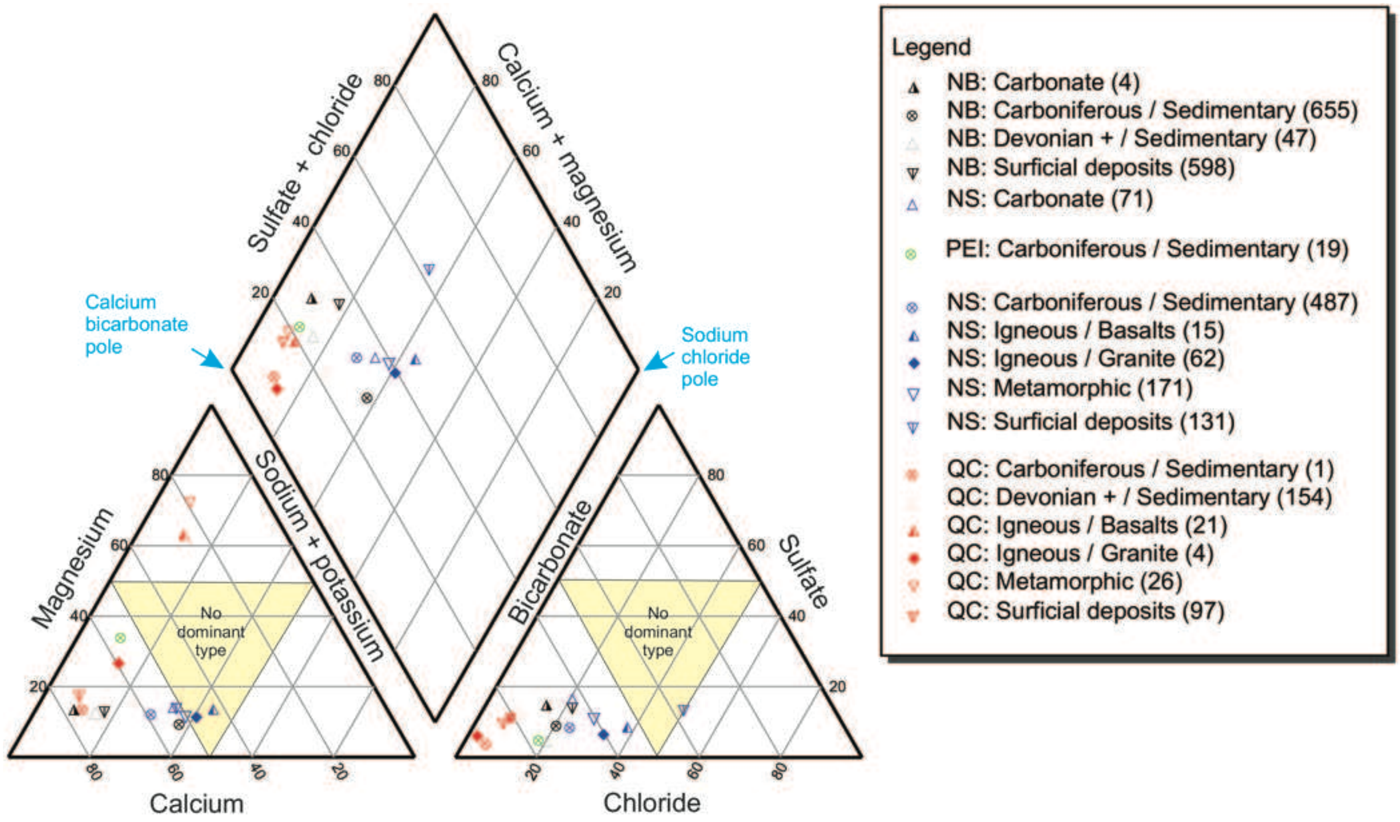


Figure 14.21 Piper plot of median water quality values for surficial deposits and bedrock types in Nova Scotia, New Brunswick, Prince Edward Island and Quebec. In the legend, "Carboniferous" is used to represent Carboniferous and younger rocks, whereas "Devonian +" refers to Devonian and older rocks.

Wilmot, Prince Edward Island, indicated a shallow (≈50 m) zone with tritium presence (therefore less than 50 years of age); carbon 14 analyses indicated older water (5,000–7,000 yr) for the lower 50 to 85 m of that well (Paradis et al., 2007).

Groundwater in the Appalachian region appears to be either of the calcium-bicarbonate type or to have no dominant type. Water from Quebec wells comes closest to the calcium-bicarbonate pole, while water from Nova Scotia wells is the furthest (closer to the middle, i.e., no dominant type). Groundwater found on Prince Edward Island's western side is typically of the calcium-bicarbonate ($Ca-HCO_3$) type, which can be attributed to calcite cements. Groundwater in the central and eastern portions of the island is characterized by $Ca-Mg-HCO_3$, attributed to dominantly dolomitic cements (Somers et al., 1999). Sedimentary rocks in provinces of NB, NS, QC or PEI tend to be closest to the calcium-bicarbonate pole, likely due to dissolution of the dolomitic cement which binds the sandstone dominating horizons where water is tapped. Water in surficial deposits and basalts usually has the lowest bicarbonate content (or alkalinity), whereas sedimentary and carbonate rocks have the highest. Chloride and sodium concentrations are normally low in bedrock, but can increase in coastal areas or in specific local regions because of evaporites (such as in the Windsor Group) or other minerals contained in rocks, or because of depth. Sodium-chloride type water is present at varying depths near the coast (<500 m).

Except for waters from carbonate rocks that are more highly mineralized, compiled data show that groundwater typically has total dissolved solids (TDS) ranging from 130 to 200 mg/L, hardness varying between 50 and 150 mg/L, and a conductivity less than 400 µS/cm (see the example for Nova

Scotia in Figure 14.22, that may be considered representative of the geochemistry across the study area for these rock types). The mean acidity (pH) approaches neutral, but is usually slightly alkaline, between 7 and 8, probably quite representative of most rock units in the Canadian Appalachians. As a comparison, median TDS of fractured nonporous bedrock was reported to be on the order of 115 mg/L, and 220 mg/L for porous sedimentary bedrock in New England (USA), a region that also belongs to the northeastern Appalachians (Randall et al., 1988). Water in surficial sediments shows values similar to those of less mineralized igneous and metamorphic rocks.

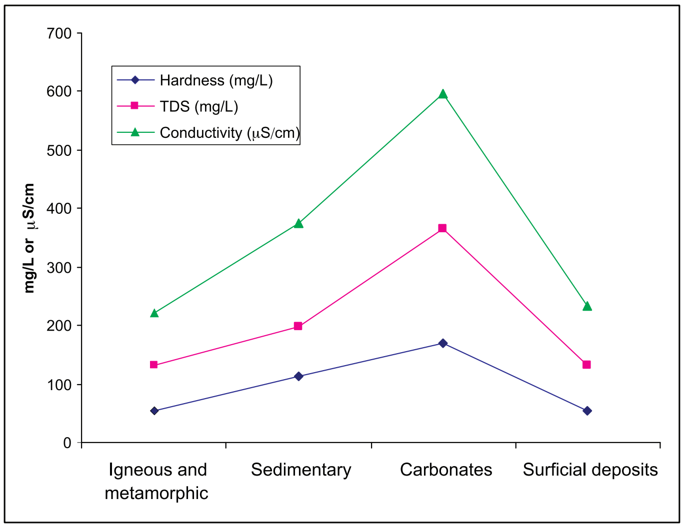


Figure 14.22 Median values for hardness, TDS, and conductivity in Nova Scotia.

14.4.6.2 Point source and diffuse pollution

Diverse point source contaminants have affected a number of municipal and residential water supplies within the Appalachian region. One of the most famous contamination cases is the Tar Ponds in Sydney, Nova Scotia. One hundred years of steel and coke production left more than a million tonnes of contaminated soil and sediment in the estuary, thereby affecting groundwater. Acid rock drainage has also been a cause of surface water and groundwater contamination in some areas of New Brunswick and Nova Scotia. The issue of acid rock drainage has been encountered not only at mine sites, but also in construction projects such as highways and the Halifax Airport. Populations located along coastlines are also at risk for saltwater intrusion, especially during the summer months when pumping increases significantly due to tourism-related activities.

Cases of municipal well groundwater contamination as a result of human activities include Sussex, New Brunswick, where groundwater in a sand and gravel aquifer in the Kennebecasis River valley was contaminated by the solvent perchloroethylene (or PCE, Broster and Pupek, 2001); and Miramichi in New Brunswick, where water was contaminated by polycyclic aromatic hydrocarbons (PAHs) believed to be linked to a pressure-treated wood facility. Industrial and commercial activities have also led to local contamination. These can be associated with deicing salts (storage or application); bacteria (e.g., Haldimand and Sandy-Beach area in Gaspésie, Quebec); organic contaminants (Trichloroethylene, or TCE, linked to a solvent bottling plant near Granby and TCE associated with tool production at Roxton Pond, Quebec); PCE from a dry cleaning business in the Greenwood area, Nova Scotia; and petroleum products from inappropriate storage or storage facility leaks as in Cap-aux-Meules on Îles-de-la-Madeleine, Quebec, in Kensington and Tignish, Prince Edward Island, and in Greenwood and Nictaux Falls, Nova Scotia.

Microbiological results from New Brunswick private wells suggested that, on average, approximately one third of wells may currently be affected, or have been affected at one time or another, by total coliforms, while 2.5% (of 4,823 wells) indicated the presence of *E. coli* (New Brunswick Department of

Environment, 2002). Similar numbers were found for the 2000–2009 period in Prince Edward Island (PEI Department of Environment, Energy and Forestry, 2011), while the presence of *E. coli* was observed in 8.8% of the 274 tested wells in the Chaudière watershed (6,682 km^2, Gouvernement du Québec, 2004). The main causes for the presence of total coliform organisms in a well include lack of well disinfection and direct surface water infiltration into poorly constructed wells. The presence of *E. coli* is likely attributable to malfunctioning or improperly maintained sewage disposal systems.

Diffuse (or non-point source) pollution can be a problem in a few locations, especially in intensive agricultural regions. In some areas of Prince Edward Island, in the upper Saint John River valley in New Brunswick, Montérégie Est in Quebec, and in the Annapolis Valley in Nova Scotia, problems related to farming activities are of great concern, particularly nitrate contamination.

Pesticides, while of great public concern, do not seem to be as large a problem, although they have been found to occur in groundwater at low concentrations, typically well below levels of health concern (Briggins and Moerman, 1995; Keizer et al., 2001; MDDEP, 2010; Mutch et al., 1992). There are exceptions, such as the study conducted by Priddle et al. (1989) between 1985 and 1988 beneath two potato fields on Prince Edward Island. Total aldicarb concentrations in this study exceeded maximum acceptable concentrations in 12% of 48 monitoring well samples at certain times of the year. A province-wide study of wells in Prince Edward Island, which sampled approximately 100 drinking wells annually, showed a gradual increase of pesticide detection incidences, from 7% in 2004 to 16% in 2009, with the exception of 2008 where 10% were found (PEI Department of Environment, Energy and Forestry, 2011).

Nitrate concentrations exceeding the 10 mg/L NO_3-N guideline have been found in 4.5% of Prince Edward Island's wells, and in more than 10% of wells in intensively farmed watersheds. 15% of wells in the Annapolis Valley exceed the 10 mg/L NO_3-N guideline (Rivard et al., 2012). The percentage of tested wells exceeding ambient (or natural) concentrations probably provides a more accurate picture of groundwater degradation, as it highlights those wells already affected by anthropogenic activities (suggesting possible increases in subsequent following years, should corrective measures not be taken). Accordingly, 81% of the wells for Prince Edward Island and 65% of the wells for the Annapolis Valley exceed 1 mg/L. These percentages have generally been attributed to intensive agricultural activities, and to the absence of significant attenuation, such as de-nitrification, in the underlying tills or bedrock.

An opposite situation occurs in Quebec's Appalachian piedmont region, where excess nutrients derived from intense farming operations have significantly impaired surface water quality (with the result that the Yamaska River is widely known as the province's most polluted river), yet, to date, groundwater does not seem to be significantly impacted (Lefebvre et al., 2011; Beaudry et al., 2011a). It has been suggested that this is due, at least in part, to the presence of dense, compact till underlying looser, more permeable reworked till at the surface, and to the dense network of collector drains that evacuate water rapidly from the subsurface (Thériault et al., 2013). Additionally, fertilizer contamination may be too young (less than 60 years) to have reached the deeper bedrock wells. This particular issue is currently under

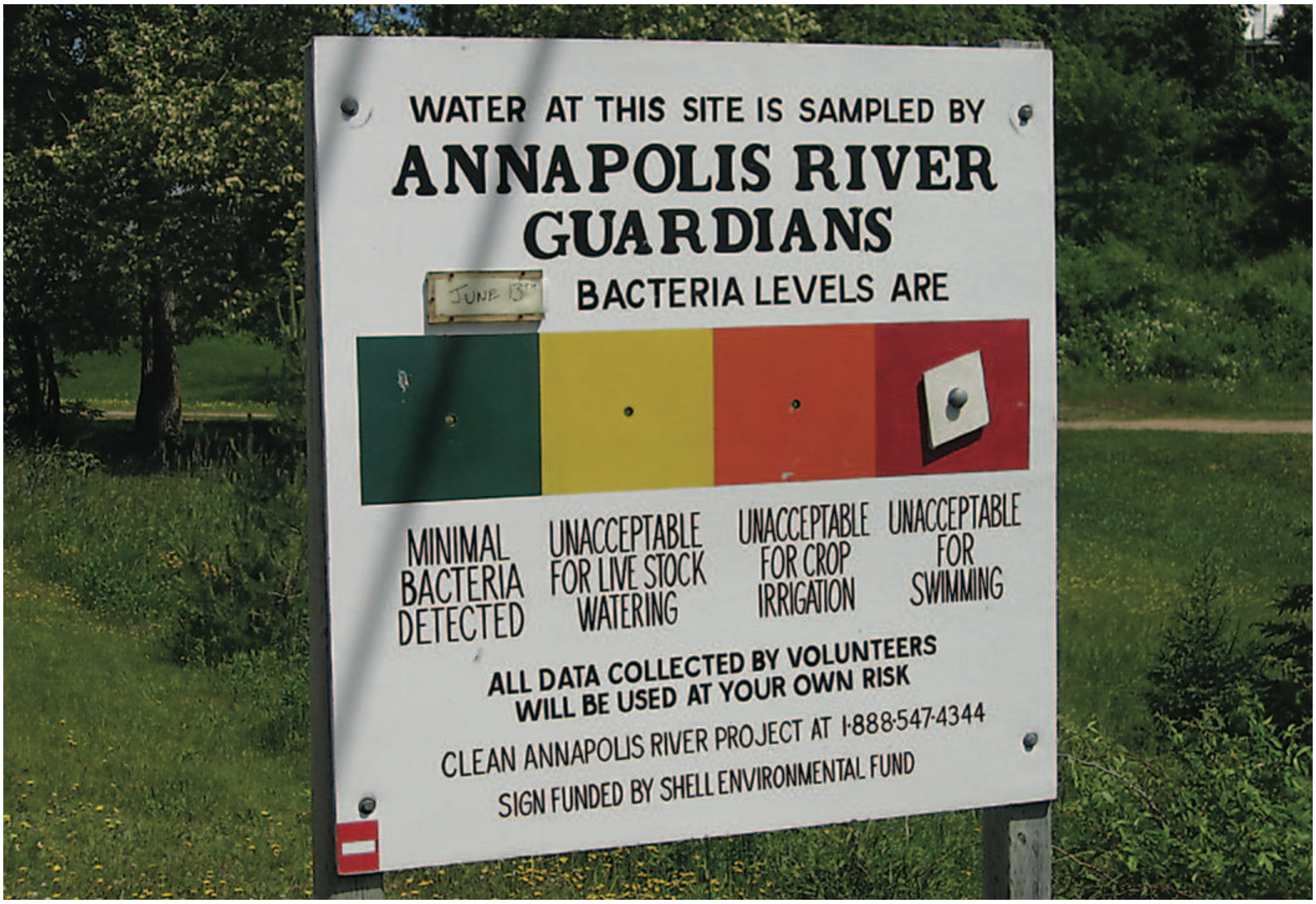


Figure 14.23 Indication of the surface water quality in the Annapolis Valley, Nova Scotia (summer 2004).

investigation as part of a regional hydrogeological study (Lefebvre et al., 2011; Beaudry et al., 2011a).

A recent study on the nitrogen cycle conducted in a region of intensive row crop production in Prince Edward Island found that nitrates in groundwater come mainly from chemical fertilizers, or mineralization and nitrification of plant residues (depending on season), and, to a lesser extent, from manure, and septic systems (Savard et al., 2007). Relative importance of specific nitrate sources in other rural regions may be expected to change, according to different land use characteristics, such as crop or livestock production.

Other concerns about nitrates and bacteria are usually related to poorly constructed or maintained septic systems, the density of these systems, and removal of riparian vegetation by agricultural and forestry operations. Elevated nitrate concentrations attributed to septic system malfunctions (Groupe Madelin'Eau, 2004) are found on Îles-de-la-Madeleine, especially in Pointe-aux-Loups and Île d'Entrée.

Surface water quality may also reflects groundwater deterioration because a significant portion of surface water is derived from baseflow. Surface water in the Annapolis Valley, during summer months, is sometimes too polluted for irrigation and even for swimming (see picture in Figure 14.23). Discharge of nitrate-rich groundwater is considered to be the major pathway for nitrogen to reach surface waters in PEI, with negative (and increasing) consequences for eutrophication of ecologically and economically important estuaries (e.g., Danielescu and MacQuarrie, 2011).

14.4.6.3 Saltwater intrusion and residual marine water

Saltwater intrusions, which can occur as a natural process in coastal areas, may be exacerbated by human-induced activities such as pumping. Brackish or saline groundwater has been reported in some areas, notably in Îles-de-la-Madeleine, Quebec, on the island of Lamèque, New Brunswick, as well as in scattered areas along the New Brunswick coastline. Notwithstanding these reports, saltwater intrusions do not seem to be a major problem, probably because of the abundant recharge that pushes saltwater back to the ocean. Nonetheless, several coastal municipalities which have not yet experienced any such problem are concerned that increasing extraction rates in the future could create a seawater zone encroachment. In Îles-de-la-Madeleine, the saltwater encroachment issue has forced municipalities to apportion pumping among several wells, and to limit pumping rates so as to avoid large drawdowns, and the subsequent upwelling of saline waters. A few PEI wells impacted by saltwater intrusion are deliberately exploited by the aquaculture and fish processing sectors due to adequate salinities, good microbiological quality and constant temperatures, factors which make this groundwater more attractive than surface water. The main risk of saltwater intrusion in the Atlantic region is likely high water demand.

Predicting location of saltwater-freshwater interfaces can be very difficult because of the stratified nature of Maritimes Basin's bedrock. This results in a succession of very distinct horizontal permeabilities, combined with confined and unconfined conditions, and complicated by the fact that water flows mainly through fractures (e.g., Carr, 1969; van der Kamp, 1981). As a result, information on the distribution of saline or brackish water comes mainly from descriptions of discrete occurrences, and the phenomenon remains poorly known and understood. It seems that the influence of saltwater intrusions can be observed only within a few tens to hundreds of metres from the coast (Rivard et al., 2008). Carr (1969), however, noted saltwater intrusions up to 350 m inland in Prince Edward Island, indicating that the zone of diffusion can encroach a considerable distance into an aquifer at shallow depths, even when the area involved has no large groundwater withdrawals. Brown (1971) and van der Kamp (1981) observed that groundwater salinity generally rises sharply in the dry period, and falls during the autumn, as abundant precipitation recharges the aquifer, increases the water table elevation and flushes out the saline water.

Climate change is expected to cause a rise in sea level to between 0.18 and 0.59 m above present by the end of the 21st century (IPCC, 2007). This increase will force changes in the position of the freshwater-saltwater interface in many coastal aquifers and could threaten water supplies. These effects will be amplified by potential reduction in water table elevation due to increases in temperature and thus evapotranspiration, and greater groundwater withdrawals (increased anthropogenic demand for groundwater). It is expected that some aquifers will react very quickly to such changes, while others may take centuries or millennia to respond. There is currently no consensus on how different aquifers within this region will behave. Several climate change–seawater intrusion studies are underway in the Atlantic Provinces under the Atlantic Climate Adaptation Solutions Association (ACASA) groundwater theme (http://atlanticadaptation.ca/groundwater).

Aquifers underlying regions below marine limit (submergence zones shown in Figure 14.4) became saline or at least brackish during the postglacial marine invasion, due to the migration and mixing of seawater with groundwaters underlying the Goldthwait, Champlain and De Geer Seas. Cloutier et al. (2010) estimated that the Champlain Sea had a TDS concentration of ~11,300 ppm, corresponding approximately to 34% seawater and 66% fresh water coming from glacial meltwater and precipitation. Since marine waters essentially withdrew from present land areas about 9,500 years ago, saline groundwater has gradually been replaced by fresh water as a result of recharge from precipitation. TDS concentrations in the Appalachian piedmont are now typically below 1,000 mg/L (Beaudry et al., 2011a). A few areas of the piedmont, however, still have TDS concentrations above 1,000 mg/L (or chloride >250 mg/L), thus above aesthetic drinking water guidelines, likely due to locally lower groundwater velocity, or to weak recharge rates. These areas are illustrated in Beaudry et al. (2011b). Similar zones with significant salt content, though usually below the saline threshold (TDS of 4,000 or 5,000 mg/L), are likely to occur in other regions subjected to postglacial submergence. Location of these zones is not well known, mainly because wells with easily detected poor water quality are abandoned and sealed without any further geochemical analysis, with the result that these occurrences are not reported in provincial databases. Work is currently being conducted to identify the origin and specific causes of the presence of brackish groundwater in southeastern Quebec (Beaudry et al., 2011a).

14.4.7 Aquifer vulnerability

Vulnerability to surface contamination is largely influenced by the nature and thickness of the surficial sediment cover, recharge rate, and water table depth. Surficial aquifers are generally more vulnerable to surface contamination than bedrock aquifers, because of their shallow depth and the common absence of confining, low-permeability units.

Both regional studies carried out in the Maritimes provinces (MGWI and Annapolis) used the DRASTIC methodology (Aller et al., 1987) to present an evaluation of the relative vulnerability of the groundwater to current and potential contamination problems. DRASTIC is a widely used groundwater vulnerability mapping method (Al-Zabet, 2002), although, for the MGWI project, only a simplified version, treating the two most variable parameters (recharge and hydraulic conductivity of the till layer) for this specific hydrogeological context was used to indicate groundwater vulnerability. Both studies concluded that bedrock aquifers of the Maritimes Basin may generally be considered as moderately to highly vulnerable. As expected, results also showed that the aquifer units with the greatest production potential also correspond to higher vulnerability potential, due to elevated values of permeability and recharge. "High" vulnerability scores (indices) were obtained for unconfined coarse-grained surficial sediments, such as the glaciofluvial sediment aquifers of the eastern part of the Annapolis Valleys, and for bedrock aquifers of Prince Edward Island, and those underlying the Annapolis Valley floor (i.e., the Wolfville Formation, supplying most of the Valley's residents). Nevertheless, it must be emphasized that the classes obtained with DRASTIC are relative; sandy till covering PEI, for instance, probably protects the underlying bedrock formations better than a sand cover alone would.

Near surface contamination in the Fredericton area has resulted from past hydrocarbon and chlorinated solvent releases (Violette and MacQuarrie, 1993; Craig et al., 1993), although such contamination has typically been limited to the surficial fluvial sand unit overlying a clay/silt aquitard: to date, this has not posed a threat to deeper production wells, and a protection plan regulating certain activities and potential contaminants within designated well field protection areas has been implemented. In Îles-de-la-Madeleine, the vulnerability of the aquifers combined with the presence of large freshwater users (fish and seafood processing plants and the tourist industry in the summer) have forced municipal authorities to execute a unique, secure water supply management plan. All provinces have recently developed programs to help municipalities implement well protection areas around production wells in order to avoid groundwater contamination problems at these sites.

14.4.8 Knowledge gaps and recommendations

Most eastern Canadian aquifers are not over-exploited, so there is opportunity to act in a proactive manner by conducting groundwater inventories, establishing monitoring networks and creating management programs to ensure that groundwater extraction remains within sustainable yields. Additional inventories, for any given region, would provide information such as a water budget, aquifer characteristics (e.g., hydraulic conductivity, storage coefficient, effective porosity, and anisotropy), and an overview of water quality, aquifer vulnerability, and groundwater depths. The main knowledge gaps, perhaps shared by all provinces, are typically overlooked in groundwater studies: these include groundwater use data, climate change impact, and groundwater–surface water interactions. Collecting this information is financially demanding, and resource intensive, because this information requires more fieldwork and more computer time. It is, however, essential to understand fully the dynamics of a hydrogeologic system and to develop well informed groundwater management and protection programs. Lack of groundwater quality information, partly due to privacy concerns associated with samples taken from private wells, is another information gap, made more difficult to overcome because it is not mandatory in all provinces to send geochemical results of new residential wells to provincial authorities.

Challenges associated with filling groundwater knowledge gaps include 1) developing tools and expertise to study interactions between various water resources, including bedrock, surficial sediments, surface water, and aquatic ecosystems; 2) collecting accurate groundwater use data through water use surveys; 3) estimating sustainable yields of aquifers; 4) developing standard approaches to account for climate change; 5) estimating water budgets and therefore, aquifer recharge, at local and regional scales; 6) converting old hard copy groundwater data to electronic databases and developing common database formats to facilitate data sharing and analysis; and 7) improving public access to groundwater data on the internet. Another knowledge gap more specific to coastal areas is the effects of climate change and increasing population (and thus water demand) on saltwater intrusion.

In addition to existing regulations for public water supplies, we recommend the following:

1) Each municipality should equip production wells and selected observation wells with groundwater level probes or pressure transducer dataloggers to measure water levels

regularly. Records of groundwater levels on a long-term basis would allow detection of problems, such as declining water levels, caused by over-exploitation, or by additional pumping at nearby sites. These records would also provide accurate and reliable historical data which would allow a better understanding of the hydrodynamics of any given aquifer.

2) All drillers should be equipped with a GPS unit (as in Nova Scotia) to provide an accurate geographical location for each new well.
3) A better knowledge of current monitoring well stratigraphy and construction should be acquired, or new monitoring wells with known characteristics should be added to observe the potential impacts of climate change and anthropogenic activities, both for groundwater levels and groundwater quality (mainly nitrates and chlorides) in areas at greater risk.
4) All acquired groundwater quality data (laboratory analysis reports) should be automatically transmitted by laboratories to provincial environmental agencies in electronic format.

Finally, greenhouse gas emissions could be reduced by promoting open- and closed-loop groundwater heat pump systems (see Box 14-3). Completing feasibility studies in representative hydrostratigraphic units could support and encourage the use of geothermal energy.

ACKNOWLEDGEMENTS

This chapter benefited from the collaboration of Ruth Boivin, Marco Boutin, and Richard Franklin from the Geological Survey of Canada (GSC) who drew and developed many of this chapter's figures and we thank them for their contribution. The authors would also like to thank Dorothea Hanchar from the Newfoundland and Labrador Department of Environment and Conservation, and Dr. Martine Savard of the Geological Survey of Canada (GSC) for their contribution to this work. Finally, authors would like to thank Dr. Grant Ferguson for his valuable comments in his critical review of this chapter.

BOX 14-1 NATURALLY OCCURRING RADIONUCLIDES IN GROUNDWATER IN NOVA SCOTIA

Naturally occurring uranium was first identified in Nova Scotia's groundwater in 1978. In 2002, lead-210 (a daughter product of the uranium-238 decay series) was identified in the water of a school near Halifax, and, as a result, a province-wide radionuclide testing program was initiated. The initial finding indicated that lead-210 and uranium could exceed drinking water guidelines in wells drilled into granite and Upper Carboniferous sandstone and shale. Subsequent investigations, however, revealed that lead-210 testing methods did not provide a realistic indication of lead-210 levels because radon gas in the water samples was rapidly decaying to lead-210. The lead-210 sampling protocol has since been modified in Nova Scotia to eliminate radon effects. The majority of water supplies which originally exceeded the lead-210 guideline were below guidelines when they were re-tested using the modified sampling protocol. For more details, see Drage et al. (2005a, 2005b).

BOX 14-2 OCCURRENCE OF ELEVATED MANGANESE LEVELS IN THE CITY OF FREDERICTON'S WELLS

Water quality from production wells in the Fredericton aquifer is generally good, with the exception of elevated dissolved manganese (Mn), which may exceed 2 mg/L (Thomas et al., 1994). This occurrence has been attributed to the flux of dissolved organic carbon (DOC) that enters the aquifer during river water infiltration through windows that exist beneath the Saint John River. These windows are regions where the clay/silt aquitard is absent (Figure 14.24), thus creating a relatively direct hydraulic connection between the river and the water supply aquifer. Pumping of the production wells causes river water infiltration and introduces DOC, which in turn, creates *in situ* conditions suitable for reductive dissolution of Mn-oxides (Petrunic et al., 2005; Al et al., 2005). Investigation of the unconsolidated sand and gravel sediments, and pore waters, beneath the riverbed windows confirms that there is a diverse microbial community possessing the ability to reduce Mn-oxides (Haveman et al., 2005), a

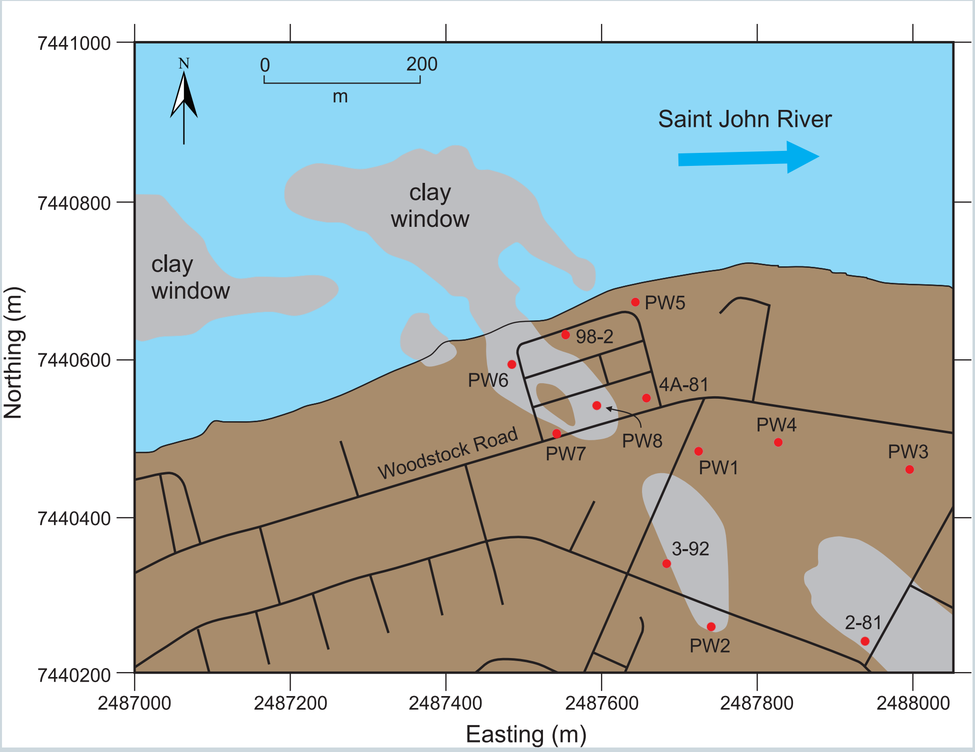


Figure 14.24 Extent of selected clay/silt windows in the Fredericton aquifer. The average thickness of the aquitard is about 15 m. For the windows that extend into the Saint John River, the aquifer is directly exposed at the river bed. There are eight production wells (PW). Selected monitoring wells are also shown.

community which is well suited to the changing redox conditions that occur as the infiltrating water temperature varies throughout the year.

Although reductive dissolution of Mn-oxides is still occurring after approximately 40 years of continuous river water infiltration, it is expected that Mn-oxide mineral depletion will eventually occur in the aquifer sediments (Al et al., 2005). The trend of Mn concentrations at some production wells suggest that this depletion may have begun. For example, in well PW5, located approximately 30 m from the river's bank (Figure 14.24), Mn concentrations increased from approximately 0.1 mg/L in the 1960s to a peak of near 2 mg/L during the early 1980s; since that time concentrations have been steadily declining. The time frame for complete Mn-oxide mineral depletion and the potential resultant water quality changes requires further investigation (MacQuarrie and Al, 2007).

BOX 14-3 HEATING AND COOLING WITH GEOTHERMAL MINE WATER

Geothermal energy from floodwater in abandoned coal mines is used to provide heating and cooling at a plastic packaging company's facility in Springhill, Nova Scotia. Although the use of mine water as a heat source is not a new concept in other parts of the world, this was the first industrial site in Canada to demonstrate its economic and technical viability. The project began in 1988.

Over 200 years of subsurface coal mining in Nova Scotia has left many square kilometres of old workings, often located directly beneath towns that grew at the pitheads. These workings have gradually filled with water over the years. Gravity circulation within the workings brings this heated water up closer to the surface where it is accessible through short drilled wells, thus providing a suitable energy source for ground source heat pumps. The heated water is a renewable source, displacing carbon emissions from coal-fired electricity or oil-fired heating.

At this site, mine water, with its temperature of 18°C, is pumped at a rate of 4 L/s and passed through a heat pump system before reinjection into another interconnected mine (i.e., in a closed-loop system). Inside the plant, 10 heat pumps with individual control thermostats provide heating and cooling. The cost of the heat pump system for the new plant was 110 K$ (Canadian dollars), compared with a cost of 70 K$ for a conventional or propane heating system. This extra capital cost was, however, offset by a saving of 110 K$, an expenditure that would have otherwise been required for dehumidifiers. The net savings in the new plant are in excess of 45 K$ annually, equivalent to a saving of about 600,000 kWh.

Source: http://oee.nrcan.gc.ca/publications/infosource/pub/ici/caddet/english/r122.cfm?attr=20

BOX 14-4 STABLE ISOTOPES REVEAL SEASONAL CHANGES IN NITRATE PRODUCTION AND SIGNIFICANT WINTER TRANSFER FROM AGRICULTURAL SOILS TO GROUNDWATER IN TEMPERATE SETTINGS

Contamination of water resources by nitrate (N) of agricultural origin is a serious problem in many temperate agricultural regions. Reducing risk of further groundwater (GW) quality degradation depends on our understanding of how nitrate (N) is transferred from agricultural lands to GW. A study combining seasonal sampling over two years with nitrate dual isotopes (δ^{15}N and δ^{18}O) recently addressed these questions in the Wilmot watershed (west-central PEI), characterized by intensive cultivation of potatoes and heavy reliance on chemical fertilizers (Savard and Somers, 2007; Savard et al., 2008).

The rapid response of the Wilmot aquifer to recharge events allows detection of seasonal characteristics with respect to nitrate δ^{18}O ratios in GW, shedding light on the timing of bacterially mediated nitrification, as the process involves oxygen from the atmosphere (constant δ^{18}O value) and soil water (δ^{18}O values varying with seasonal characteristics of precipitation). The shift in δ^{18}O values from summer/fall to winter/spring periods is inferred to represent nitrification of crop residues using soil water derived from warm season to cold season precipitation respectively, highlighting the importance of nitrification even during the winter (Figure 14.25). The nitrate δ^{18}O and δ^{15}N values of GW and key N sources in the watershed suggest striking differences in the relative seasonal contribution of N sources to the aquifer (Figure 14.26). While inorganic fertilizers are the most important anthropogenic N source in the watershed, they marginally dominate the summer/fall GW load. Nitrate produced by the degradation of crop residues dominates the winter/spring period and accounts for almost 60% of the total nitrate load transported to the aquifer on an annual basis.

These findings highlight the role of soil organic matter as a key transitory reservoir in the N cycle. Understanding the role of this reservoir helps in the development of remedial strategies to reduce agricultural impacts on GW quality.

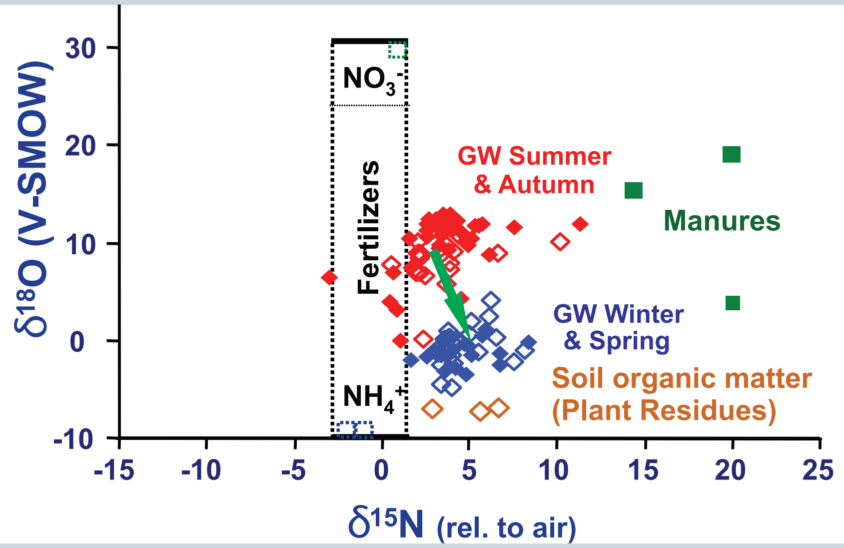


Figure 14.25 Nitrate isotope results for seasonal groundwater samples from the Wilmot watershed compared with measured values for key N-sources and chemical fertilizer domain from literature. The green arrow illustrates a shift of -10.2 per mil in oxygen isotope ratios in nitrate between summer-fall samples and winter-spring samples (modified from Savard et al., 2007).

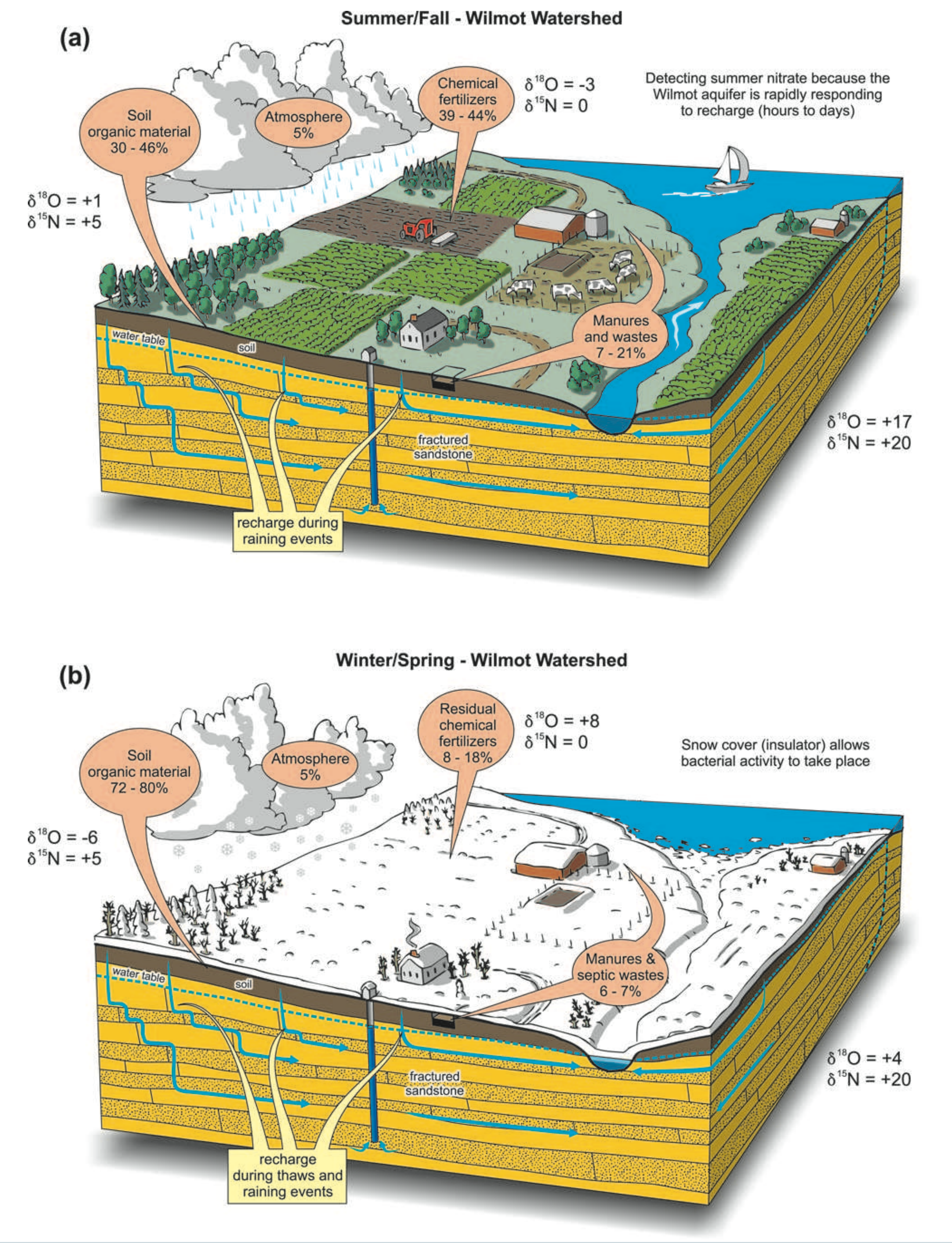
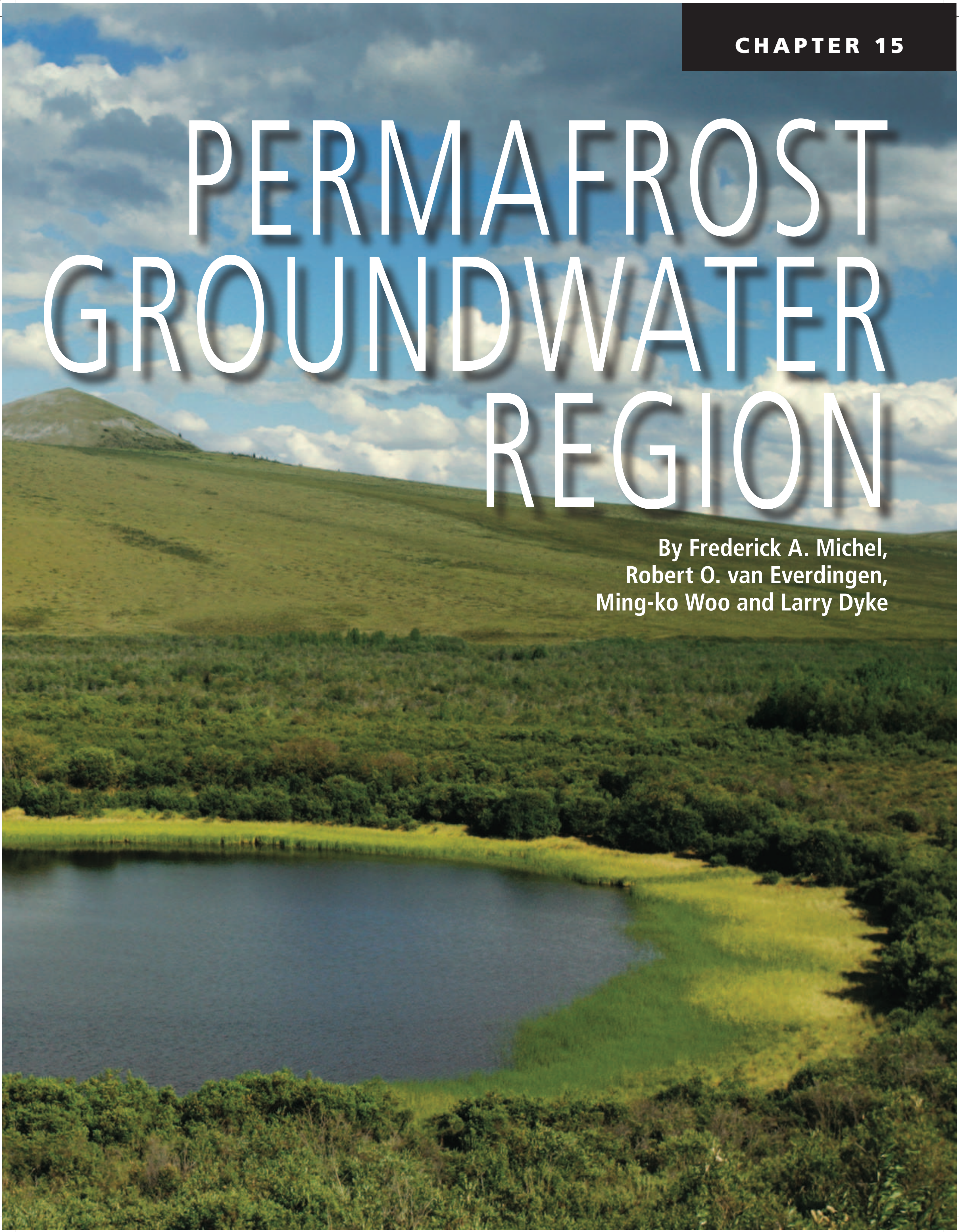


Figure 14.26 Estimated nitrate source contributions for (a) summer/fall and (b) winter/spring conditions (adapted from Savard and Somers, 2007).



CHAPTER 15

PERMAFROST GROUNDWATER REGION

By Frederick A. Michel,
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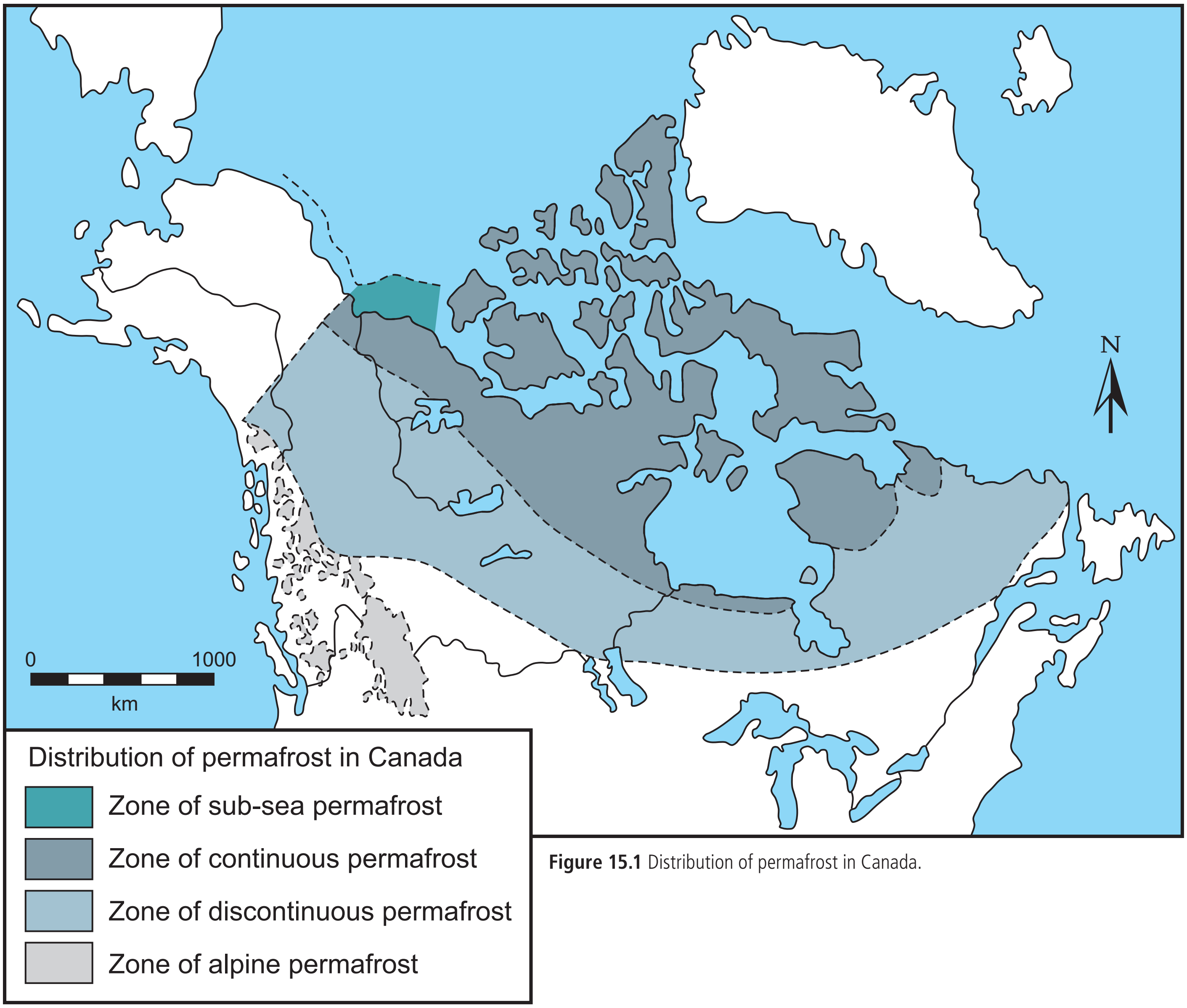


Figure 15.1 Distribution of permafrost in Canada.

15.1 INTRODUCTION

15.1.1 Permafrost

The northern groundwater region was first described by Brown (1970) as that portion of Canada north of the southern limit of discontinuous permafrost. Permafrost (or perennially frozen ground) is defined as the region exhibiting temperatures in rock or soil that remain below 0°C continuously for two or more years (Muller, 1943).

The distribution of permafrost is determined most closely by climate and its effects on the local ground thermal regime. Other influencing factors include geology, topography, slope aspect, vegetation, surface water bodies, snow cover and glacial history. The polar and subpolar regions north of the tree line are within the zone of continuous permafrost, where virtually all terrain exhibits permafrost conditions to depths ranging from tens to hundreds of metres (Figure 15.1). The continuous zone grades southward into the thinner discontinuous zone where permafrost and non-permafrost areas are interspersed. Further south, permafrost occurs only sporadically in isolated favourable settings, such as peat bogs or on north-facing slopes. Extensive relict permafrost, formed during the last ice age, has also been documented in offshore regions such as the

Beaufort Sea (Judge, 1974).

In his delineation of the northern region, Brown (1970) included areas with very patchy or sporadic permafrost, even though the territory contained large intervening areas where permafrost was absent. As a result, the northern region comprises over 50% of the land mass of Canada. Since the non-permafrost portions are similar to the more southern parts of Canada that experience only seasonal frost penetration, and since the presence of permafrost is one of the major distinguishing characteristics of the northern region, most of this chapter will focus on the region north of the southern limit of widespread discontinuous permafrost (Figure 15.1).

15.1.2 Moisture conditions in permafrost

A wide range of moisture conditions can exist in permafrost. Water contained in pores and fractures within permafrost is often frozen as ice due to the negative ground temperatures; however, unfrozen water may occur at temperatures several degrees below 0°C due to the presence of dissolved salts or if the water is under pressure. Permafrost can also be dry and contain no ice, particularly in well-drained coarse-grained clastic material and in massive unfractured crystalline rock. Therefore, the 0°C temperature condition used to define permafrost does not necessarily indicate the physical state of the moisture content.

Permafrost has often been considered as simply an impermeable barrier (or aquiclude) to groundwater movement because the pore spaces and fractures may be filled with ice. As a consequence, many people consider northern Canada to lack active groundwater flow systems. Permafrost does have a significant impact on groundwater flow regimes, especially the recharge component; however, active groundwater flow can be found to varying degrees throughout the permafrost regions of Canada. As permafrost areas become more discontinuous, isolated and patchy, the influence of permafrost on the hydrogeologic regime also decreases. Throughout all of Canada, seasonal ground freezing will affect the local groundwater regimes to some extent during the winter months.

15.2 THE NORTHERN REGION

15.2.1 Physiography and geology

The permafrost region of Canada encompasses all of Nunavut (NU), Northwest Territories (NWT), and Yukon Territory (YT), as well as the northern portions of the western provinces from British Columbia to Manitoba, and the northern half of Ontario, Quebec, and most of Labrador (Nfld). Four broad physiographic subregions are defined on the basis of diverse geology and topography; they are the Canadian Shield, northern Interior Platform, northern Cordillera, and Arctic Archipelago (Figure 15.2).

The Canadian Shield is the most extensive region, spanning the northern portions of Saskatchewan, Manitoba, Ontario, Quebec, and Labrador (Nfld), the eastern half of NWT, and much of the mainland and Baffin Island of Nunavut. The gently undulating to rugged terrain of the Shield is predominantly composed of Precambrian-age igneous and metamorphic crystalline rocks with smaller, relatively undeformed, Proterozoic-age sedimentary basins (e.g., the Thelon and Athabasca Basins). Younger undeformed Paleozoic sedimentary rocks form a broad basin that blankets the Shield rocks throughout Hudson Bay and is best exposed along the northern Ontario coast (see Chapter 11).

Bordering the Shield to the west in the NWT are the relatively undeformed flat-lying sedimentary

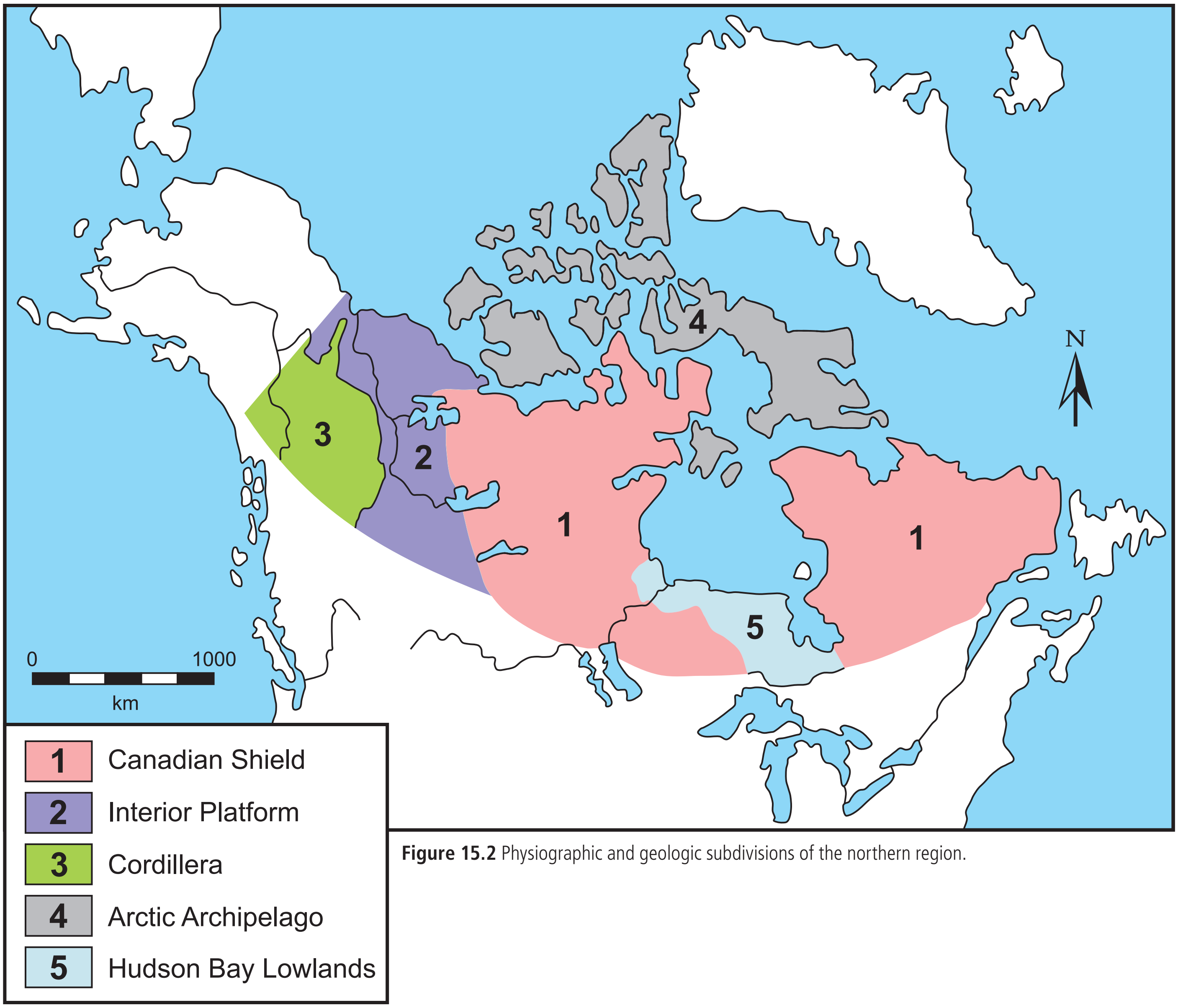


Figure 15.2 Physiographic and geologic subdivisions of the northern region.

rocks of the northern Interior Platform. This wedge of Paleozoic-age rocks is the northern extension of the broader platformal sequence that underlies the Prairies (see Chapter 10). These rocks are composed of clastics (sandstones to shales), evaporites (gypsum/anhydrite and halite), and a dominant carbonate (limestone and dolostone) sequence. The sedimentary rocks of the Mackenzie Valley are a westward continuation of the Interior Platform, but have been affected by foreland thrusting of the Cordillera. The Mackenzie Valley is a broad plain 15 to 40 km wide, bounded on the east by the low-lying Franklin Mountains and to the west by the Mackenzie Mountains of the Cordillera.

The Cordillera represents an accumulation of accretionary slices that contain a mix of crystalline rocks and steeply folded and faulted sedimentary and volcanic rocks (see Chapter 9). The northern Cordillera is composed of the Mackenzie and Yukon Mountains. The Cordilleran geosynclines experienced their main folding events during the Triassic in the Yukon Plateau region and in the late Cretaceous to early Tertiary in the Mackenzie Mountains. In northern Yukon, the British Mountains rise to over 2,000 m above sea level, while the Ogilvie and Wernecke Mountains reach 2,200m. The St. Elias Mountains, along the southwest Yukon/Pacific coast, peak at 5,959 m with Mount Logan, the highest elevation point in Canada.

The Arctic Archipelago includes a series of islands that contain a younger wedge of folded and faulted platformal sedimentary rocks north of the Canadian Shield. The western islands are composed of less deformed low-lying terrain under 600 m in elevation, while the northern islands are mountainous, rising to over 2,000 m on Axel Heiberg and Ellsemere Islands.

With the exception of northern and western Yukon, the northern region has been affected most recently by continental and alpine glaciation during the latest Wisconsinan ice age. The Canadian Shield and Interior Platform were scraped bare of most soil cover and are now blanketed with a thin veneer of stony glacial moraine and numerous eskers radiating out from the centres of glacial retreat. Adjacent to Hudson Bay, especially the southwest portion, there is a sequence of marine clay-rich sediments and abandoned shorelines. Mountainous areas have bare to talus-covered peaks, whereas thick complex sequences of glacial and glaciofluvial sediments blanket the valley floors. The Mackenzie Valley is covered with unconsolidated Tertiary and Quaternary clastic sediments that include fine-grained glaciolacustrine sediments deposited by proglacial lakes that temporarily flooded the valley during deglaciation. The Mackenzie Delta and near-shore Beaufort Sea contain the largest and thickest accumulation of unconsolidated sediments in the northern region.

15.2.2 Population

The total population of the three territories comprising the northern region (north of 60° latitude) was 101,310 in 2006 (Statistics Canada, 2007), with 30% living in Yukon, 41% in NWT, and 29% in Nunavut. The total population for those portions of the provinces contained within the northern region was estimated at approximately 40,500 in 2001.

In Nunavut, most communities are small Inuit settlements located adjacent to the coastline; Baker Lake is a notable exception. Increased mineral exploration and development eventually will lead to the development of small local mine site populations inland that will exist for the duration of mining activity. Iqaluit, as the centre of the territorial government, is the largest community in Nunavut with a population of 6,184 in 2006.

Population centres in NWT are located primarily adjacent to inland waterways such as the Mackenzie River. Yellowknife, located on Great Slave Lake, originally developed as a mining community, later grew as the seat of the territorial government and as a major supply point for smaller northern communities. The recent development of diamond mines north of Yellowknife has led to continued growth in the city's population, which increased to 18,700 in 2006. Norman Wells was established during the 1940s to develop local oil reserves for the war effort. Inuvik was established in the 1950s as a more stable site for the local aboriginal population, and as a supply point for resource development in the Mackenzie Delta. Communities based solely on resource development tend to be abandoned following the cessation of mining activities (e.g., Pine Point).

The population of Yukon is more diverse with a mix of small communities primarily located in river valleys. In addition to native and resource-based communities, tourism is a major driver of the local economy. The city of Whitehorse is the largest community in Yukon (22,898), serving as a legislative and administrative centre for activities throughout the territory.

15.2.3 Water supply

An estimated 9 million Canadians (30.3%) relied on groundwater for their domestic water supply in 1996. According to Environment Canada's analysis of Statistics Canada 1996 data, 47.9% of Yukoners and 28.1% of the residents in Nunavut and NWT utilized groundwater as their supply source (Rutherford, 2004). Over 99% of Yukoners rely at least partially on groundwater for their domestic supply and 75.4% of the total licensed water use in Yukon is from groundwater sources (Rutherford, 2004).

Groundwater use within the northern region is restricted by the presence and extent of frozen ground and depends on groundwater availability. No communities within the zone of continuous permafrost utilize groundwater as a water supply (with the exception of Old Crow, YT; see Box 15-1), either in the low-relief areas of the Canadian Shield, or in the mountainous areas of the Arctic Archipelago and northern Labrador (Nfld). Groundwater of good quality is available in the mountainous Cordillera of Yukon and in western NWT, where local-scale groundwater flow systems are active and permafrost is discontinuous. Freezing conditions can create problems during drilling and maintenance of wells, while deep freezing reduces recharge to aquifers, in addition to seasonally cutting off water supply to shallow wells. Shallow wells completed within the active layer are also very susceptible to contamination.

In areas of crystalline rocks, where groundwater flow is restricted to weathered zones, fractures and faults, the potential for obtaining a year-round supply is generally much reduced because yield generally decreases with depth, and near-surface zones are subject to annual freezing. As a result, it is the alluvial and coarse-grained glacial deposits that provide the only potential source for groundwater supplies on the Canadian Shield.

Bedrock aquifers generally have not been exploited in those areas underlain by sedimentary rocks. Tertiary sands and gravels, in addition to Paleozoic sandstones, limestones, and dolostones are potential aquifers due to their intergranular and/or fracture permeability. Michel (1986a) identified the dolostones of the Bear Rock, Franklin Mountain, and Mount Kindle Formations in the Mackenzie Valley as the most suitable bedrock aquifers on the basis of water quality. Most communities along the Mackenzie and Liard Rivers rely at least partially (seasonally) on groundwater supplies; however, these wells are completed within unconsolidated fluvial or glaciolacustrine sand and gravel aquifers. Van Everdingen (1974) noted that fine-grained sediments associated with lakes and ponds generally have too low a permeability for development.

Sediment type greatly influences water quality, as demonstrated at the community of Wrigley along the Mackenzie River. Michel (1977) reported that the airport well, completed prior to 1960, in sand and gravel, at a depth of nearly 46 m, with the lowermost 12 m screened, produced good-quality calcium bicarbonate water. The nearby community well was completed in 1974 at a depth of 40 m, most likely in a finer-grained glaciolacustrine unit. Water quality in this second well was of much poorer quality, with a dominantly sodium bicarbonate composition that included significant concentrations of chloride and sulphate.

Groundwater extraction has been dominated in the NWT by mining operations. The former

Cominco mining operation at Pine Point in the discontinuous permafrost of southern NWT was the largest groundwater user in the entire northern region. The municipal supply for the community averaged 1,260 m^3/day, while the mill operations at the mine utilized an additional 18,000 m^3/day. Dewatering of the mine site required the extraction of another 157,000 m^3/day (van Everdingen, 1974). These quantities reflect the large flow capacities of the karstic limestone present at the site and draw attention to the large water requirements associated with mining, requirements that must be attained from either groundwater or surface water sources.

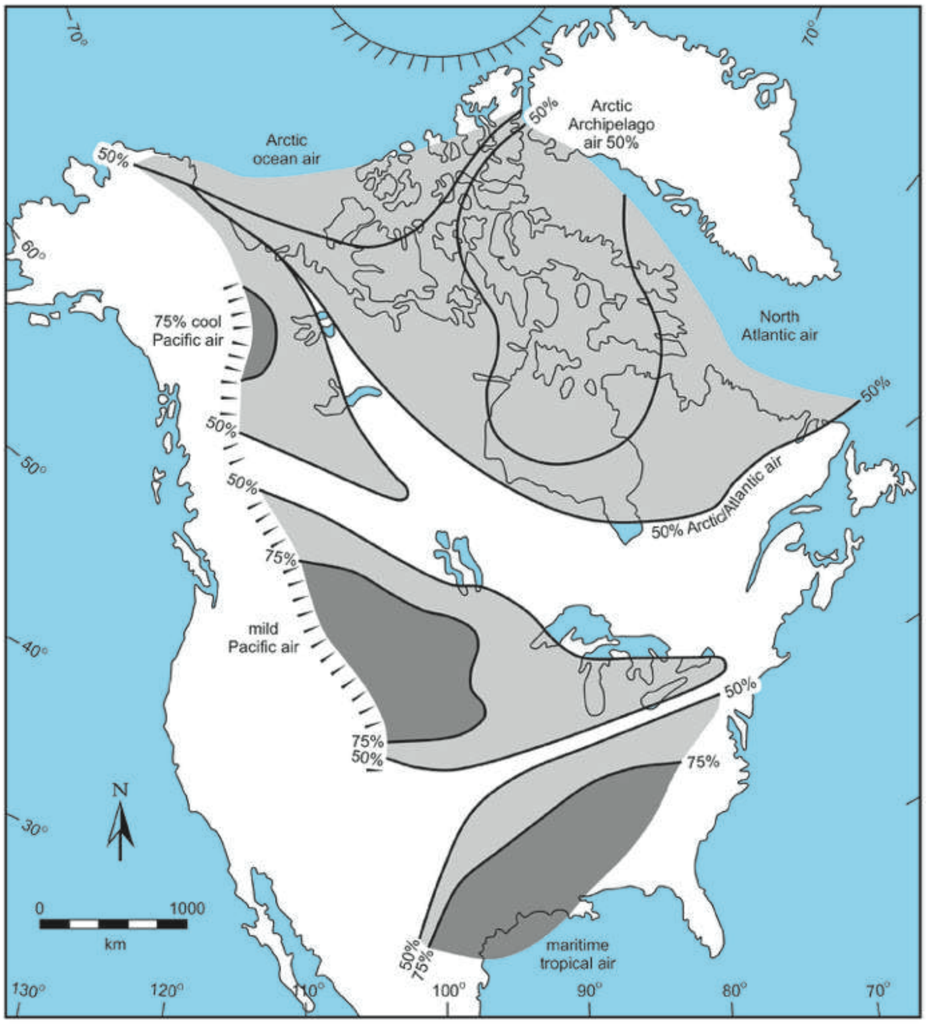


Figure 15.3 Distribution of dominant air masses in North America. The 50% frequency lines correspond to mean frontal positions in July (modified from Barry and Chorley, 1982).

According to the Yukon government's "State of the Environment Report" (Yukon government, 1999), not much is known about the quality or quantity (capacity) of groundwater aquifers throughout the Territory; however, alluvial and glaciofluvial unconsolidated deposits generally provide adequate quantities of good-quality groundwater for most communities. Within Yukon, almost all communities currently rely on groundwater, and most rural residents have wells. Carcross is the only exception because its groundwater supply was found to contain elevated arsenic concentrations. As a result, its citizens now rely on Lake Bennett for their water supply. Groundwater in several other communities contains elevated concentrations of manganese, but this is seen as more of an aesthetic issue.

The community of Old Crow, located within the continuous permafrost region of northern Yukon, has utilized a bedrock aquifer (limestone and dolostone) since 1982 for its water supply because permafrost extended throughout the thickness of the alluvium intended as the original target (see Box 15-1). Further south, in Dawson City, where permafrost is absent in the alluvium immediately adjacent to the Yukon River, the community has drilled wells in the alluvium for their water supply. Pumping of these wells induces infiltration of the river water through the alluvium where it is naturally filtered to remove any suspended particles.

Historically, Whitehorse obtained its municipal water supply from Schwatka Lake and

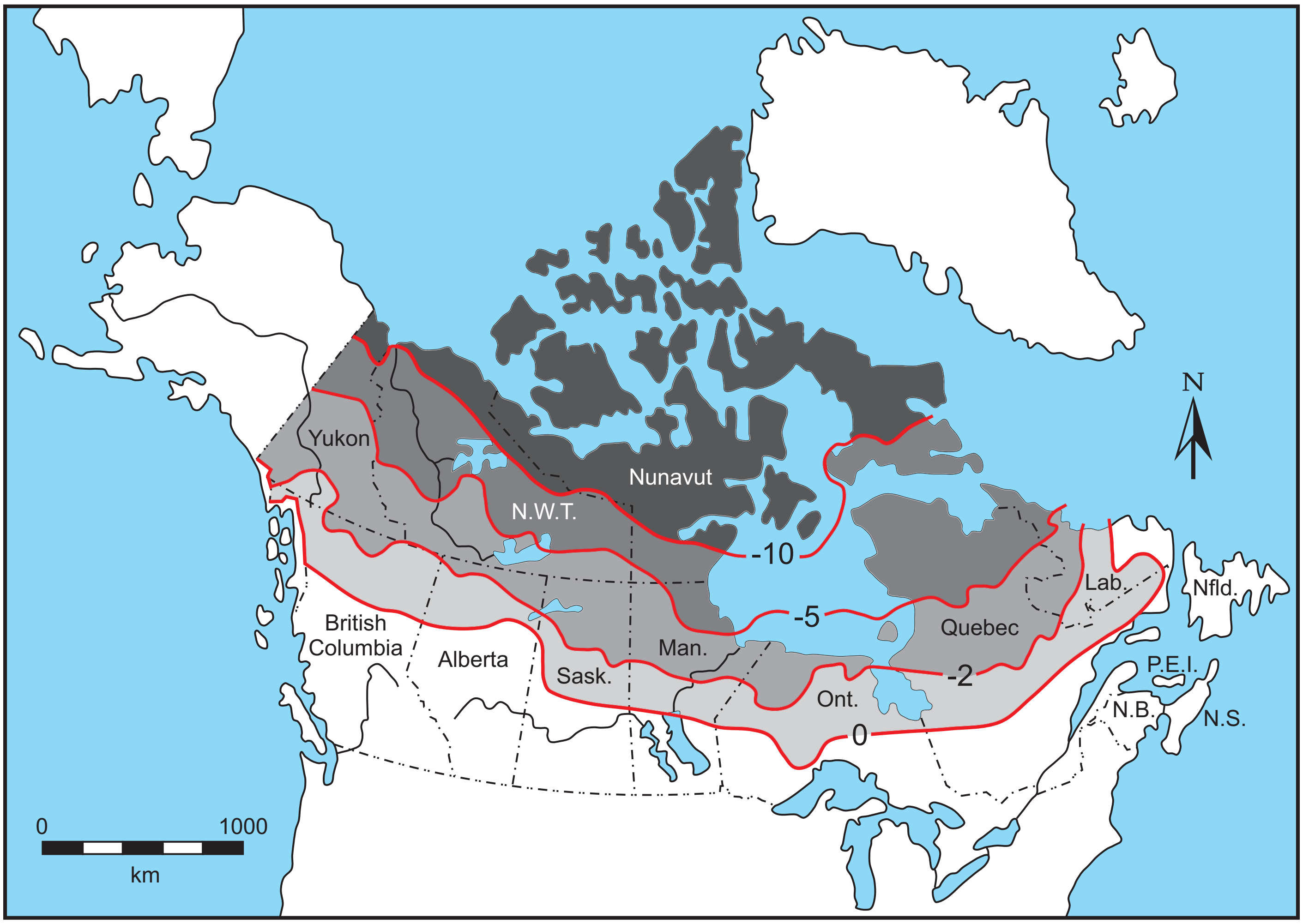


Figure 15.4 Distribution of mean annual air temperature (MAAT) in Canada (from NRCan website, 2012). The −5°C and 0°C MAAT correspond with the boundaries of continuous and discontinuous permafrost, respectively as seen in Figure 15.1.

two local aquifers, the Selkirk and the deeper Whitehorse. In 1997, approximately 30% of the total supply was from groundwater; in December 2009, the city switched entirely to groundwater. The groundwater aquifers provide a reliable, good-quality supply, but their best attribute is the constant positive temperature that they produce. Previously, Whitehorse's groundwater was mixed with the cold surface water supply to raise water temperatures and prevent freezing of pipes during winter, and to reduce the silt load found in the surface water during spring melt. Constant water flow through the bleeder systems during winter, coupled with water loss due to leakage from pipes, meant that the average consumption of water in Whitehorse in 1998 was 842 litres/person/day, compared to the Canadian average of 326 litres/person/day (Yukon Government, 1999). The switch to 100% groundwater and recent pipe repairs are expected to reduce this rate of usage significantly.

Installation and operation of monitoring wells within and through permafrost can result in changes in the thermal regime, which in turn can cause local changes to the groundwater flow system. Frost heave acting on the well casings can cause significant frost jacking (changing the elevation of the casing), potentially breaking pipe joints, and allowing migration of water between aquifers (J. Miller, personal communication).

15.2.4 Climate

The northern permafrost region encompasses the arctic (tundra) and subarctic (boreal) climatic regions where winters are long and cold, while summers are short (2 to 3 months) and cool. The boundary between the two regions is delineated by the tree line, which corresponds to a mean July temperature of approximately +10ºC, a mean annual air temperature (MAAT) of –8.5ºC, and a mean annual ground temperature of –5ºC. This boundary also approximates the division between continuous and discontinuous permafrost.

The climate of the North American continent is controlled by three major air masses originating in the Arctic/North Atlantic, Pacific, and Gulf of Mexico (Barry and Chorley, 1982) (Figure 15.3). Each of these air masses dominates at different times of the year, resulting in differing temperatures and precipitation patterns across the continent. The northern region corresponds to that area dominated by the cold and relatively dry Arctic/North Atlantic air mass. The mountains of the northern Cordillera form a partial barrier that results in a stronger Pacific influence for southern Yukon. Within the mountainous regions of the Cordillera and Arctic Archipelago, temperature inversions occur during winter: when the coldest air sinks to valley floors, higher elevations are somewhat warmer.

Negative winter air temperatures cause near-surface ground freezing throughout Canada. These seasonally frozen soils thaw completely in southern Canada, as temperatures rise during the spring. In northern Canada, the near-surface frozen soils also thaw gradually, during the short summer season of above 0ºC temperatures, to form an unfrozen active layer (which can range from 0.2 to 2.0 metres in thickness) above the permafrost. The rate of thaw depends primarily on air temperature, ice content of the soil, and vegetation and snow (insulation) cover. Within the continuous permafrost region, the lower boundary of the active layer usually corresponds to the upper permafrost surface (table) where ground temperatures remain below 0ºC. Depending on the ground thermal regime, the permafrost table in the region of discontinuous or sporadic permafrost may be deeper than the active layer zone of annual freeze/thaw. Winter temperatures often below –30ºC ensure refreezing of the active layer and result in MAAT as low as –20ºC in the Arctic Islands (Figure 15.4).

Mean annual precipitation (MAP) is relatively low throughout northern Canada, ranging from 500 to 600 mm per year in central Quebec, Labrador (Nfld), and southwest Yukon, to less than 100 mm per year in the high Arctic Islands, thereby creating a polar desert. Snowfall accounts for 35 to over 80% of the total annual precipitation in the permafrost region and provides a moisture store that is released rapidly during the melt period each spring. Evapotranspiration exceeds 60% of the total precipitation over most of the region (see Figure 4.3).

15.3 SURFACE HYDROLOGY

15.3.1 Surface ponding

Surface ponding and wetland formation are prevalent in flat terrain because deep percolation is inhibited by the presence of frozen ground. Thermokarst lakes are produced by permafrost thaw (Mackay, 1992). The presence of these lakes increases the open water area, thus enhancing evaporation. Where lake density is high, the regional energy and water fluxes can be affected. Nagarajan et al. (2004) observed this relationship in the northern Mackenzie Basin. Increased evaporation from lake areas provides more moisture to the atmosphere, which is then recycled back as precipitation, thus accelerating the land-atmosphere water circulation. Lake ice regime has a significant effect on annual lake evaporation because a long ice-covered period shortens the evaporation season. A warmer climate will lead to a longer evaporation season and can raise the lake water temperature which, when transmitted to the lake bottom, will promote development of a deeper active layer or a talik below the lake.

Tundra lakes are sensitive to changes in the permafrost. A recent study by Smith et al. (2005) found that in the continuous permafrost zone of western Siberia, there has been an increase in both the number and the area of tundra lakes, attributable to climate warming and thermokarsting. In the discontinuous permafrost zone further south and where the permafrost is thin, continued deepening of the active layer may lead to lake drainage by thawing.

Areas with abundant surface water storage also support wetland development. Wetlands in the continuous permafrost zone are areas with extraordinarily rich and diverse flora. Winter freezing of saturated soil in wetlands yields considerable seasonal ground ice. In the discontinuous permafrost zone, valley wetlands are also prone to icing formation, with water supplied by lateral drainage from adjacent hill slopes. For almost all wetlands, the accumulation of peat insulates the ground against deep thaw in the summer; peat holds large amounts of ground ice which requires much latent heat to melt. The consequence is preservation of a shallow thawed zone in the organic terrain (Woo et al., 2006a), thus limiting the subsurface storage capacity and enabling the water table to rise and saturate the entire active layer. Feedback between soil saturation and slow thaw of ground-ice–rich terrain ensures that wetlands are a self-sustaining system (Woo et al., 2006b).

15.3.2 Streamflow

Depending on the primary water sources or the water storage mechanisms that influence the temporal pattern of flow, three groups of streamflow regimes (or seasonal rhythm of streamflow) can be recognized within the permafrost region.

15.3.2.1 Nival regime

Snow in permafrost regions accumulates over many winter months without melt interruption. In spring, most or all of the snow melts within days or weeks, yielding large quantities of water in a short time. Because shallow ground thaw inhibits infiltration, runoff responds quickly to snowmelt to produce sharp hydrograph rises. Surface flow is prevalent, efficiently delivering abundant runoff to nearby streams. The dominance of snowmelt runoff in the seasonal rhythm of streamflow is evident in most rivers of the permafrost region (Figure 15.5a). This pattern of flow was termed the nival regime by Church (1974) to signify the importance of snowmelt contribution.

High flows in Arctic rivers are complicated by deep snow drifts in the channels (Xia and Woo, 1992). In subarctic rivers, breakup of river ice intensifies the magnitude of floods (Prowse and Ferrick, 2002). Once the flow begins, it usually exhibits a marked diurnal rhythm, reflecting the daily melt cycle. A spell of warm, sunny days will generate increasingly high daily flows, while the onset of cool, overcast conditions will curtail snowmelt, thus leading to a decline in streamflow. After the snow is melted, spring high flows recede rapidly to baseflow. Low flows are occasionally interrupted

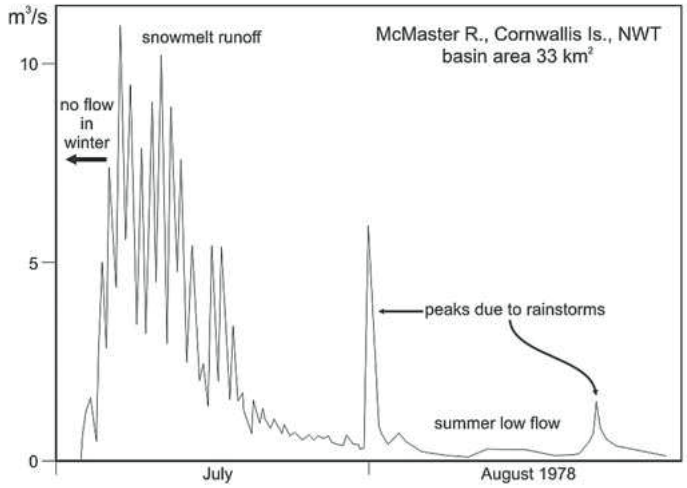


Figure 15.5a Typical streamflow regimes in permafrost areas: Nival regime, with example from McMaster River, Cornwallis Island (after Woo, 1986).

by hydrograph rises, caused by rainfall or summer snowfall, but the summer peaks are generally lower than those in the spring.

Flow patterns can be further subdivided into arctic and subarctic nival regimes. The subarctic regime is distinguished from its arctic counterpart by a longer streamflow season and more prominent summer peaks generated by heavy rainfall events. Taliks in the discontinuous permafrost permit winter flows to be maintained by the discharge of subpermafrost and intrapermafrost groundwater. In some areas, river icing formation is enhanced by a continuous discharge of groundwater supplied from deep sources. The result can be an extensive and thick icing covering a large part of the local valley (Clark and Lauriol, 1997).

15.3.2.2 Modifications of the nival regime

The presence of glaciers, lakes, and extensive wetlands modifies the summer low flows of the nival regime (Figure 15.5b). Glaciers provide an available water source after the basin snow cover is depleted, so that snowmelt runoff is extended and superseded by glacier melt contribution. Rivers issuing from glaciers show a proglacial regime (Church, 1974), with the summer yield controlled largely by the energy available for ice melt. Lake storage reduces the magnitude of peak inflows, but enhances the low flow discharges. Consequently, compared with the nival regime, a lake-modified or prolacustrine regime has lower peaks and higher baseflows. Timing of peak flow in response to rainfall or snowmelt is also delayed. Wetland storage is far less effective

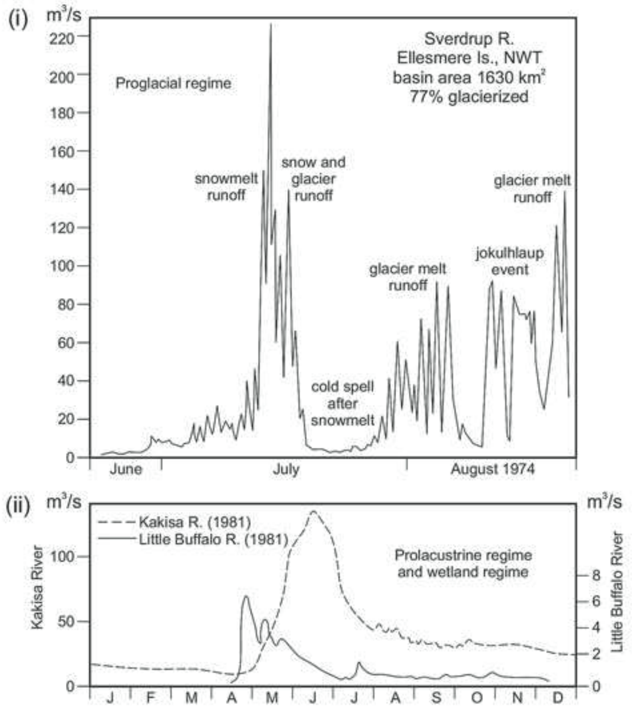


Figure 15.5b Typical streamflow regimes in permafrost areas: (i) modifications of nival regime— proglacial regime of Sverdrup River, Ellesmere Island; (ii) prolacustrine regime of Kakisa River, NWT; and wetland regime of Little Buffalo River, NWT (after Woo, 1986).

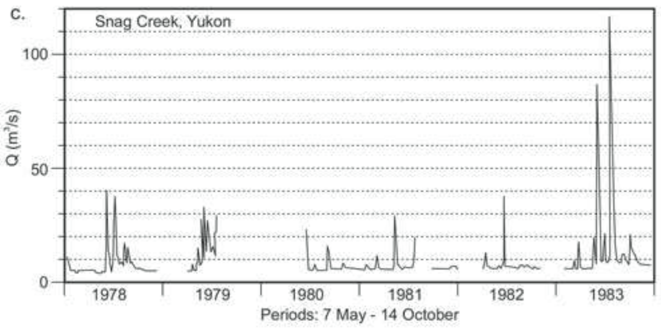


Figure 15.5c Typical streamflow regime in permafrost areas: spring-fed regime, Snag Creek, Yukon (after van Everdingen, 1988).

than lakes in regulating runoff. Streams with a wetland regime are fed by poorly drained areas which, when thawed, may have relatively large water-retention capacity in their peaty soil to attenuate high flows. This detention mechanism is ineffective in spring, however, when the wetland is frozen (Woo, 1988), and storage is then provided only by surface depressions and ponds.

15.3.2.3 Spring-fed regime

Deep-seated groundwater within or below the permafrost may be connected to the ground surface via taliks, and emerge locally as mineral springs, or as a water supply to streambeds (van Everdingen, 1987). Streams fed principally by this water source are found mainly in carbonate terrain. They have a stable baseflow which is maintained throughout the year (e.g., Figure 15.5c charts Snag Creek, Yukon, described by van Everdingen [1988], with a baseflow rate of approximately 4 m^3/s); the hydrographs may contain spikes induced by snowmelt and rainfall inputs.

15.4 GROUNDWATER

15.4.1 Permafrost hydrogeology

The hydrogeology of the northern region has received little attention over the years. Brown (1970) provided a brief summary based on early work by Brandon (1965), permafrost investigations by R.J.E. Brown and G.H. Johnston of the National Research Council, and discussions with mine operators. Van Everdingen (1974) published the first comprehensive review of groundwater in the permafrost regions of Canada, coauthored reviews for North American studies of groundwater in permafrost (Williams and van Everdingen, 1973; Sloan and van Everdingen, 1988), and authored report chapters on northern groundwater hydrology (van Everdingen, 1987, 1990). Similar reviews written for Alaska (Williams, 1965, 1970; Zenone and Anderson, 1978; Heath, 1984) and Russia (Tolstikhin and Tolstikhin, 1974) provide the basis for our understanding of groundwater systems in permafrost regions.

The knowledge of permafrost hydrogeology in Canada has been limited largely to observations of karstic recharge (Brook, 1976, 1983; Michel, 1977; Michel and van Everdingen, 1988; van Everdingen, 1981); groundwater discharge as springs, seeps, and related phenomena (Brandon, 1965; Gulley, 1993; Hamilton, 1990; Hamilton et al., 1988, 1991, 2003; Michel, 1977, 1986a,1986b; Michel and Paquette, 2003; Michel and van Everdingen, 1987; Pollard, 1983; Pollard et al., 1999; van Everdingen, 1974, 1978, 1981, 1982, 1988); mine studies (Douglas et al., 2000; Frape and Fritz, 1987; Ruskeeniemi et al., 2004), and data from municipal water supply wells (Brandon, 1965; Trimble et al., 1983). Detailed surface hydrology studies examining potential infiltration through the active layer and upper permafrost are more numerous (e.g., Carey and Woo, 1999, 2000; Marsh, 1988; Marsh and Woo, 1993; Woo, 1988; Zhao and Gray, 1999) because of the impact of frost heave on man-made structures, and the potential for rapid contamination of the surface environment.

Groundwater movement direction and rate in permafrost regions are generally dependent on the same physical parameters as in areas without permafrost. However, the presence of permafrost constitutes a low-permeability layer and exerts a significant but variable influence on groundwater recharge and discharge. It is important, therefore, to place aquifers in a context of their position relative to the permafrost zone, and scientists find it convenient to group aquifers into three categories related to that position: suprapermafrost, intrapermafrost, or subpermafrost (Figure 15.6).

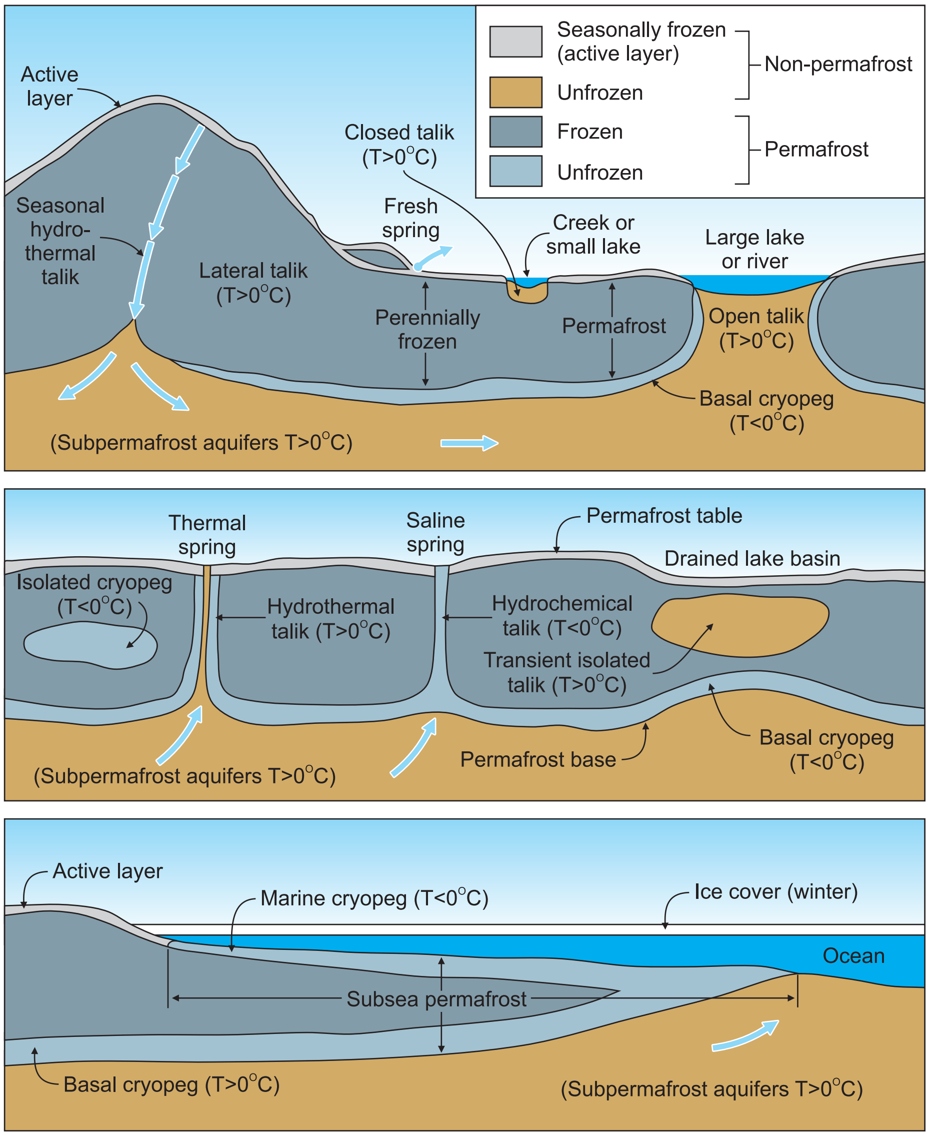


Figure 15.6 Cross sections illustrating terminology for groundwater flow in a permafrost environment (from van Everdingen, 1998).

Suprapermafrost aquifers are situated above the permafrost. In areas of continuous and widespread discontinuous permafrost, the seasonally frozen active layer above the permafrost forms the suprapermafrost aquifer. Thickness of this layer, usually consisting of organics and weathered mineral soil, is generally restricted to less than two metres. Refreezing of the active layer during winter makes it unsuitable for water supply considerations; however, suprapermafrost water plays a significant role in geotechnical problems involving frost heave and slope instability (Williams, 1979; Williams and Smith, 1989). Where degradation of the upper permafrost surface has occurred, such that winter freezing does not reach the permafrost table, a perennially unfrozen zone will exist that may contain coarse-grained material to form a near-surface aquifer capable of providing groundwater year round. Areas covered by surface water bodies that retain some unfrozen water throughout the year (water depths greater than 2.0 to 2.5 m) are especially important since they provide a source of heat to maintain a relatively thick unfrozen zone beneath. These suprapermafrost aquifers are capable of providing annual water supplies and form important conduits for groundwater discharge as baseflow in rivers.

Intrapermafrost aquifers exist within the zone of permafrost and are not subject to seasonal freezing. Their extent is usually relatively constant, being affected primarily by long-term climatic trends. Water temperatures are usually above 0°C and are maintained by the upward flow of deeper, warm groundwater or downward heat flow from large surface water bodies (lakes and major rivers). Depending on the size and depth of the surface water body, unfrozen zones can extend through the entire thickness of the local permafrost as an open talik, which connects groundwater flow above and below the permafrost, or as a thaw bulb (closed talik) containing suprapermafrost water. Where permafrost aggradation is occurring, such as beneath the bottom of a recently drained lake or abandoned river channel, taliks can become isolated and gradually decrease in size as freezing continues. Unfrozen water can also exist in intrapermafrost aquifers at subzero temperatures if the dissolved solids content is sufficient to cause a freezing-point depression. Intrapermafrost aquifers represent permeable zones through which unfrozen water can migrate. They may take the form of an open karst passageway, a fault zone, or a permeable geologic unit.

Subpermafrost aquifers comprise all permeable materials below the base of the permafrost, and contain water with above 0°C temperature. As a result of salt expulsion during freezing, a thin zone of unfrozen saline water may exist within the bottom portion of the permafrost, forming a basal cryopeg where the temperature is still below 0°C. Within areas of thick permafrost, subpermafrost aquifers will be restricted to bedrock. In the igneous and metamorphic terrain of the Canadian Shield, groundwater flow will be limited to interconnected fractures and fault zones. In the western and northern areas of the northern region with thick sedimentary sequences, subpermafrost groundwater flow will be similar to non-permafrost regions. Valleys containing alluvial sediments that exceed the thickness of the permafrost provide ideal targets for water supply wells. However, because of the length of time it may have been in the ground, subpermafrost water may contain an elevated dissolved-solids concentration, making it unacceptable for human consumption. Residence times can vary greatly. Michel (1977) found that most groundwater within the active flow systems of the Mackenzie Valley are postglacial in age, while some ice from within permafrost contains isotope signatures indicative of water recharged during glacial times (Michel and Fritz, 1978; Michel, 1982).

15.4.2 Infiltration and recharge

Infiltration, or water entry into the ground, is the principal mechanism of recharge, which is predicated upon the amount of water supply and the capacity of the land to accept the water. Light drizzle on vegetation, and on the land surface, is largely lost to evaporation and becomes unavailable for infiltration. Rapid release of ample water such as during heavy rain or intense snowmelt, on the other hand, often exceeds the infiltration capacity, with the result that much of the water may run off instead of recharging the ground. In permafrost areas, snowmelt and rainfall are the common water sources, although, locally, water can be supplied by lateral overland flow.

The bulk of water input in the permafrost region arrives in spring (from snowmelt)when the ground is frozen. Infiltration into frozen soil is a major consideration of recharge. The work of Gray's team (Granger et al., 1984), although conducted in Saskatchewan for seasonally frozen soil, is equally applicable to all permafrost areas when the active layer is frozen during the snowmelt period.

Infiltration into frozen soil can be unlimited, as in the case of gravels or peat without interstitial ice, restricted, as in ice-rich clay or silt where the soil pores are sealed with ice to prevent water entry, or limited, in which case the cold soil permits some infiltration (Figure 15.7a). Zhao et al. (1997) noted that infiltration into frozen soil occurs in two phases: an early transient regime of larger heat and water fluxes than the later steady-state regime, when infiltration is more subdued (Figure 15.7b).

Zhao and Gray (1999) provided an equation to describe cumulative infiltration into frozen soil of limited infiltrability (INF in mm):

$$INF = cS_o^{2.92}(1-S_I)^{1.64}[(273.15-T_I)/273.15]^{-0.45}t_o0.44 \quad (15.1)$$

where c is a coefficient, S_o is surface saturation minus moisture content at the soil surface, T_I (in degree K) and S_I are, respectively, average temperature and average soil saturation (water and ice) of 0–40 mm soil layer at the start of infiltration, and t_o is infiltration opportunity time (in hours). Here, S_I is the ratio of the volumetric soil moisture content to the soil porosity. When the active layer is thawed, infiltration is governed by the intrinsic soil property, since ground ice no longer plays a role in blocking the soil pores within the active layer. However, ice contained in the permafrost, at the base of the active layer, still restricts deeper penetration of the infiltrating water.

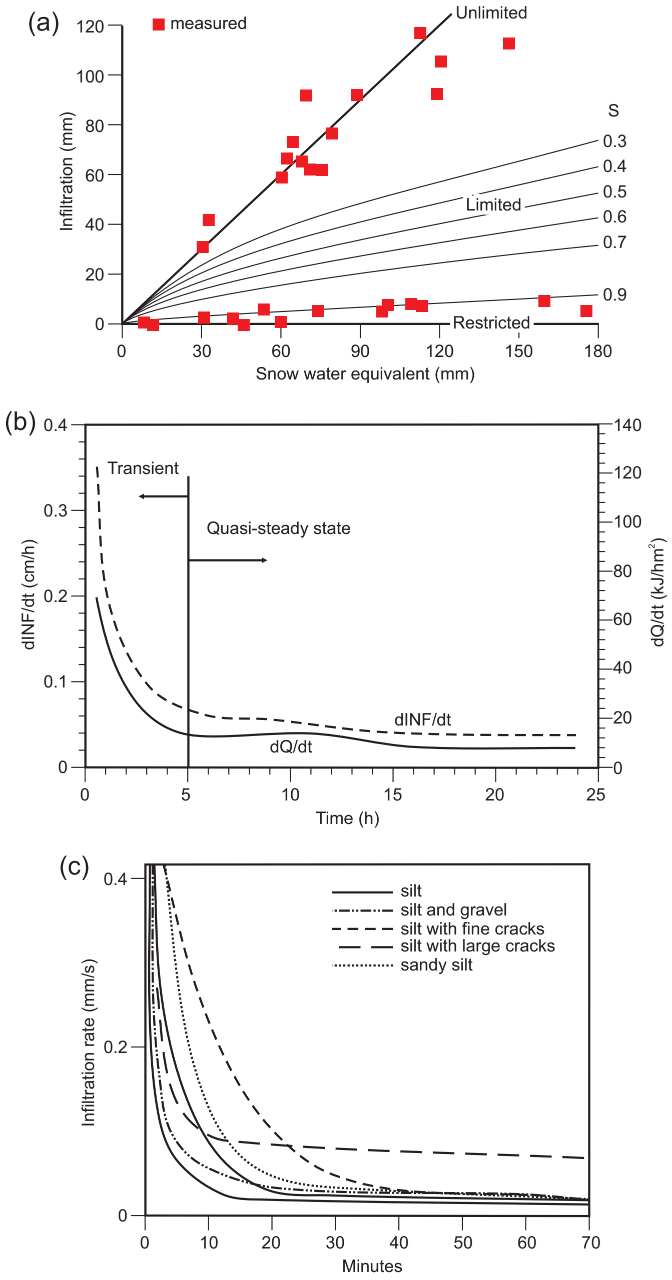


Figure 15.7 Infiltration into frozen soil: **(a)** unlimited, limited and restricted infiltration versus snow water equivalent; **(b)** variations in infiltration rate (dINF/dt) and heat flux rate (dQ/dt) plotted against time, for limited infiltration; and **(c)** infiltration curves for frozen soils with and without cracks. Figures after Granger et al. (1984), Zhao et al. (1997) and Woo et al. (1990).

The presence of soil cracks can greatly enhance infiltration. Woo et al. (1990) measured infiltration in silty soils of Hot Weather Creek area, Ellesmere Island, and found that, in the absence of cracks, silt has the lowest infiltration rate, followed by gravel and silt mixture, while sandy soil allows the highest infiltration. The presence of small cracks in silt initially permits a high rate of infiltration, although infiltration declines when silt swells to close the cracks, (Figure 15.7c). A high infiltration rate is maintained, however, when the silt has large cracks. Another feature that affects infiltration is the presence of a surface layer with highly porous organic materials that may include living plants and peat. The abundance of pores, unless filled with ice in the spring or saturated during the thawed season, allows ready infiltration of meltwater or rainwater. When the substrate is frozen and impervious, however, the infiltrated water can quickly saturate the thawed layer, causing infiltration to cease.

Frozen, coarse materials have a higher infiltration capacity than fine-grained soils. In Resolute,

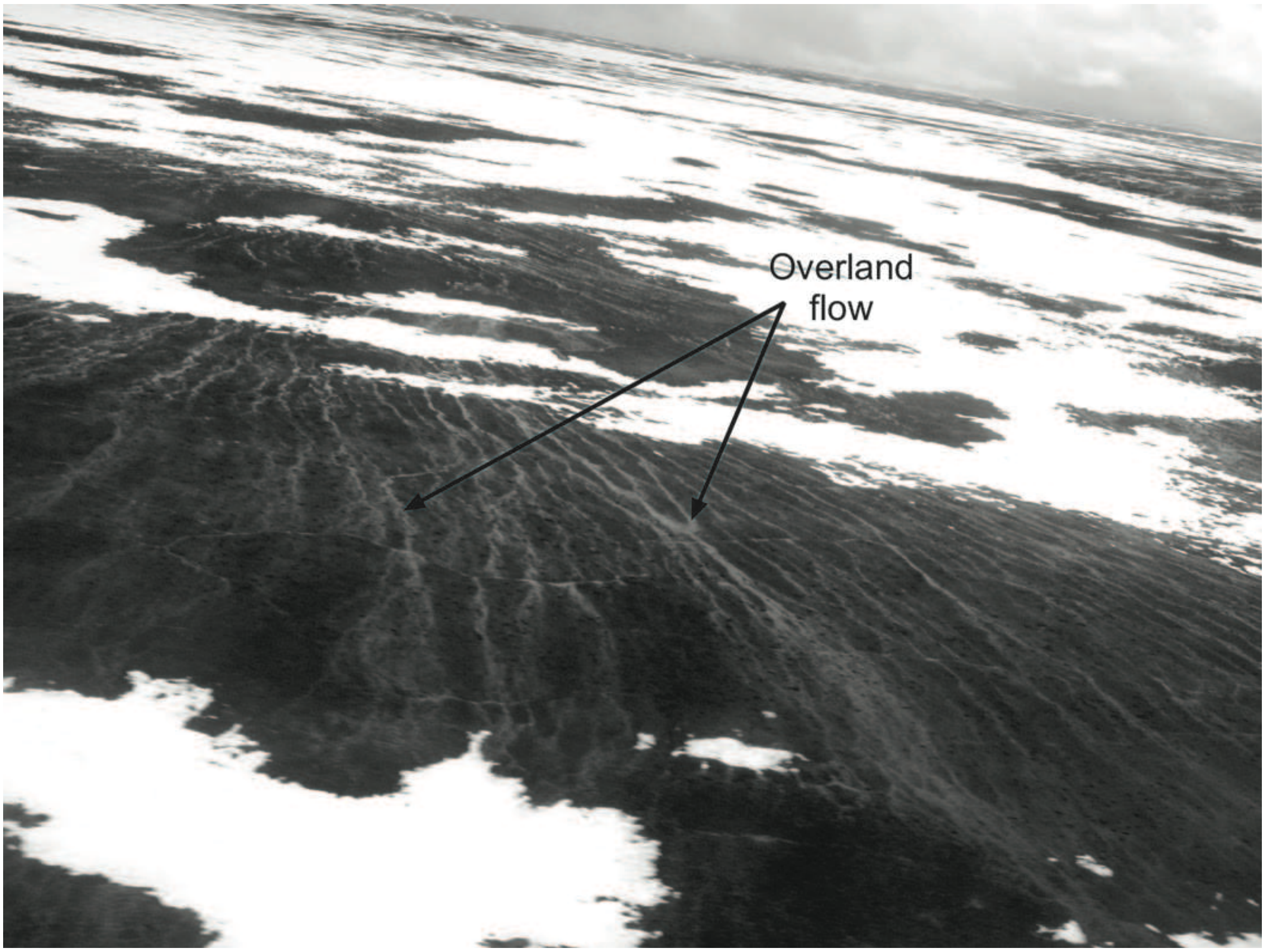


Figure 15.8 Extensive overland flow occurring during snowmelt due to limited infiltration of meltwater into frozen soil, eastern Bathurst Island, Nunavut (photo: M. K. Woo).

Nunavut, for example, a site with 70% gravel and 20% sand content had 3.5–4 times more water infiltrate than an adjacent site with 30% gravel and 40% sand (Marsh and Woo, 1993). Infiltration in continuous permafrost areas represents a small portion (about 5% to 20%) of total snowmelt, although the infiltration rate in some frozen coarse sand has been found to be high enough that little surface runoff remains (Marsh, 1988). In many areas with discontinuous permafrost, meltwater infiltrates along soil cracks and through the lichen and moss cover to be stored in the organic mat (Kane et al., 1981). This infiltrated water usually freezes in the interstitial spaces within the soil, thus increasing soil imperviousness.

Downward percolation is generally considered to be restricted by imperviousness of the frozen substrate. This is predicated upon the pores and cracks in the permafrost or the frozen active layer being filled by ground ice. However, Burt and Williams (1976) have shown that infiltration can occur even when ice is present because of the large thermal gradients present in the upper permafrost. Michel (1982) and Burn and Michel (1988) found that young tritiated water exists in the uppermost ice-rich permafrost; some of this tritiated water may also be related to an aggrading permafrost table caused by changing climatic conditions (Michel, 2008).

Intrapermafrost taliks can provide conduits for deep percolation. Similarly, karst terrain, with many solution openings in its carbonate rocks, allows easy movement of groundwater. One example was provided by Brook (1983), who observed flooding of depressions in the Nahanni karst area during the snowmelt season; when the ice blocking the drainage routes melted in autumn, these temporary ponds (measuring over 100 m in length) disappeared quickly as the water drained through the subterranean passages. Similar observations reported by van Everdingen (1981) for the karst of the Interior Platform east of Norman Wells demonstrate the importance of recharge in the late summer and autumn when maximum thaw conditions exist.

The general imperviousness of frozen soils limits infiltration and deep percolation, thus enhancing surface runoff, particularly for snow meltwater. Widespread surface flow of this nature (Figure 15.8) occurs in the continuous permafrost region during and immediately after the snowmelt season, when the considerable volumes of meltwater cannot be absorbed by the thin layer of thawed soil (Woo and Steer, 1982). During summer, the thawed zone within the active layer can be too shallow to accommodate inputs from intense rain events; as a result, the suprapermafrost water table rises to the ground surface and generates overland flow.

Frozen and unfrozen ground coexist in areas with discontinuous permafrost; this can give rise to large spatial contrasts in runoff. Many permafrost-free (e.g., south-facing) slopes with little ground ice allow meltwater and rainwater to infiltrate, and then percolate deeply. These slopes seldom generate surface runoff (Carey and Woo, 1999; Kane et al., 1981). Slopes underlain by permafrost are often covered by peat and living moss and lichen. Snow meltwater may enter the porous organic layer, but cannot penetrate the frozen substrate containing pore ice and segregated ice. Consequently, the organic layer becomes saturated, permitting surface flow and/or rapid lateral drainage in the organic soils. Runoff concentrates along rills and soil pipes, most of which develop at the organic-mineral soil interface (Carey and Woo, 2000).

15.4.3 Karst systems

Active groundwater flow through sedimentary rocks of carbonate or evaporite composition in northern Canada has increased the development of karstic terrain. Enlargement of channelways by the dissolution of exposed outcrops and near-surface bedrock is important for recharge, and continuation of these discrete channels (as taliks) through the subsurface often yields large-volume cold-water spring discharges. To a large extent, dissolution of near-surface carbonates within the Arctic islands has been confined to enlargement of joints since deglaciation (Bird, 1963). Saline springs discharging on Axel Heiberg Island are considered to represent groundwater flow through karstified gypsum domes (Beschel, 1963; Pollard et al., 1999), where the evaporites form a sink for meltwater runoff from nearby alpine glaciers. Discharge temperatures of the springs are above 0°C, but quickly drop during winter as the water flows over the ground surface. Downstream unfrozen water temperatures as low as –12°C have been recorded (Heldmann et al., 2003) as a result of the high concentration of dissolved salts in the groundwater.

Groundwater flow through well-developed karstic terrain within the Cordillera is confined to carbonates. Extensive networks of poljes, caves,

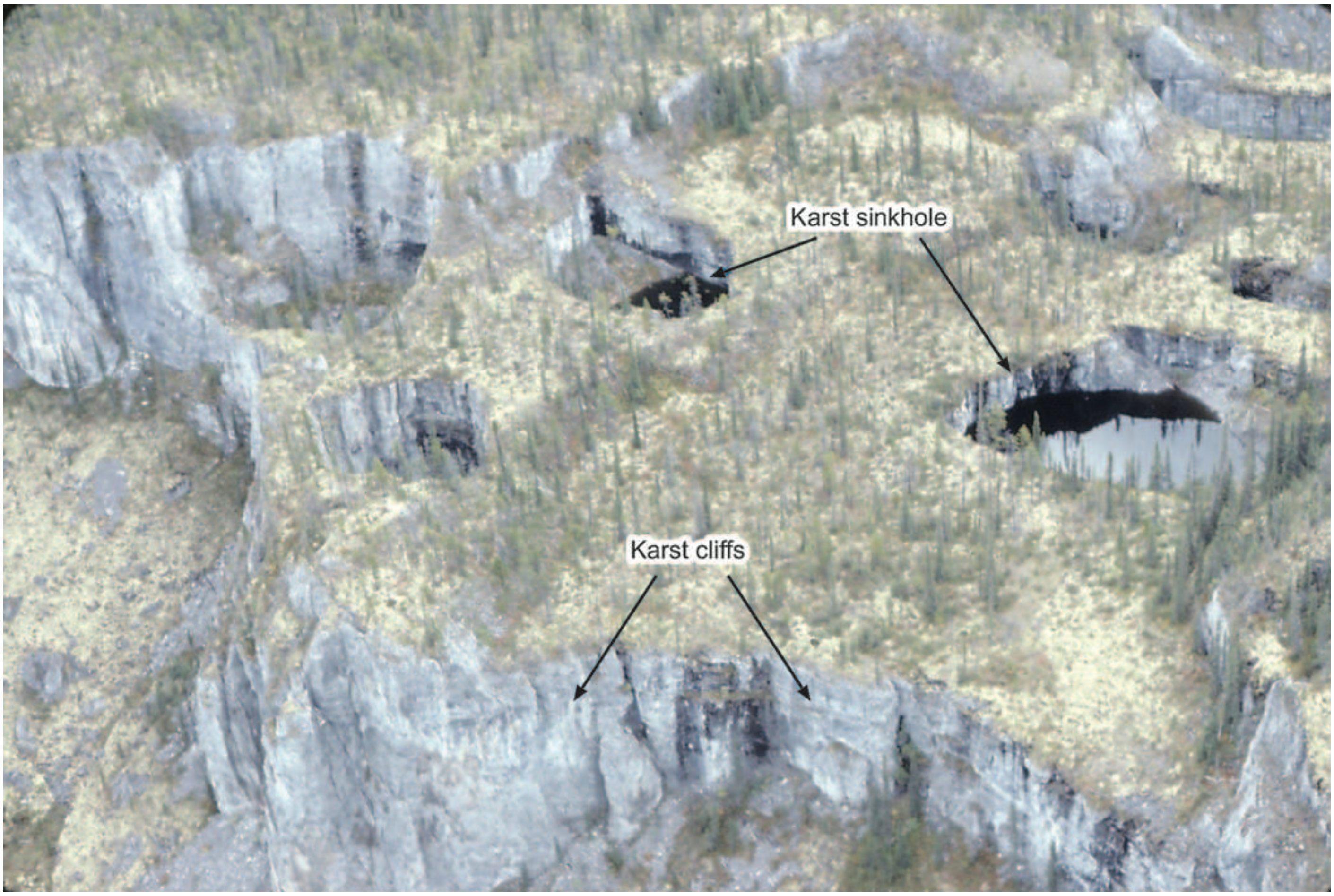


Figure 15.9a Photos of karst-related features, showing: (a) karst terrain of Nahanni North (photo: F. A. Michel).

Figure 15.9b, c Photos of karst-related features, showing: (b and c) full and empty lake in Nahanni North Karst North (photo: F. A. Michel).

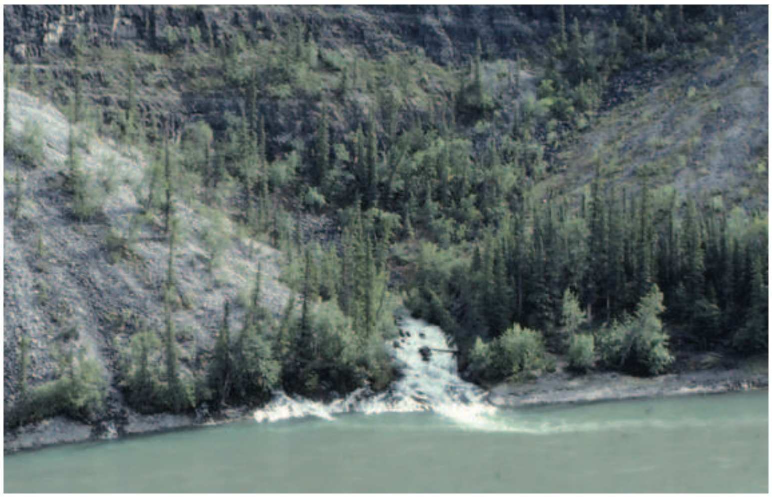


Figure 15.9d Photos of karst-related features, showing: (d) White Spray spring discharging into the South Nahanni River (photo: F. A. Michel).

and deep canyons have developed in response to the large topographic relief (Figure 15.9a). The best-developed area, adjacent to the eastern edge of Nahanni National Park, has been well documented by Brook (1976, 1983). Several large poljes in the Nahanni North Karst area typically fill with water during spring melt and, after heavy summer rainfall events, form temporary lakes (Figure 15.9b) that then gradually drain through conduits in the floor (Figure 15.9c), ultimately discharging locally as large-volume cold springs (Figure 15.9d). Further west, Hamilton et al. (1988) reported the development of immature high-altitude karst near the upper end of Nahanni National Park. Northward, within the Cordillera, karst has also been studied west of Norman Wells, and in northern Yukon (Williams and van Everdingen, 1973; Lauriol and Clark, 1993).

Karstic terrain and groundwater flow have also been reported in association with carbonate and evaporite formations in the Mackenzie Valley and the adjacent northern Interior Platform (Great Bear Plain) by Michel (1977) and van Everdingen (1981).

Figure 15.9e Photos of karst-related features, showing: (e) drained Lake 142 east of Norman Wells (photo: R. O. van Everdingen).

Figure 15.9f Photos of karst-related features, showing: (f) Vermilion Creek sinkhole south of Norman Wells North (photo: R. O. van Everdingen).

The platform rocks range in age from Cambrian to Devonian and are dominated by carbonates, but do contain two evaporite units: gypsum/anhydrite in the Lower Devonian Bear Rock Formation, and halite and gypsum/anhydrite in the Upper Cambrian Saline River Formation. The evaporites display evidence of dissolution where exposed; groundwater chemistry of spring discharges also indicates significant subsurface dissolution of both evaporite units.

The majority of sinkholes in this area are associated with dolostones of the Ordovician Mount Kindle Formation and Upper Cambrian Franklin Mountain Formation, but these may, in part, be due to the collapse of karst developed within the underlying evaporites. Sinkholes are most easily identified when associated with surface water bodies, either a stream that disappears into a sinkhole, or temporary snowmelt lakes that drain through sinkholes in the lake floor once ice plugs have melted due to the heat input from the lake water (Figure 15.9e) (van Everdingen, 1981). Detailed examination of bedrock exposures in this area indicates that carbonate dissolution and early stages of karstification are widespread and some well-developed sinkholes already exist (Figure 15.9f). Most of the groundwater discharges locally in topographic lows; however, some flow systems may be more regional in extent. The development of karstic terrain and saline groundwater discharges (springs) has been reported as far south as Wood Buffalo National Park by Brandon (1963).

15.4.4 Groundwater discharge

Groundwater flow, from recharge to discharge, is driven by differences in the hydraulic head and the resulting hydraulic gradient. Discharge in the northern region, as in non-permafrost regions, is expressed as springs, seeps, and baseflow into rivers, streams, and lakes. The location of discrete discharge points is usually controlled by structural or stratigraphic (aquifer/aquitard) features, while baseflow is often topographically controlled. The presence of permafrost in the northern region acts as a low-permeability layer with frozen pore waters: this layer can be considered as a continuous to discontinuous aquitard of varying thickness and depth. Beneath larger lakes and rivers, taliks are usually through-going and permafrost is absent; thus there is no impediment of subpermafrost groundwater movement to the surface. Subpermafrost groundwaters, and some intrapermafrost groundwaters, usually discharge throughout the year and form perennial springs.

Since most field investigations are conducted during the summer, Sloan and van Everdingen (1988) prepared criteria to identify subpermafrost groundwater likely to discharge perennially. They considered all springs with a temperature greater than 10°C; most springs with discharge rates exceeding 5 L/s; and most springs with a TDS concentration greater than 1 g/L (1,000 mg/L) to represent subpermafrost water. Where present, permafrost will control groundwater flow as an aquitard and restrict the amount of groundwater discharging into shallow lakes, ponds, and streams.

This discharge, which may be seasonal due to winter freeze-back, will frequently be suprapermafrost water, which often has a low temperature, low flow rate, and low TDS content.

Major regional studies of groundwater flow in the north have been confined primarily to two areas: the east side of the Mackenzie Valley, along the proposed highway and pipeline transportation

Figure 15.10a Photos of groundwater discharge features: vegetation at Meilleur River Hot Spring showing deciduous trees (photo: F. A. Michel).

Figure 15.10b Photos of groundwater discharge features showing carbonate terrace of South Redstone Hot Springs (photo: F. A. Michel).

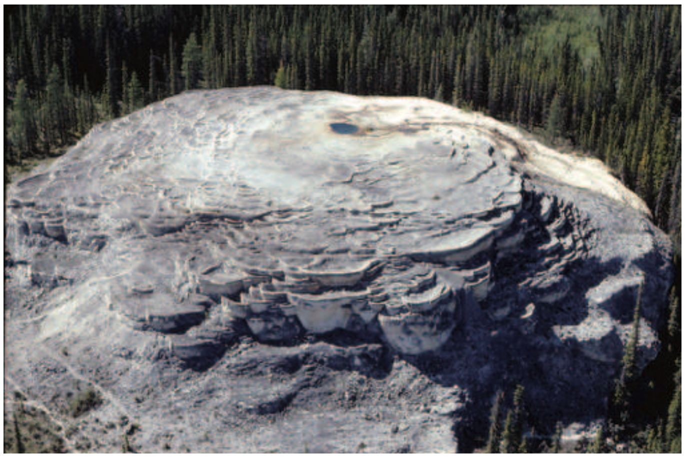


Figure 15.10c Photos of groundwater discharge features showing Rabbitkettle carbonate deposit in Nahanni National Park (photo: F. A. Michel).

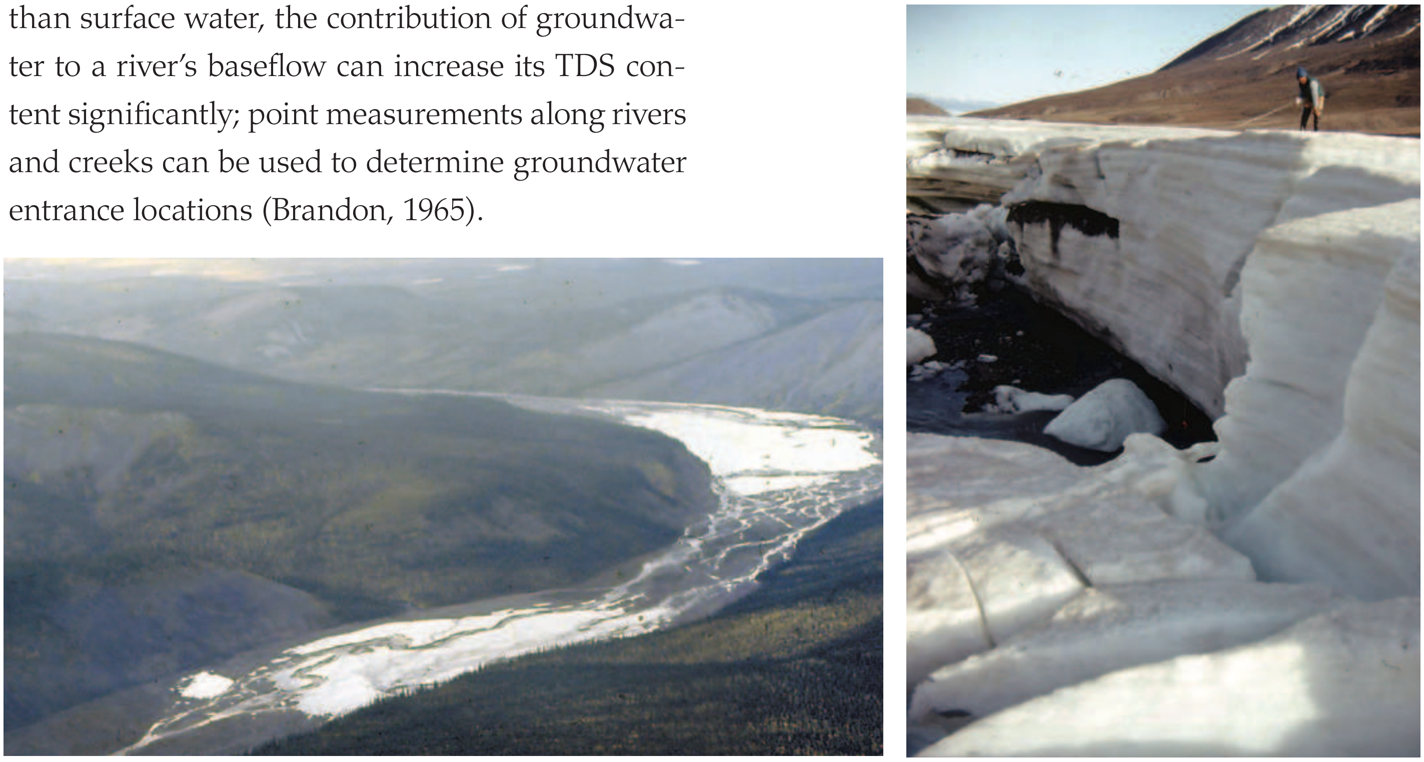
Figure 15.10d Photos of groundwater discharge features showing Iron Spring near Flat River, NWT (photo: F. A. Michel).

corridor investigated during the mid-1970s (Michel, 1977, 1986b), and the area including and adjacent to Nahanni National Park, examined as part of a mineral resource evaluation program in the late 1980s (Jefferson and Spirito, 2003). Both groups of studies focused on the identification and sampling of springs and seeps as discrete points of groundwater discharge. For the Mackenzie Valley (and north Yukon coast), some consideration was also given to baseflow in major rivers as it related to the impact on fish overwintering locations (Templeton Engineering, 1973).

Over 100 distinct groundwater discharge sites were visited in each of the study areas. Many locations were identified by the sudden increase in water flow, vegetation, deposition of precipitates, water colour, or, in the case of thermal springs on a cool day, misty water vapour rising from the vents. Spring flow rates varied from less than 0.1L/s to several hundred litres per second and emanated from a single source or numerous outlets. Vegetation adjacent to springs is often different due to the creation of microclimatic conditions at the vent (Figure 15.10a). Plants can vary from larger growth, to deciduous trees instead of spruce, to bright-green mosses and, occasionally, to exotic vegetation such as wild mint. Halophytic vegetation may be present when the discharging groundwater is highly mineralized or saline. Tan-coloured travertine deposits and terraces are common where groundwater is carbonate rich (Figures 15.10b, c); iron-rich springs precipitate reddish brown amorphous oxides (Figure 15.10d); sulphurous springs may deposit white precipitates, and thermal springs related to granitoid intrusives often have noticeable whitish alteration minerals (clays) on the rocks adjacent to the vent. Where highly mineralized water discharges into a small pool or pond, the water colour may be milky white (sulphurous) or green (reduced iron or carbonate) as a result of changes in the chemistry that occur upon discharge.

Streams and rivers receiving diffuse groundwater discharge are likely to continue to flow even during dry periods. Baseflow can be derived from the melting ice in the active layer, or from suprapermafrost flow throughout the summer, but it is the addition of subpermafrost water that maintains many rivers throughout the entire year. Williams and van Everdingen (1973) estimated that groundwater contributes on average 2.0 to 5.0 L/s/km^2 of drainage basin in the discontinuous permafrost zone. MacKay and Loken (1974) estimated that the groundwater contribution to surface runoff (streamflow) in areas of discontinuous permafrost is 20% to 40%, and decreases to less than 10% in areas of continuous permafrost. Baseflow can also occur as the discharge of water from lakes. Since the groundwater tends to be more mineralized than surface water, the contribution of groundwater to a river's baseflow can increase its TDS content significantly; point measurements along rivers and creeks can be used to determine groundwater entrance locations (Brandon, 1965).

Major springs discharging subpermafrost water can provide a significant baseflow to rivers even in winter. Williams and van Everdingen (1973) reported that a large spring on a tributary of the Porcupine River in northern Yukon maintained open-water conditions on the river for 30 km downstream during the middle of winter. Such areas form important overwintering locations for fish populations. The open-water area depends on volume of flow, the TDS content of the mixed water, groundwater temperature, air temperature, and the channel configuration. Continual flow of water from the spring provides a constant supply that will eventually freeze once the water cools sufficiently. Continued freezing of this constant supply builds up along the river to form an icing, or aufeis/naled, deposit (Figures 15.10e, f). Most icings are related to perennial springs, and the size of the icing will depend on the volume of water flow during the winter. Large springs can produce thousands of cubic metres of ice that persist into



Figures 15.10e and **15.10f** Photos of groundwater discharge features showing icing in river valley (photos: F. A. Michel and B. J. Moorman).

Figures 15.10g and **15.10h** Photos of groundwater discharge features showing pingos in the Mackenzie Delta region (photos: F. A. Michel).

the summer and are readily visible on aerial photographs or satellite imagery.

Van Everdingen (1990), with reference to long-term studies of icings in Russia by Sokolov (1973), approximated the volume of an icing with the equation:

$$Vi = 0.96Ai^{1.09} \qquad (15.2)$$

where Vi is the ice volume in 100 m^3, and Ai is the icing area in 100 m^2. If the time period over which the icing formed is known, then it is also possible to calculate the average groundwater discharge rate. Melting of the icing provides an additional input of water to the stream during the spring and early summer.

Depending on the channel geometry, icings may block the normal river flow and force the water to cut channels through the ice. The restriction in flow caused by icing during the period of high-volume snowmelt runoff in spring will slow the river flow sufficiently to allow it to drop some of its sediment load and develop a braided stream drainage network across the icing footprint. This area of braided channels is in stark contrast to the usual single stream channel found upstream and downstream of the icing area, and the change in the stream pattern can facilitate identification of icing areas even after the ice has melted completely.

When stream water freezes entirely to the underlying sediment, it

Figure 15.10i Photos of groundwater discharge features showing frost blisters at North Fork Pass, Yukon (photo: F. A. Michel).

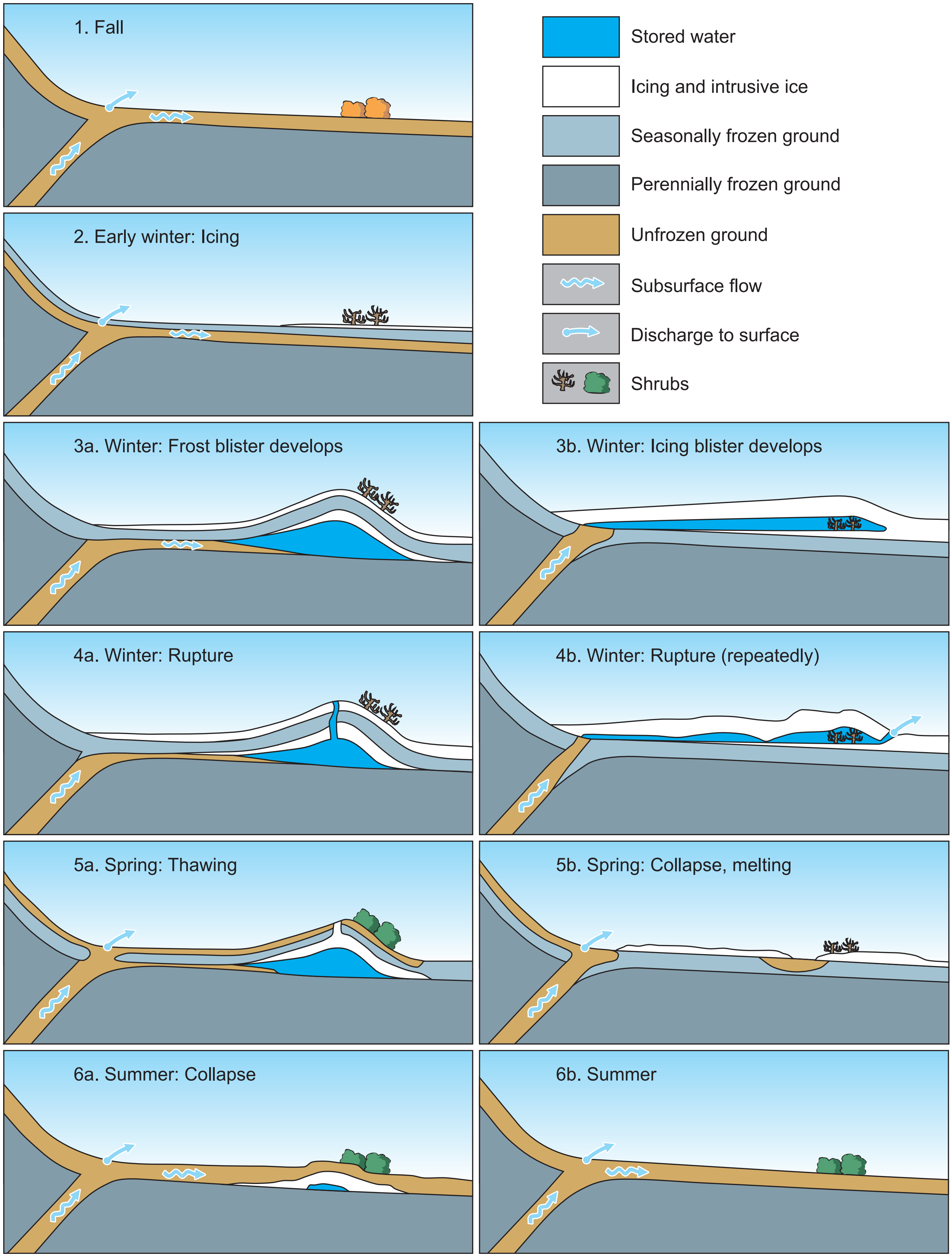


Figure 15.11 Formation and decay of frost blisters and icing blisters (from van Everdingen, 1998)

can form anchor ice, which coats the stream bed. This ice may persist into the period of spring melt, causing changes to streamflow and even, perhaps, affecting local groundwater discharge.

When groundwater discharges directly into the stream bed sediments, and the point of discharge becomes covered by the icing, hydraulic pressure of the contained water can build up to create an icing blister (a pocket of water under pressure) within the icing; this blister will gradually freeze as a small mound, and, as it does so, dissolved solids within the water will eventually precipitate onto the blister floor (Michel and Paquette, 2003).

Icings can also form downstream from glaciers as a result of early winter freezing of late-draining water from the glacier's internal plumbing (Elver, 1994); or from baseflow provided to rivers from lakes during winter as the river channel shallows. These icings are not indicative of groundwater additions to baseflow and can usually be identified on the basis of their geographic setting.

Closed-system pingos (Figure 15.10g), common in the low-relief continuous permafrost terrain of the Mackenzie Delta, are related to the freezing of suprapermafrost groundwater found in closed taliks beneath recently drained lakes (Mackay, 1979, 1985). After lake drainage, the unfrozen lake bed begins to refreeze, forming a surficial confining layer. As groundwater in the talik freezes to form pore ice, its volume expands, placing the remaining water under pressure. The combination of pressure and volume expansion results in an upward heave of the lake bottom sediments. Migration of this pressurized water to the stabilized freezing front creates a separate pure ice core (Figure 15.10h). Continued heave of the lake bed over a period of years forms the characteristic dome-shaped pingo. Open-system pingos, described by Hughes (1969), are another subpermafrost groundwater discharge phenomenon in areas of discontinuous permafrost with significant topographic relief.

Groundwater migrating through a suprapermafrost aquifer also experiences annual refreezing during winter. As in non-permafrost regions, the suprapermafrost groundwater often forms seeps and springs at the break in slope near the floor of a valley. When winter freezing creates a surficial confining layer, the residual flowing suprapermafrost water from springs becomes restricted, resulting in an increase in hydraulic pressure. Provided the surficial frozen layer is sufficiently strong, this hydraulic pressure can increase until the ground starts to heave (Figures 15.10i and 15.11), forming a frost blister with a water-filled core (van Everdingen, 1978, 1982; Pollard, 1983; Michel, 1986a). If the frozen ground is not strong enough to contain the pressurized water, the blister can rupture and allow the water to escape. Freezing of the confined water will form a separate ice core, similar to a pingo, which causes further heave due to the volume expansion. Blisters (both frost and icing) tend to be annual features that collapse every summer.

15.4.5 Geothermal systems

All geothermal waters reported in the literature for the northern region are spring discharges located in the mountains of the Cordillera and the adjacent Mackenzie Valley. These spring discharges can be subdivided into two main groups; those associated with Cretaceous-age granitoid intrusions, and those discharging along fault structures. The maximum reported temperature for the intrusion-related springs is 63.5ºC (Hamilton et al., 1988), while that for structurally controlled springs is 53.5ºC (Michel, 1977). A compendium of known localities was compiled by Crandall and Sadlier-Brown (1976) as part of a geothermal resource inventory, and recently updated by Woodsworth (1997) (see Chapter 7).

Thermal springs, such as the Takhini hot springs near Whitehorse, the MacArthur hot springs in central Yukon, and the Cache Creek thermal springs in northern Yukon (van Everdingen, 1974), can be found throughout the Yukon portion of the Cordillera. Elsewhere in the Cordillera, a number of thermal springs have been identified in the Tungsten area; these are primarily associated with young intrusions (Williams and van Everdingen, 1973; Crandall and Sadlier-Brown, 1976; Hamilton et al., 1988; Hamilton, 1990). With the high heat flow from these intrusions, groundwater circulation depths are probably only a few hundred metres.

A second group of travertine-precipitating thermal springs in the Tungsten area has been described by Atchison (1964), Gabrielse et al. (1973), Bowman (1990), Hamilton (1990), and Gulley (1993). The latter study focused on the rate of travertine accumulation and groundwater flow history for the spectacular Rabbitkettle hot springs site in Nahanni National Park (Figure 15.10c). Hamilton (1990) also discovered a previously unreported fault-related travertine thermal spring along the Meilleur River at the east end of the Park.

Further north, two groups of structurally controlled hot springs along the Redstone River were reported by Gabrielse et al. (1973). Michel (1977) described the main group of these springs in detail. Multiple spring outlets discharge water at temperatures between 31.3°C and 53.5°C; these combine into a single stream prior to flowing into the South Redstone River. Total flow, estimated at over 30 L/s, makes this one of the largest known hot springs in the northern region. Given the high elevation and northern location of this site, the springs have created an ecological oasis just below tree line, with travertine deposits and terraces covering an area of over 30,000 m^2.

Brandon (1965) and Michel (1977) investigated thermal discharges within the Mackenzie Valley near Wrigley, where thermal waters, with temperatures as high as 31.3°C, were found discharging into the Mackenzie River via a thrust fault cutting across the river. Geochemical investigations indicate that precipitation recharged in the mountains flows primarily through the Bear Rock Formation until it reaches the thrust fault along which the thermal groundwater rises.

All of the structurally controlled thermal water discharges indicate that deep regional-scale groundwater flow systems are active where topographic relief is substantial. Elevated water temperatures have caused permafrost adjacent to the groundwater flowpath (talik) to disappear, and not affect the location of discharge. Many thermal springs have probably never been identified or reported because of the region's remoteness.

15.4.6 Groundwater chemistry

Most municipal groundwater supplies have low total dissolved solids (TDS) concentrations and are dominantly calcium bicarbonate in composition. However, some communities may be forced to utilize marginally acceptable waters from wells that intersect subpermafrost aquifers. Tulit'a (formerly Fort Norman), at the junction of Great Bear River with the Mackenzie River, originally relied on a shallow hand-dug well, which was located near the Roman Catholic mission, and collected active-layer water. High nitrate concentrations (55 mg/L) provided the impetus for a deeper drilled

TABLE 15.1 CHEMICAL ANALYSES (IN MG/L) FOR SELECTED SPRINGS IN THE NORTHERN REGION

NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13
NAME	WHITE SPRAY	GRIZZLY LAKE SPRINGS	GYPSUM HILL	MVP MILE 359	WILLOWLAKE RIVER SPRINGS	FLAT FRUIT	MEILLEUR RIVER	PRAIRIE CREEK MINE (200 LEVEL)	GOLDEN DEPOSIT	NAHANNI HEADWATER HOT SPRING	ROCHE QUI TREMPE A L'EAU	YELLOWKNIFE CON MINE BRINE	NORMAN WELLS OIL BRINE, BEAR ISLAND
T°C	4.3	1.5	6.1	13,	10.9	8.9	5,	3,	3.7	63.5	31.3	22.5	N/A
Elec. Cond.	770,	395,	N/A	>8,000	2,050,	870,	2,730,	937,	8,700,	390,	17,800,	N/A	N/A
pH (units)	7.8	7,	N/A	7.2	7.2	6.2	3.8	7.6	2.9	7.9	7.6	5.5	N/A
Ca	39,	84,	1,823,	1,450,	522,	530,	344,	148,	341,	30,	900,	57,300,	10,300,
Mg	7.9	23,	346,	183,	70,	54.5	212,	54,	800,	0.2	149,	920,	1,700,
Na	40.3	1.4	27,100,	27,000,	7.6	29.1	14.8	0.5	500,	53,	3,240,	32,600,	35,600,
K	<0.2	1,	25,	106,	1,	5.6	2.1	0.5	7,	1.5	49,	495,	N/A
Fe	0.136	0.25	N/A	N/A	0.32	0.028	1.4	0.337	220,	0.026	0.21	18.6	Trace
Mn	<0.01	N/A	N/A	N/A	<0.01	0.158	5.4	0.092	6.5	<0.01	0.032	21.8	N/A
Cu	0.004	N/A	N/A	N/A	0.002	0.005	0.049	0.448	0.03	0.005	<0.001	0.81	N/A
Zn	0.01	N/A	N/A	N/A	0.017	<0.005	5.35	61.9	0.17	0.008	0.032	0.59	N/A
Ni	0.006	N/A	N/A	N/A	N/A	<0.002	2.31	0.065	N/A	<0.002	N/A	12.7	N/A
Co	0.006	N/A	N/A	N/A	N/A	0.004	0.405	0.009	N/A	<0.002	N/A	5.8	N/A
HCO3	147,	128,	32.3	204,	218,	1,918,	0,	272,	0,	79.5	177,	2,	320,
SO4	9,	176,	3,995,	3,400,	1,350,	38,	2,285,	393,	5,300,	37.9	2,920,	1,	0,
Cl	1,	1.7	42,340,	44,300,	7.3	3.8	2.5	1.2	24,	11,	5,210,	142,000,	77000,
F	0.12	N/A	N/A	N/A	1.22	0.53	0.48	0.49	0.15	7.8	2.86	26.9	N/A
SiO2	3,	N/A	N/A	8.8	6.3	15,	19,	6,	37,	83,	23,	8,	N/A
Sum	208,	415,	75,661,	76,652,	2,184,	3,371,	2,890,	874,	7,236,	313,	11,716,	237,100,	124,900,
Latitude	61°18' N	66°01' N	79°24' N	65°25'20" N	62°39' N	61°41' N	61°11' N	61°33' N	65°14' N	62°48' N	63°18' N	62°26'30" N	65°15'30" N
Longitude	124°07' W	125°25'45" W	90°43' W	127°17' W	122°57' W	127°38' W	124°48' W	124°45' W	124°52' W	128°50' W	123°37'30" W	114°24' W	126°54' W
Source Ref. #	65	114		93	2B	58	72B	67	72	38	35E	4500-6C	BI-3
Sample Date	Aug 86	21-06-75	18-08-62	21-03-75	12-06-75	July 86	Aug 86	Aug 86	15-09-75	July 86	17-06-75	1980	28-05-44
Notes:													

Data for samples, 2, 4, 5, 9, 11, and 13 from Michel (1977); samples 1, 6, 7, 8, and 10 from Hamilton (1990); sample 3 from van Everdingen (1974); and sample 12 from Frape and Fritz (1987) community well, which produced mineralized subpermafrost water dominated by sodium and chloride with an average TDS concentration of 1,250 mg/L (Michel, 1977).

Investigations of groundwater chemistry, outside of municipal communities, focus either on spring discharge locations, or on the sampling of groundwater seepage within mine workings. Most of the regional-scale research has been driven by development of a transportation corridor (highway and pipeline) through the Mackenzie Valley (Michel, 1977), and the exploration and development of potential mineral resources in the Cordillera (Hamilton, 1990): both are subregions with active regional groundwater flow systems. Studies of site-specific groundwater-related issues have been conducted elsewhere in the north, especially in association with environmental studies of new mine developments.

Water chemistry throughout the northern region can be highly variable (Table 15.1, Samples # 1–13), reflecting the vast range in geological terranes and hydrogeological conditions. Examples given in Table 15.1 include springs with low water temperature and low TDS content (Samples #1 and 2); those with low water temperature and moderate to very high TDS content (Samples # 3 to 9); those with high water temperature and low TDS content (Sample # 10); those with high temperature and high TDS content (Sample # 11); those with elevated trace metal concentrations (Samples # 7 to 9); and deep formation brines (Samples # 12 and 13).

Many of the groundwater systems studied are confined largely to the thick sequences of carbonate rocks found within the Mackenzie Valley and Cordillera. The development of karst in these carbonates channels the groundwater and often results in large-volume discharges that can exceed 100 L/s. Consequently, the pH for most of these spring waters ranges between 6.9 and 8.4; temperatures are usually <10°C; TDS contents are low to moderate; and the major dissolved ionic species are calcium, magnesium, and bicarbonate (Samples # 1 and 2).

Michel (1977) found that the groundwater chemistry, within the Mackenzie Valley, represented a mixture of three endmember groups defined as Ca-Mg-HCO_3, Ca-SO_4, and Na-Cl types. The latter two categories are the result of groundwater flow through the evaporite units of the Bear Rock (gypsum/anhydrite) and Saline River (halite + gypsum/anhydrite) Formations, which add dissolved constituents (Ca, Na, SO_4, and Cl) to the original Ca, Mg, and HCO_3 derived from the carbonates (Samples # 4 and 5). Similar evaporite sequences are not as prevalent within the Cordillera, where the groundwater chemistry is carbonate dominated. Exposed gypsum domes on Axel Heiberg Island (Sample # 3) actually produce NaCl dominated brine waters, indicating the presence of halite along the subsurface flowpath. On northern Ellesmere Island, springs discharging from the surface of an alpine glacier have been reported to precipitate calcium carbonate (as vaterite), gypsum, and native sulphur (Grasby, 2003).

Timlin (1991), Hamilton (1990), and Hamilton et al. (1991), investigated a series of lower pH (5.9 to 6.3), high pCO_2 (> 1 atm), travertine-depositing cold springs (Sample # 6) in the Flat River Valley near Tungsten. Their data suggest that the high CO_2 concentrations are generated by metamorphic decarbonation reactions adjacent to granitoid intrusives at depth. The escaping CO_2 rises along structural lineaments, and mixes with shallow circulating groundwater prior to discharge within the valley. These springs are unique in Canada, but are similar to a class of springs identified worldwide as associated with tectonic activity (Barnes et al., 1978; Hamilton, 1990).

High pH (7.5 to 9.0), low TDS hot springs discharge (Sample # 10) where these granitoid intrusions are exposed. Although the TDS concentrations are low, some trace metals associated with the plutons, such as Mo and W, are elevated, as are Si and F (Hamilton et al., 1988; Hall et al., 1988). Other thermal springs, not directly associated with exposed intrusions, are caused by the rapid ascent along structural lineaments. These springs represent deep circulation and tend to reflect the chemistry of the rocks through which the groundwater flows; thus they often have elevated TDS concentrations dominated by carbonates or, in some instances, evaporites (Sample # 11).

Iron-rich springs in the Nahanni area of the Cordillera are associated with granitoid intrusions, carbonates, sandstones, and shales (Hamilton et al., 1988), whereas in the Mackenzie Valley and northern Yukon they are primarily associated with shales. Iron springs are easily visible from a distance due to the bright red precipitates found adjacent to the discharge vents. These waters typically have a lower pH (3.0 to 6.5), a moderate electrical conductivity (350 to 1,500 μS/cm), and of course a high dissolved-iron concentration (1.0 to 122 mg/L) (Hamilton et al., 1988). The iron is usually derived from oxidation of Fe-bearing sulphides (van Everdingen et al., 1979, 1985).

The presence of elevated iron concentrations in some spring waters is often accompanied by acidic conditions and higher concentrations of other trace metals, while in other instances, elevated trace metals may be found without significant iron. The source of these metals depends on the geology. Hamilton et al. (1988) and Hall et al. (1988) identified three economically interesting metal associations in the Nahanni Park area. These were W-Mo anomalies associated with granitoid intrusions in the Tungsten area, shale-hosted waters with a suite of base metals (Fe, Mn, Ni, Co, Cd, Zn, and Cu), and a highly anomalous group of fault-related springs in shales along the Meilleur River with extremely high concentrations of Ni, Co, Cd, and Zn (Sample # 7). The geology at the latter site indicates that this area may be a southern extension from the Prairie Creek (Pb-Zn-Ag) mine where groundwater sampled within the mine was also anomalous in some trace metals (Sample # 8).

Groundwater that encounters shale-rich formations along its flowpath often undergoes cation exchange, which can significantly alter the overall chemical composition of the water. Michel and van Everdingen (1987) described a groundwater system (Sample # 9) west of Great Bear Lake where cation exchange in conjunction with pyrite oxidation resulted in a groundwater chemistry with a pH of 2.9 , an iron concentration of 220 mg/L, and dominated by sodium, magnesium and sulphate. Upon discharge, a mixture of jarosite, amorphous iron hydroxides (goethite) and clay minerals is deposited as a yellow ochre, which led to the site being referred to as the “Golden Deposit”.

Near Baker Lake in Nunavut, Urangesellschaft Canada Limited (1989) reported radionuclides being transported to local surface water bodies by water flowing through the active layer overlying a uranium-bearing deposit.

All of these examples demonstrate that analysis of groundwater chemistry has the potential to enhance mineral exploration programs in the region, providing an important window to the subsurface geology.

Deeply circulating groundwater experiences an increase in TDS concentration due to prolonged water-rock interaction times. The formation of ice in the subsurface during permafrost aggradation results in expulsion of salts into the residual unfrozen water. This creates a higher salinity fluid that lowers the freezing point, ultimately creating a chemical cryopeg below or within the permafrost. In some instances, groundwater encountered at depth, within mine workings, may be a highly saline brine migrating within taliks or in the subpermafrost zone. Groundwater investigations in the mines at Yellowknife discovered Ca-Na-Cl brines at depth with >237 g/L dissolved salts (Sample # 12) (Frape et al., 1984; Frape and Fritz, 1987; Clark et al., 2000). Detailed groundwater studies at the Lupin mine, north of Yellowknife, revealed Na-Ca-Cl brines beneath the permafrost; the highest salinity waters (39.5 g/L), however, were found within the permafrost, and concentrations decreased with depth (Ruskeeniemi et al., 2004). At the Polaris mine on Little Cornwallis Island, north of Resolute, proximity to the ocean resulted in the mining operations encountering saline waters that may be related to the overlying seawater. The highest salinity brine reported to date (324.5 g/L) was found at a depth of 1,500 m in Thompson, Manitoba, an area with only sporadic permafrost conditions (Frape and Fritz, 1987).

Brines are often considered to represent formation water that has remained in the rock for millions of years, gradually increasing its TDS content through prolonged water-rock interaction. During development of the Norman Wells oil field in the 1940s, formation water, typical of oil field formation waters throughout North America, was encountered in the reservoir rocks (Sample # 13). Comparison of this water with other saline waters encountered in the Mackenzie Valley (Sample # 4) revealed many similarities, although Michel (1977) has shown that most regional groundwater in the Mackenzie Valley is postglacial in age. This suggests that formation water may, in fact, be much younger groundwater that encountered evaporites along its flowpath, and saturated pore spaces within the reservoir rock. The Norman Wells reservoir is known to be leaky.

Drillers are often leery of using cold surface water as a circulating fluid during drilling because of the increased freezing potential in permafrost areas. As a result, they add salt to the groundwater, creating brine that will depress the freezing point. Since some of this saline drilling fluid may escape through fractures in the rock, subsequent sampling programs must be careful to identify any man-made brine present.

15.5 OUTSTANDING ISSUES

15.5.1 Construction of pipeline and highway infrastructure

The widespread distribution of perennially frozen ground throughout the northern region requires special consideration of hydrogeologic characteristics during the planning, design, and construction of buildings, roadways, and pipelines.

Buildings, storage facilities such as fuel tanks, and fixed structures like bridge abutments are susceptible to long-term frost heave. Frost heave by itself is not unique to the northern region; however, the limitations placed on the infiltration of precipitation by the presence of permafrost restricts the drainage of soils, which can result in high ice contents during re-freezing of the active layer each winter. Migration of moisture within the upper permafrost due to large thermal gradients, as demonstrated by Burt and Williams (1976), has been studied extensively and reported in the permafrost literature (Andersland and Anderson, 1978; Williams and Smith, 1989). A significant portion of the water content in a soil can remain unfrozen at subzero temperatures due to increasing solute concentrations (exclusion of salts during freezing) causing depression of the freezing point (Burt and Williams, 1976; Marion, 1995). Anderson and Tice (1972) related unfrozen water contents to the surface area of a soil, such that fine-grained soils (with a large surface area) can remain essentially unfrozen at temperatures well below 0˚C. Combined with large temperature gradients in the shallow subsurface, it is possible for large quantities of unfrozen high-salinity water to migrate through the upper permafrost.

Even more critical is the melting of ground ice beneath various structures resulting from the transfer of heat into the ground. Construction projects in coastal regions and on fine-grained marine deposits, which may contain highly saline waters, are of special concern since depression of the freezing point may result in the presence of a significant proportion of unfrozen water within the permafrost. These fluids are subject to migration along strong thermal and concentration gradients, in addition to the normally considered hydraulic gradients, and may be highly corrosive to the steel piles utilized to mitigate frost heave and issues of thaw settlement.

Roadways within northern communities are normally constructed using coarse-grained aggregate or crushed rock; these materials drain water, inhibit frost heave, and insulate the ground to prevent thaw subsidence of ice-rich material. Layout of these relatively short, community roads usually avoids the ice-rich or water-saturated terrain that could result in differential settlement or heave problems. Similarly, airport runways are located and designed at sites where water migration is not an issue.

Major transportation corridors for roadways and pipelines between communities may not always be able to avoid sensitive terrain; these projects require extensive engineering design following selection of the most appropriate route. Differential heave/thaw can result in serious problems in those cases where the engineering design is inadequate; this is especially true of railroads, which have very strict tolerances. Infrastructure construction within the permafrost regions raises three major concerns that need to be considered from a hydrogeologic perspective:

1. Prevention of frost heave or thaw settlement along roadbeds should be addressed during the design phase. Construction of the road base with an adequate thickness of coarse-grained aggregate usually suffices. Pipelines, which are usually buried within the native soils, require special consideration. Unless the pipeline is to be elevated above the ground surface, as portions of Alaska's Alyeska pipeline are, soil thermal and water-migration properties must be taken into account. Uninsulated, chilled gas pipelines will cause water migration toward the pipe; this water accumulates as ice lenses beneath the pipe, and can result in significant differential frost heave along the length of the pipeline (Williams, 1979), unless large earth or rock berms are placed on top of the pipe to counteract heave and buoyancy. Heated oil pipelines can cause thawing of ice-rich permafrost, leading to subsidence. Significant subsidence by buried oil pipelines in Siberia has led to the development of drainage streams, erosion along the pipeline

right of way, and instability of adjacent ice-rich permafrost. Thermal siphons have been installed along portions of the Alyeska pipeline to prevent thaw.

2. The positioning of roadways and pipelines relative to concentrated groundwater discharge points, such as springs, and the modification of near-surface aquifers can be critical in the design of these structures. Groundwater discharge provides significant baseflow to rivers and small streams that can persist through winter at some locations. Construction of linear structures that can restrict groundwater discharge or streamflow in winter often leads to development of icings on the upstream side. Even multiple oversized culverts can become entirely blocked with ice such that subsequent water flow is ponded adjacent to the structure and eventually overflows the structure's top. Freezing of this water has led to ice masses stretching across roadways, blocking the movement of winter traffic. Freezing of the saturated roadbed aggregate can create significant pore ice and ice lenses, which can cause slumping and failure of the structure during spring melt. Restriction of near-surface aquifers, caused by compaction of soils, or the creation of a frozen barrier surrounding a chilled gas pipeline within a stream bed, can also create groundwater discharge features such as icings or frost blisters. Recognition of these groundwater discharge zones, coupled with proper design, may prevent the need for expensive annual maintenance or future reconstruction.
3. The clearing of vegetation along transportation corridors can lead to an increase in the thickness of the active layer. The maintenance of high water contents in these newly thawed soils because of underlying frozen ground and poor drainage can raise the potential for slope failure, especially on south-facing slopes. Increased water flow over the slope surface can also increase erosion rates and, as a result, increase the sediment content of adjacent streams and rivers. Re-insulation of the entire right of way and special design considerations are necessary to control these processes.

15.5.2 Mining development

Mining activity has been a major economic force in all parts of the northern region. Knowledge of and experience with groundwater flow in permafrost terrain has been gained from mining operations in discontinuous permafrost south of Great Slave Lake at Pine Poin; in the thick continuous permafrost at Polaris, north of Resolute; from Nanasivik on Baffin Island; from deep mines in the Canadian Shield at Yellowknife, Thompson, and Lupin; and from mines in the mountainous terrain of the Cordillera at Tungsten and Keno Hill. New mineral discoveries will create new mining activities throughout all the northern subregions, leading to the development and expansion of infrastructure facilities, each with its share of groundwater issues.

Construction at mine sites requires coarse-grained aggregates for roads, building pads, air strips, and cover material for tailings. Eskers and other glaciofluvial and near-shore glaciolacustrine deposits represent the main source of aggregates for many of these locations. The coarse nature of the aggregates and their higher elevation, compared to the surrounding terrain, has reduced the amount of water present, in many of these settings. Lower water contents mean less ice bonding and easier extraction. However, massive ice has been encountered in esker and deltaic sediments at some localities. This ice presence reduces the volume of material available for extraction and requires controlled drainage of the meltwater. Ice bonding within an orebody can also create additional problems for blasting operations, because of the ice's cohesive nature.

Permafrost may be beneficial in the construction of tailings facilities because of frozen ground's low-permeability characteristics. One major concern is water flow within the active layer, the unfrozen solute-rich groundwater in fine-grained tailings within permafrost, and the potential loss of contaminated tailings' fluid to nearby surface streams and lakes. Tailings embankments need to be carefully constructed to encourage permafrost aggradation. Permafrost aggradation upward through the tailings and into the cover material at the time of mine closure is important, as is the long-term maintenance of this elevated permafrost table under changing climatic conditions. Creation of permafrost conditions around open pits has also been considered as one method of reducing groundwater flow into the workings. Artificial permafrost aggradation is being examined at Yellowknife as an option to prevent groundwater flow in the upper levels of abandoned mines from interacting with large quantities of stored iron-arsenic trioxides.

Groundwater flow within mine workings, whether open pit or underground, can also be of major concern. As noted in our earlier discussion on water supply, Cominco, at its Pine Point operation, pumped 157,000 m^3/day from dewatering wells around the open pit. The karstic nature of the carbonate rocks at Pine Point, and the discontinuous nature of the permafrost, permitted significant unrestricted groundwater flow, which became a major issue for the mine operation.

The kimberlite of the new Victor diamond project, on the Attawapiskat River in northern Ontario, is also located within locally karstic Paleozoic limestones (AMEC, 2004). Permafrost in this part of the Hudson Bay Lowlands is sporadic, found mainly on peat plateaus, and totals less than 5% in areal extent. Water levels in shallow bedrock wells have been reported to fluctuate seasonally by up to 2 m, while deeper wells have flowing artesian conditions. A pumping test in the country rock surrounding the kimberlite was able to sustain a yield of 3,815 m^3/day, with only a 3 m depression in the groundwater table (AMEC, 2004). The effect on this pumping test of an adjacent fault zone, with a reported hydraulic conductivity of 500 m/day, is unknown at present. Nevertheless, development of an open-pit mine will require significant dewatering of local bedrock, which will impact the water table of a large portion of the area surrounding the mine. In addition, water quality concerns for the discharge from dewatering need to be addressed, since the deeper (200 m) groundwaters have TDS concentrations exceeding 2,000 mg/L.

Unrestricted groundwater flow has also become a serious issue for uranium mines in the Athabasca sedimentary basin of northern Saskatchewan, especially with the 2006 flooding of the Cigar Lake mine, which completely shut down operations (see Box 15-2). Again, permafrost in the area is sporadic.

At the Cadillac mine in the Nahanni region, groundwater discharging through the mine portal was considered a serious environmental issue for the adjacent Prairie Creek. However, the region experienced a major earthquake in 1985 that changed the groundwater flow regime such that there was no longer any discharge from the mine entrance after that event.

Brown (1970) reported large mineralized groundwater flows in the Yellowknife mines at depths exceeding 700 m, whereas the base of permafrost is found at a depth of just over 100 m. This flow was concentrated along fractures and faults in the shield rock. Mining operations at Tungsten, N.W.T., also encountered highly pressurized groundwater flow from faults. Detailed investigations of subpermafrost groundwater flow in fractured shield rocks at the Lupin mine were undertaken recently (Ruskeeniemi et al., 2004). Again, groundwater flow is limited to major fracture and fault zones. Structural heterogeneities across the mine site have resulted in variations in hydraulic head, and very little recharge of the subpermafrost system.

The high dissolved-solids concentrations in many of the deeper groundwaters may be the result of water-rock interactions occurring during long subsurface travel times, or, perhaps, the result of salt expulsion during permafrost aggradation. At the Polaris mine on Little Cornwallis Island, saline waters were encountered below the base of the continuous permafrost. In this case, mining beneath the adjacent bay may have intersected a through-going talik that connected the mine workings to the marine waters of the bay. The presence of brine waters associated with oil deposits at Norman Wells suggests that ancient formation waters may also be present at some localities, although as noted earlier, the Norman Wells brines may also reflect dissolution of local evaporites.

Through-going taliks are likely to exist throughout the zone of continuous permafrost in areas inland from the coast. Large deep lakes provide heat sources that can maintain such taliks, and act as point sources of recharge for subpermafrost groundwater systems. Lakes in the Arctic usually freeze to a maximum depth of approximately 2.0 to 2.5 m. Therefore, any lake deeper than 2.5 m could maintain an unfrozen section throughout the winter. Lakes with a diameter greater than about 500 m, and a depth exceeding 2.5 m, will likely form through-going taliks. Depending on the thickness of the permafrost, smaller diameter lakes may also be of concern, especially if major structural features, such as faults, connect the lake directly to subpermafrost aquifers or to subsurface mine workings. Terrain elevation differences of a few metres between proximal lakes may be sufficient to create an active groundwater flow system, with the lakes acting as recharge and discharge points.

15.5.3 Contamination issues

The sparse population of Canada's permafrost region implies that all waters there should be pristine, groundwater in particular. This is largely the case although industrial and military activities, facilitated by improvements in northern transportation since World War II, have left behind local contaminant sources, for which mining, hydrocarbon exploration, and operation of military installations are primarily responsible. Contamination originates from the waste products of these activities. Waste rock and tailings from base-metal operations release acidic leachate upon weathering. Abandoned sumps used to contain drilling fluids collapse and release drilling-mud additives. Military surveillance stations established waste dumps from station operations, including electrical components containing Polychlorinated Biphenyls (PCBs). The contaminants listed above are not unique to permafrost regions, but permafrost will play an important role in determining how these wastes disperse.

When a saturated soil is frozen, the ice-filled pores render the material essentially impermeable. This attribute has resulted in the perception that ice-bonded permafrost can serve as a waste disposal medium. Excavations are created, waste placed and allowed to freeze, and finally a cover is laid down to complete the containment. The concept is sound as long as freezing is maintained. However, departures from complete ice bonding, freezing point depression due to elevated solute concentrations, freeze-thaw processes, and the ground thermal regime of the site will reduce the effectiveness of permafrost containment. Should the fluid component of any waste escape containment, these site characteristics will act to promote further contaminant dispersal.

Permafrost is always associated with a surficial active layer that thaws in summer. This thaw zone can approach two metres in thickness in soils, deeper in rock. When thawed, the active layer functions as an unconfined aquifer above permafrost. Any fluid within this layer is free to flow during the thaw period. Although the active layer is often within fine-grained, presumably low-permeability sediments, the formation of ice lenses by ice segregation results in large water-filled pores during active-layer thaw. This pore fabric has been demonstrated to greatly increase the permeability of thawing sediments relative to the permeability that would be exhibited in the same material if never frozen. Should any contaminant reach the active layer, an avenue is available for further contaminant movement. In the case of solutes, active layer freeze-back will tend to concentrate the dissolved components (Michel, 1982). The resulting higher pore-water densities may promote contaminant movement even beneath level ground.

Where metal concentrating accompanies mining, waste residue from the mill is termed tailings. Tailings are usually placed as a slurry that forms a pond behind a specially constructed dam. In permafrost regions, the tailings pond will freeze, resulting in encapsulation of the pond contents between existing permafrost below the tailings and aggrading permafrost above. Pore-water expulsion ahead of the freezing front should tend to raise the pressure in the remaining unfrozen water, and also to concentrate salts. These processes have been observed to occur in natural settings. Although there is little documentation to date for tailings facilities, licensing conditions for new mining projects tend to include provisions for assessing the possibility of later contaminant escape. Contaminant dispersal is most likely to occur via the active layer in permafrost regions; however, subpermafrost movement is possible if contaminants enter recharge areas for subpermafrost flow.

Little documentation of aquifers confined by permafrost exists. Understanding groundwater flow under permafrost confinement would be warranted most where groundwater is produced for individual or community consumption, and where potential contaminants exist from septic or other local activities. Not only is protection of recharge areas required, but preservation of the permafrost confinement is as well, given that loss of ice bonding could radically alter the flow pattern in the vicinity of any producing well, and lead to downward migration of contaminants.

15.5.4 Climate change

The widespread existence of frozen ground within the northern region has already been shown to have a significant effect on the hydrogeology of the region. In 1990, the International

Geosphere-Biosphere Programme (IGBP, 1990) concluded that northern wetlands and permafrost regions play a vital role in the global climate system. Current global climate models (GCMs) predict that global temperatures will rise during the 21st century, and that the most dramatic changes in temperature will occur at higher (polar) latitudes. Over the long term, any significant temperature change, whether increasing or decreasing, will lead to changes in permafrost distribution, which will affect all components of the water balance in the northern region. Smith (1990) predicted that a temperature rise of 0.5°C per decade over a 60-year period would cause permafrost degradation ranging from seven metres in ice-rich areas to complete disappearance of permafrost in areas of unsaturated frozen sand. The effects of a warming climate on permafrost hydrogeology were originally considered by Michel and van Everdingen (1994). It must be remembered that climate is dynamic and constantly changing, as evidenced by the succession of glacial and interglacial cycles during the Pleistocene, and the climatic fluctuations (warm and cold) throughout the Holocene. Such changes continuously affect the distribution and thickness of permafrost (Koster, 1993; Vaikmae et al., 1995). More recently, concerns about global cooling and the start of a new ice age (in the 1970s) have given way to concerns about global warming.

An increase in air temperature will have several important effects on the water balance, the scale of which will depend on the seasonal distribution and magnitude of the temperature change. These effects may include shifts in the ratio between rainfall and snowfall; changes in evapotranspiration rates, glacier melt, and the total amount of precipitation; and changes in the ground thermal regime. Indirect effects would include changes in vegetation, surface albedo, and runoff rates. Most GCMs predict that global warming will cause an increase in total precipitation as precipitation patterns shift northward in the northern region. This overall increase in precipitation and the seasonal redistribution of that precipitation could result in increased runoff, increased evapotranspiration, and/or increased infiltration and groundwater recharge changing the overall hydrologic balance.

In mountainous areas of the region (Yukon and the Arctic islands), global warming will most likely cause a general retreat of glaciers, although locally increased precipitation could lead to temporary surging if that precipitation falls as snow. The retreat of glaciers will expose ground that may be free of permafrost and, therefore, provide new areas for groundwater recharge. The increased rate of glacier melting will provide an increase in meltwater volumes for both surface-water drainage systems and groundwater recharge, at least over the short term.

The landscape in non-mountainous areas is dotted with numerous small lakes and ponds due to the presence of frozen ground. Degradation of the upper permafrost will remove many of the flow barriers, resulting in the development of more coherent drainage networks and possibly some lake drainage. Permafrost degradation in ice-rich areas could also lead to an increase in thermokarst activity, thereby increasing the number of small lakes and ponds. Changes in drainage could significantly affect the areal distribution of wetlands, which serve as the primary breeding grounds for many wildlife species, and are considered major carbon sinks.

Moderate increases in MAAT can lead to melting of near-surface ground ice, and increased groundwater flow within the active layer. A thicker unfrozen layer developed over a longer portion of the year would allow infiltration rates to increase and would permit longer periods of recharge to both shallow and deep groundwater flow systems. Improved drainage of the active layer, along with increased ground temperatures, also will affect the type and distribution of vegetation. A northward shift in vegetation zones, including the tree line, will impact transpiration rates, surface albedo, and snow cover, which in turn will affect runoff rates.

Lowering of the permafrost table and less freeze-back in winter will create a near-surface perennially unfrozen zone between the active layer and permafrost that will be capable of transmitting groundwater throughout the year and could alter geotechnical conditions locally. The disappearance of permafrost from some areas would increase the areal extent of recharge, and increased rates of recharge for warmer water would cause further degradation of the permafrost at its base and through the creation and enlargement of taliks. Enhanced talik development, and thus better connectivity between deeper subpermafrost aquifers and the surface, will result in more rapid groundwater circulation at both the local and regional scale, coupled with higher rates of recharge and discharge. Increased groundwater discharge will probably affect baseflow characteristics of rivers and lead to a rise in the dissolved-solids content of river water. Additional groundwater discharge enhancing baseflow could cause some rivers to maintain longer open-water seasons, or result in increased icing activity. Specific effects of climate change on any given groundwater system will depend on local characteristics and conditions.

15.6 CONCLUSIONS

The northern region comprises over 50% of Canada's land mass, encompassing all of Canada north of the southern limit of discontinuous permafrost. The region includes a wide variety of geologic and physiographic terranes, which create a large range of groundwater conditions. Relatively little is known about the permafrost control of groundwater flow since the region is sparsely populated, and groundwater is utilized primarity as a water supply for communities within Yukon. Permafrost is known to act as a barrier to groundwater recharge when the permafrost is ice-bonded and continuous. Groundwater flow through permafrost is restricted to taliks created by the thermal or chemical conditions of the groundwater. Groundwater that discharges directly into rivers from taliks can provide perennial baseflow, and result in open reaches within the rivers during winter: these provide important fish habitat. Major issues in the region related to groundwater flow, or the effects of phase change between water and ice, include the construction of infrastructure (especially pipelines and highways), mining development, contaminant migration, and climate change.

BOX 15-1 OLD CROW, YUKON

The community of Old Crow, Yukon, is located on an old floodplain of the Porcupine River, just below the confluence of the Porcupine and Old Crow Rivers. Situated 120 km north of the Arctic Circle and 50 km east of the Yukon/Alaska border (67° 33′ N, 132° 52′ W), the community is within the zone of continuous permafrost. Until 1982, the community relied on the Porcupine River for its water supply.

In March 1982, drilling was undertaken in an attempt to locate a new groundwater supply from within alluvial gravels of the old river channels or adjacent to the current river. Due to the thickness of the permafrost (determined as extending to a depth of 63 m), two deep 15 cm diameter wells were drilled into bedrock to explore for a potential subpermafrost aquifer. Bedrock was encountered at depths of 37.6 m (WW #1) and 35.8 m (WW #2) in the two wells, which were drilled 17 m apart. The bedrock stratigraphy consisted of sandstone to 64 m, shale and siltstone to 79 m, and limestone/dolostone below.

The 15 m of shale and siltstone form a confining layer above the permeable carbonates. Water well #1 encountered artesian flow at 79.3 m that was estimated at 6.1 L/s (80 Igpm). The second well also encountered artesian conditions upon entering the carbonates at 79 m; however, drilling was continued to a depth of 122 m. Flow from the second well was approximately 2.3 L/s (30 Igpm). Water temperatures ranged from +0.5 ºC to +2.5ºC, stabilizing after two months of pumping at +0.8ºC. TDS values averaged 340 mg/L with elevated Mn and Fe concentrations.

Initial testing demonstrated that the two wells intersected the same hydrostratigraphic unit, but at different depths. A 72-hour pumping test was conducted on WW #1 at a rate of 17 L/s (225 Igpm), while WW #2 was employed as an observation well. The data was analyzed, using both Theis and Jacob methods, yielding transmissivity values ranging from 17.1 m^2/day to 42.2 m^2/day, and storativity values from 1.52×10^{-3} to 3.62×10^{-3}. Analysis of 20 hours of recovery data produced a transmissivity value of 122 m^2/day.

The two wells were connected to insulated shallow buried service lines to provide the community with a new groundwater supply. Both the wells and the service lines were installed with heater cables to prevent freezing. A winter-time ($T < -35$ºC) fire at the local school demonstrated that even fire hoses should contain heater cables to prevent freezing and loss of access to the water supply. For details on this work refer to Trimble et al. (1983).

BOX 15-2 CIGAR LAKE, SASKATCHEWAN

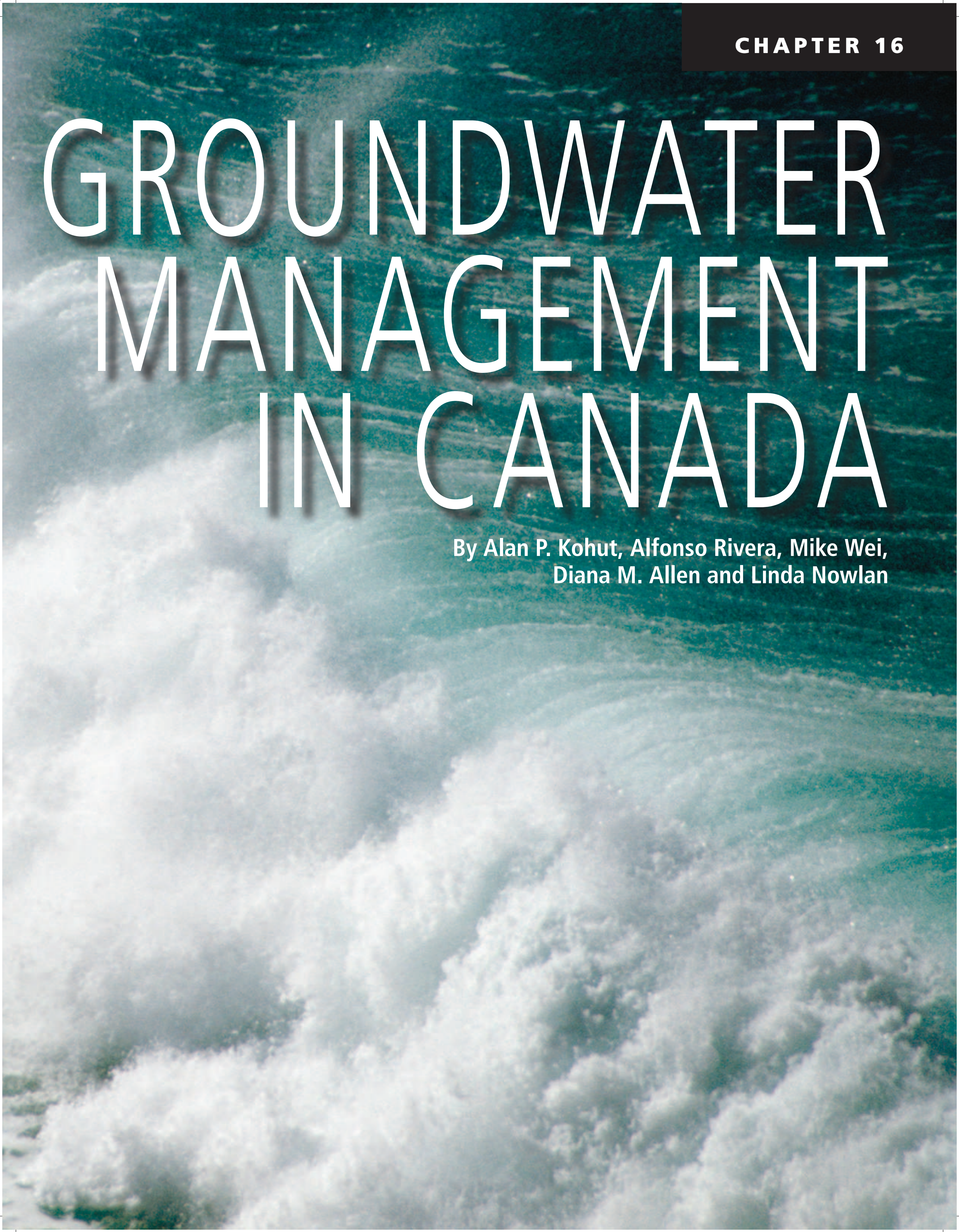
The mid-Proterozoic-age Athabasca Basin in northern Saskatchewan contains a thick sequence of relatively undeformed fluvial, quartz-rich sandstones that unconformably overlie a basement complex of deformed and metamorphosed Archean and early Proterozoic rocks. The basal unconformity hosts several known large, high-grade hydrothermal uranium deposits, primarily near the eastern margin of the basin. The Cigar Lake deposit, one of the richest in the world (up to 55% U), was the subject of a detailed study led by Atomic Energy of Canada Limited (AECL) in the 1980s and early 1990s, because the deposit was viewed as a natural analog for a nuclear waste repository. Groundwater investigations were an important aspect of the study. Thin sporadic permafrost exists in the area.

The uranium orebody, located at a depth of 430 m, was considered to be isolated from groundwater flow in the overlying permeable sandstones by a clay cap, and underlain by impermeable metamorphic rocks. The regolith along the unconformity was also estimated to have low hydraulic conductivity. Modelling of field data indicated that three flow regimes exist (local to semi-regional), all with a southwest to northeast groundwater flow direction, discharging locally into Waterbury Lake. Recharge was calculated to be approximately 5% of annual precipitation, or 25 to 30 mm/year to maintain steady-state flow conditions. Modelled flow rates were calculated to be 1 to 4 m/year in the sandstone and <0.01 m/year in the basement. However, tritium age dating suggested that at least some groundwater in the upper unconfined overburden aquifer and the two deeper confined flow systems within the sandstone was less than 45 years old, possibly due to fracture flow. Particle tracking from within the ore zone through the clay cap produced model groundwater ages of 18,000 to 85,000 years.

Observations from underground workings indicated that the regolith was much less permeable than calculated from borehole test data, that groundwater flow through fractures intersected was minimal (Q < 19 L/h), and that there was no connection to the permeable sandstone above. Although fractures in the rock were not pervasive, one probe hole drilled at the 420 m level in the workings encountered a 10 to 20 m wide highly permeable fracture zone with a flow of 75 L/s.

Groundwater inflow and weak rock zones were expected during development of the mine. Design plans included freezing of the ground to increase rock stability, reduce groundwater flow, and reduce radiation exposure due to radon gas dissolved in the groundwater. However, in 2006, a rockfall in the production area led to water inflow at a rate of 1,500 m^3/h. Flooding of the entire subsurface workings occurred when a steel door, installed to contain water inflow, could not be fully closed. Remediation efforts are in progress and Cameco, the mine operator, announced in February 2008 that a large concrete plug had successfully sealed the workings from further groundwater inflow at the rockfall location. The analysis was based on rising head tests conducted utilizing the shaft as a large diameter pumping/monitoring well over an 8-day period. Flooding occurred again during the summer of 2008, further delaying the start date for production until some time after 2011, more than three years behind schedule. See Cramer and Smellie (1994) for further details on the AECL-led study.

PART V:
EMERGING ISSUES, CONCLUSIONS, AND PERSPECTIVES



CHAPTER 16

GROUNDWATER MANAGEMENT IN CANADA

By Alan P. Kohut, Alfonso Rivera, Mike Wei,
Diana M. Allen and Linda Nowlan

16.1 INTRODUCTION

This chapter provides an overview of the current and diverse state of groundwater management in Canada, the roles of the management agencies, and the scope of their activities.

Canada is a large federation of ten provinces (British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, Nova Scotia, New Brunswick, Prince Edward Island, and Newfoundland and Labrador), three territories (Yukon, Northwest Territories, and Nunavut). Each province and territory has its own government. Additionally there is a federal government. As such, there is a variety of legislative framework under which groundwater resources are governed and managed. It is not surprising, then, that there are significant differences across the nation.

In recent years, several publications (Rivera et al., 2003; Nowlan, 2005; Côté, 2006; Council of Canadian Academies, 2009) have noted the diverse groundwater management approaches which have evolved in various parts of the country. Several of these publications speak to the need for a more collaborative, coordinated and integrated approach among all levels of government, and with the public, to ensure groundwater sustainability. Although coordinated and integrated assessments are being undertaken, some persistent and emerging issues still need to be addressed.

16.2 GROUNDWATER USE IN CANADA

In order to manage our groundwater resources properly, it is important to have information on how much groundwater is available and how much groundwater is used. To date, there is no recent comprehensive compilation of groundwater use data in Canada. This is because it is very difficult to obtain information on groundwater use within individual provinces and territories, all of which regulate the resource differently. The picture is also incomplete because water use is not always measured and reported (e.g., lack of compliance with measurement and reporting requirements, groundwater extraction not regulated in British Columbia, and domestic use exempt from permitting). Groundwater is also vital for sustaining ecosystems, but no information is available on how much groundwater is "used" for this purpose.

Based on 1996 statistics data, Environment Canada (2011a) reports that 30.3% of Canada's population relies on groundwater for municipal, domestic and rural use. Based on the 2010 population of 33.7 million, this means 10.2 million Canadians depend on groundwater. Approximately two thirds of these users live in rural areas, wherein wells may produce a more reliable and less expensive water supply than that obtained from nearby lakes, rivers and streams. The remaining users (or 33%) are located primarily in smaller municipalities and/or communities, where groundwater is the primary source for their water supply systems. The percentage of population dependent on groundwater ranges from 23.1% in Alberta to 100% in Prince Edward Island (Figure 16.1).

Groundwater use in Canada has increased by 500% in recent decades, with the total volume pumped increasing from 200 Mm^3/year (million cubic metres per year) in the 1970s to more than 1,000 Mm^3/year in the late 1990s (Statistics Canada, 2003). The amount of groundwater used for domestic purposes has risen right along with the increase in population (Figure 16.2), from 10% in the late 1960s to 30% in the late 1990s.

Groundwater also sustains economic activity by providing significant water supplies to industries involved in manufacturing, mining and petroleum.

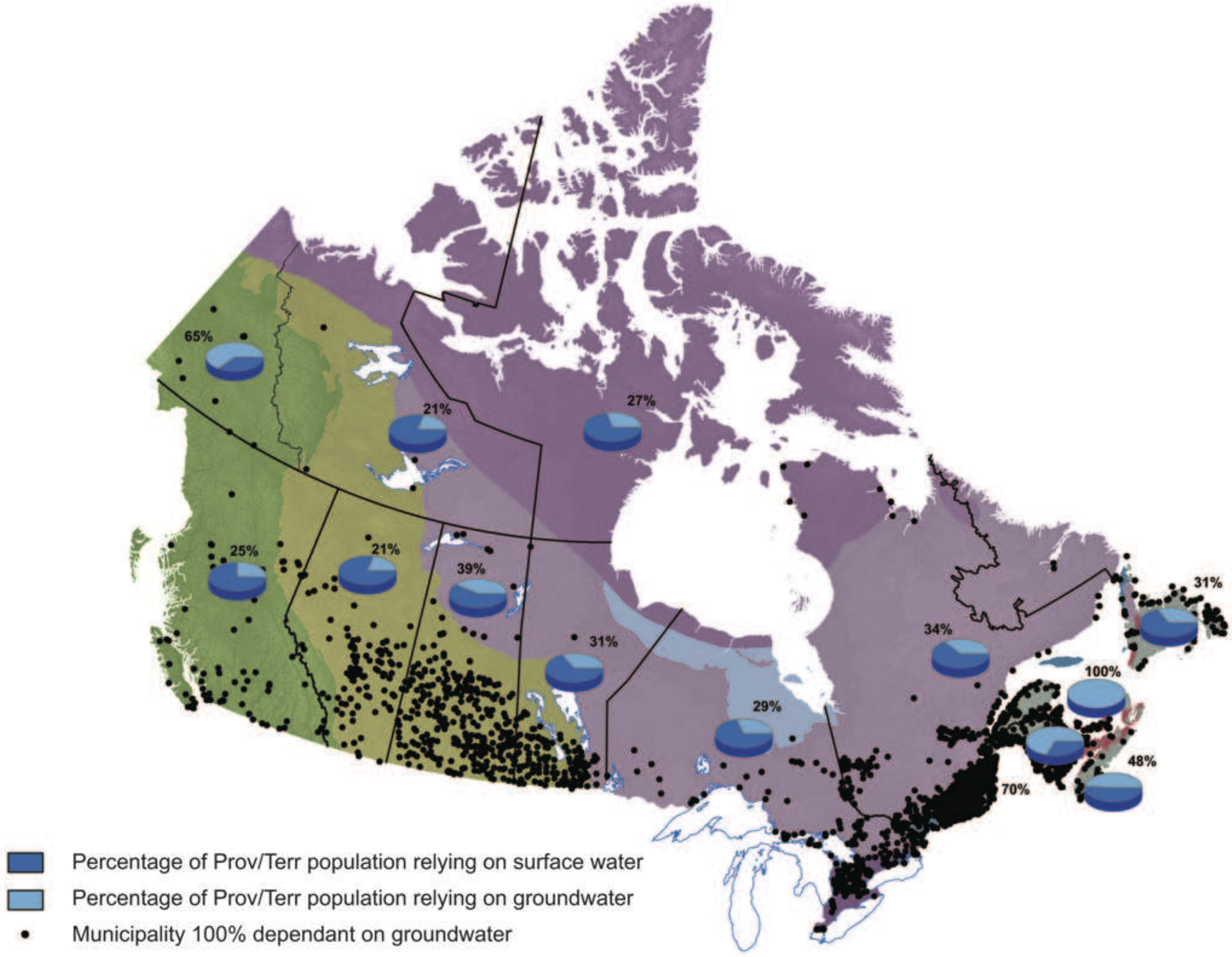


Figure 16.1 Groundwater use in each province and territory. Also shown are the hydrogeological regions in Canada.

Information on groundwater use in Canada for various sectors has been compiled by Rutherford (2004) from several data sources spanning a number of years. Table 16.1 provides a representative indication of sector use based on allocation permits and estimates. The following descriptions of water use for various sectors are adapted from Rutherford (2004).

The groundwater use data by Rutherford (2004) in Table 16.1 has been pooled and organized into five categories. Although logical, these categories have been created on a somewhat arbitrary basis, representing a compromise between managing the unevenness within the data and finding some common basis for comparison. Establishing five categories for BC was challenging, because data for BC is usually presented in four groundwater use categories. Saskatchewan's data is usually presented in 14 groundwater use categories. In some cases domestic wells are included in the "municipal" category. The "other" category includes a variety of uses, ranging from fish management, to recreation, irrigation of parks, space heating/cooling, firefighting, etc.

The largest quantities of groundwater are most often allocated for industrial purposes. Specific industrial applications vary significantly from province to province, with some overlaps. One

TABLE 16.1 GROUNDWATER ALLOCATION BY SECTOR USE. DATA FROM RUTHERFORD (2004) ARE BASED IN PART ON PERMIT ALLOCATIONS AND VARIOUS ESTIMATES. NOTE THAT VALUES HAVE BEEN ROUNDED OFF TO THE NEAREST PERCENT.

PROVINCE / TERRITORY	INDUSTRIAL	AGRICULTURAL	MUNICIPAL	COMMERCIAL / INSTITUTIONAL	OTHER
British Columbia (estimated)	55 %	20 %	25 %	No	No
Alberta	35 %	17 %	26 %	14 %	8 %
Saskatchewan	52 %	3 %	43 %	1 %	1 %
Manitoba	22 %	44 %	17 %	?	17 %
Ontario	35 %	27 %	24 %	6 %	8 %
Quebec	30 %	16 %	54 %	?	?
New Brunswick (estimated)	27 %	No	73 %	No	No
Nova Scotia	n/a[1]	n/a	n/a	n/a	n/a
Prince Edward Island (estimated)	Some	Some	#1 use	No	No
Newfoundland and Labrador (estimated)	No	No	#1 GW use	#2 GW use	No
Yukon (estimated)	No	No	#1 and only real use	No	No
Northwest Territories	n/a	n/a	n/a	n/a	n/a
Nunavut	n/a	n/a	n/a	n/a	n/a

[1] n/a: data not available.

common industrial set of customers, and a heavy user of groundwater, is the manufacturing sector. Paper and allied products, food, and primary metals manufacturing are among the largest consumers of fresh groundwater in this sector, with each withdrawing 65.8 Mm^3/year, 44.6 Mm^3/year and 22.9 Mm^3/year, respectively. Nonmetallic mineral products (9.9 Mm^3/year), wood products (9.5 Mm^3/year), and beverage manufacturing (8.1 Mm^3/year) follow. The thermal power generation industry in Canada utilizes 137.6 Mm^3/year of self-supplied fresh water from groundwater sources. Of this, 129.7 Mm^3/year is used by the electrical power industry and 7.9 Mm^3/year is used by paper and allied industries.

It is estimated that 97.9% of the Canadian mining sector's total water needs of 518.2 Mm^3/year are self-supplied; of this, groundwater sources comprise 40.4 Mm^3/year or 7.8% of mining's freshwater needs, and 4.0 Mm^3/year or 0.8% of the sector's brackish water needs. The metal mining sector is the largest user of fresh, self-supplied groundwater, at 23.5 Mm^3/year; coal mines follow at 10.3 Mm^3/year; then nonmetal mines at 6.5 Mm^3/year. It is also common practice in mining for large quantities of groundwater to be withdrawn in place because mines are dewatered in preparation for mining. Dewatering of mine pits and adits reduces groundwater pressures, stabilizes the site by reducing risk of landslides and rockslides, and improves mine safety.

Aquaculture is another common industrial use

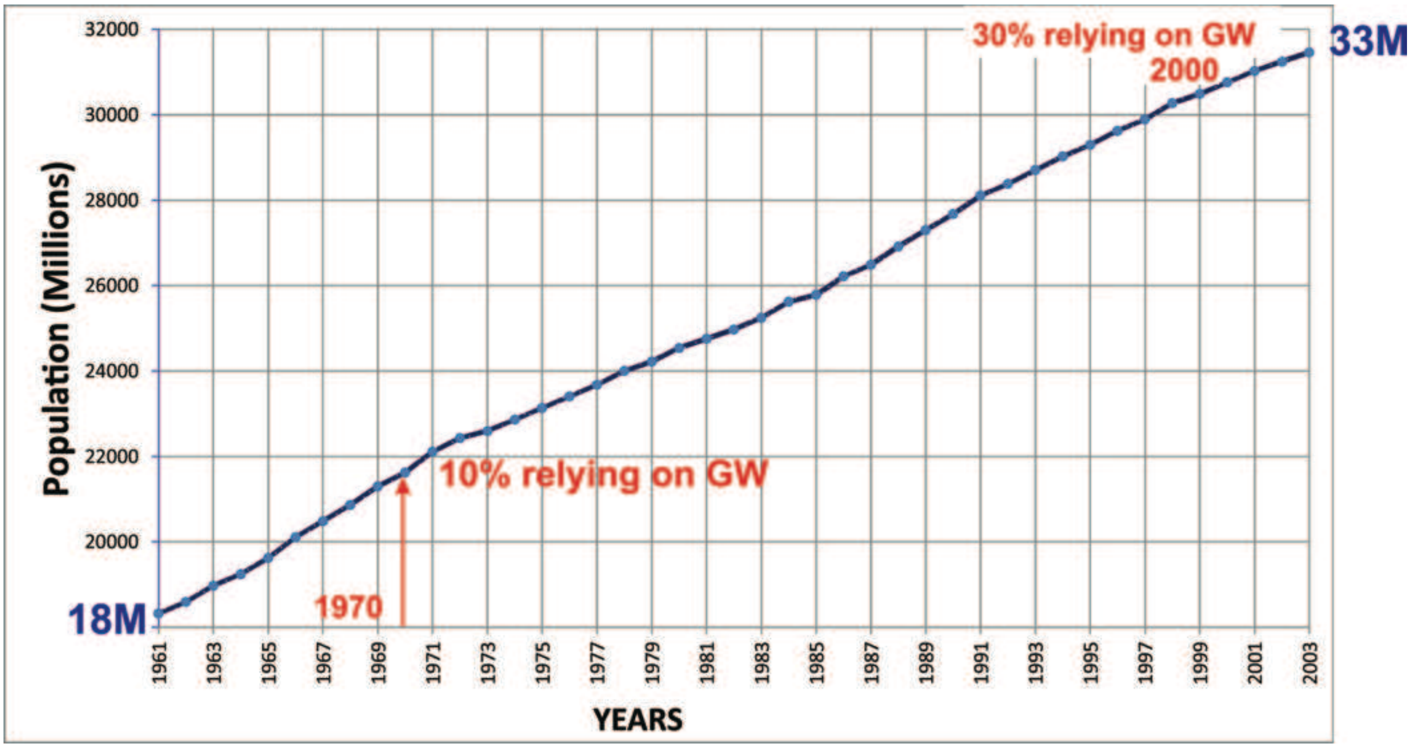


Figure 16.2 Groundwater use in Canada since the 1960s.

of groundwater across Canada. The aquaculture industry's use of groundwater is tracked in at least six provinces. Groundwater is often used in fish-rearing ponds, which are gravity-fed; its constant water temperature and quality make it a valuable supply source for hatcheries as well. Groundwater used in aquaculture operations is typically recycled because of high water demand.

Public waterworks and/or municipal systems are other regular groundwater users. Municipal systems service not only residential consumers, but also many city-dwelling commercial and industrial operations. It has been estimated that only 1% of the municipally-supplied treated water in Canada is used for human consumption (Rutherford, 2004). Some of the many uses of water in municipal systems for industrial, commercial and institutional use include pulp and paper production, industrial processing, heating, ventilation and air conditioning for buildings, restaurants (for cooking and washing), hotels (for washing bedding, flushing toilets, etc.), schools, universities and hospitals (for cooking, washing and bathroom uses).

Groundwater is commonly used in agriculture, especially for crop irrigation and watering of livestock. Brook et al. (2004) report that "Groundwater provides nearly all of the water used to produce livestock in Canada."

Water bottling is another common use of groundwater in Canada. Saskatchewan, Manitoba, Quebec, New Brunswick, and Newfoundland and Labrador all specifically track allocations for bottled water operations. Compared to some other uses, water bottling is not a currently high-volume use, but unlike some other uses, it is 100% consumptive (consumptive water use is water removed from available supplies without being returned to a water resources system, e.g., water used in manufacturing, agriculture, and food preparation that is not returned to a stream, river, or aquifer).

Finally, groundwater baseflow provides a critical ecological function. Rivera et al. (2003) report that

TABLE 16.2 FEDERAL JURISDICTION OVER SURFACE WATER AND GROUNDWATER RESOURCES

FEDERAL GOVERNMENT	COMMENTS
Water on federal lands (e.g., National Parks), federal facilities (e.g., military bases), in the Northwest Territories and Nunavut and on First Nations reserves	"Federal waters" means, other than in Yukon, waters under the exclusive legislative jurisdiction of Parliament and, in Yukon, waters in a federal conservation area within the meaning of section 2 of the *Yukon Act* (*Canada Water Act*).
Federal works and undertakings (including international or interprovincial)	Water is taken for use by federal works, for instance, in federal lands, transboundary aquifers, or the north.
Interprovincial and international boundary waters	"International waters" means water that flows in rivers that cross the international boundary between the United States and Canada (*Canada Water Act*). "Boundary waters" are defined as the waters in lakes that straddle the international boundary between the United States and Canada and rivers that cross the international boundary between the United States and Canada (*International Boundary Waters Treaty Act*). Formally, the *Boundary Water Treaty Act* does not include groundwater. "Inter-jurisdictional waters" means any waters, whether international, boundary or otherwise, that, whether wholly situated in a province or not, significantly affect the quantity or quality of waters outside the province (*Canada Water Act*).
Environmental assessment for any project involving a "facility for the extraction of 200,000 m^3/year or more of groundwater"	Covered under the *Canadian Environmental Assessment Act*, and triggered in cases where there is direct federal interest, such as federal funding or extraction on federal land.
Fisheries (groundwater sustains streams, lakes and wetlands particularly during the dry season)	Prohibits damage to fish habitat and the deposit of deleterious substances in fish-bearing waters and which may be useful to protect groundwater essential to fish habitat (*Fisheries Act*).
Drinking water quality	Sets guidelines for water quality (*Canadian Drinking Water Guidelines*). Binding only if incorporated into provincial/territorial laws.
Water management planning and water quality management plans	Enables the preparation of plans where water quality management of any inter-jurisdictional waters has become a matter of urgent national concern (*Canada Water Act*). *The Great Lakes Charter Annex*, signed by eight states in the U.S. and two provinces, (Ontario and Quebec) requires both countries to better understand and conserve groundwater as well as surface-water resources. In 2010, the International Joint Commission (IJC) released its report, *Groundwater in the Great Lakes Basin*, calling for greater effort to protect groundwater in the basin.
Research, data collection and inventory	Enables establishing and maintaining an inventory of water resources and conducting research (*Canada Water Act*).

Note: This listing is for illustrative purposes and not necessarily comprehensive.

"all Canadians rely indirectly on groundwater because it is the primary source of water for livestock watering and crop irrigation. As groundwater is an integral component of the hydrological cycle, the health of our streams, lakes, wetlands, and associated ecosystems depends upon groundwater." Groundwater also maintains baseflows in rivers and streams during periods of drought, and is critical for sustaining wildlife habitat and fish spawning areas.

16.3 EXISTING LEGISLATIVE FRAMEWORK

Although Canada's Constitution is silent on the specific issue of groundwater, specific elements of groundwater governance are embedded within other jurisdictional responsibilities (Côté, 2006). As set out in the Constitution, however, provinces and territories have primary legal jurisdiction over water and groundwater through their powers of ownership over public land, and jurisdiction over natural resources and public land. The federal

TABLE 16.3 PROVINCIAL AND TERRITORIAL JURISDICTION OVER WATER AND GROUNDWATER RESOURCES

PROVINCIAL GOVERNMENTS	COMMENTS
Allocation of water within their respective land areas	Includes regulation of water use and administration of water rights through water-use licences or water-taking permits (e.g., *BC Water Act, Alberta Water Act, Ontario Water Resources Act*).
Inter-basin water transfers and bulk water removal	Prohibits large-scale diversions and water removal from province or territory (e.g., *BC Water Protection Act, Saskatchewan Watershed Authority Act, and Manitoba Water Resources Conservation and Preservation Act*).
Environmental assessments	Provides for systematic evaluation of the environmental, socioeconomic and cultural aspects of proposed major developments (e.g., *BC Environmental Assessment Act, Saskatchewan Environmental Assessment Act, Ontario Environmental Assessment Act*).
Water quality protection	Includes the regulation of waste discharges into the environment including water and groundwater (e.g., *BC Environmental Management Act, Yukon Environment Act, Quebec Environmental Quality Act*).
Water management planning	Allows for the designation of water management planning areas and preparation of water management plans (e.g., *BC Water Act, Ontario Water Resources Act, New Brunswick Community Planning Act*).
Drinking water quality	Sets standards and guidelines for drinking water quality, treatment and water quality monitoring requirements and requirements for source water protection (e.g., *BC Drinking Water Protection Act, Manitoba Drinking Water Safety Act, Ontario Safe Drinking Water Act*).

Note: This listing is for illustrative purposes and not necessarily comprehensive.

government, on the other hand, has legislative and proprietary powers to manage groundwater on federal lands, including national parks and military bases (Council of Canadian Academies, 2009). Federal jurisdiction over surface water and groundwater also extends to interprovincial and international waters and fisheries (Table 16.2).

Provincial/territorial jurisdiction in Canada includes the prime responsibility for allocation of water and administration of water rights, or water use authorizations, and other related management activities (Table 16.3). Both federal and provincial/territorial levels of government are also involved in various water management activities such as planning, environmental assessments, water quality standards and protection, water monitoring, water research, dissemination of groundwater information and the promotion of water stewardship.

Hill et al. (2007) provide a comprehensive overview of water legislation and policies in Canada's provinces and territories, in addition to listing the most relevant federal water legislation and/or programs and policies enacted by federal government agencies with direct roles in water management. Nowlan (2007) provides an overview of groundwater- permitting processes in provincial and territorial jurisdictions. The Guelph Water Management Group (2007) has compiled a detailed and comprehensive summary of the various water allocation systems within each province and territory.

16.4 MANAGEMENT VERSUS GOVERNANCE

Although this chapter focuses primarily on groundwater management, we think some mention of water (and groundwater) governance is appropriate for setting the groundwater management context. Many Canadian scholars have defined the difference between management and governance as the difference between operational, on-the-ground activity (management), and the range of political, organizational, and administrative processes through which interests are articulated, input is received, decisions are made and implemented, and decision makers are held accountable (governance) (Council of Canadian Academies, 2009, University of British Columbia, 2010).

Table 16.4 compares various water management activities and governance principles.

Despite efforts to clarify terminology, terms are used differently by various agencies.

The *Canada Water Act* (Government of Canada, 2010), for example, takes a broad view defining water resource management as the conservation, development and utilization of water resources including activities such as research, data collection, maintaining of inventories, planning, implementation of plans, and control and regulation of water quantity and quality.

Environment Canada (2011b) reported that "governments in Canada are moving to integrated ecosystem and watershed management approaches that draw on sustainable development principles." These are designed to ensure that decision making reflects the interests of many stakeholders and balance a range of goals, including sustainable water and aquatic resource management, protection from water quality–linked health threats, protection of aquatic ecosystems and species, and reduction of the health, economic and safety impacts from floods and droughts.

The Expert Panel on Groundwater (henceforth referred to as the Panel) , which prepared the report of The Sustainable Management of Groundwater in Canada, states that "good water governance" includes elements such as inclusiveness, participation, transparency, predictability, accountability, and the rule of law (Council of Canadian Academies, 2009). Providing relevant information to the decision maker and the public in a form that is accessible (e.g., maps, reports, databases) is regarded as a prerequisite for any fair and transparent decision-making process. The Panel views the "application of good governance" as a key goal for a sustainable groundwater management strategy. According to the Panel, the concept of groundwater sustainability should encompass five interrelated goals: three that involve primarily the physical sciences and engineering domain, and two that are largely socioeconomic in nature. The Panel's five sustainability goals are characterized in Figure 16.3.

No matter what the terminology, the current trend is toward more holistic and inclusive forms of governance and management—forms that include many of the elements which shape how groundwater (and, indeed, water) is allocated and used, and on what bases those use and allocation decisions are taken.

TABLE 16.4 COMPARISON OF MANAGEMENT ACTIVITIES AND GOVERNANCE PRINCIPLES

MANAGEMENT ACTIVITIES	GOVERNANCE PRINCIPLES
• Water allocation • Regulation of drillers, pump installers and well construction and closure • Protection of environment or water quality • Water and land use planning • Data collection, including monitoring of regional groundwater conditions • Acquisition of science (e.g., hydrogeological mapping and characterization)	• Facilitates decision making through inclusiveness, shared responsibility and accountability • Assures the quality, consistency and transparency of decision making • Improves the efficiency of water management and water use • Improves government responsiveness

16.5 GROUNDWATER MANAGEMENT ACTIVITIES

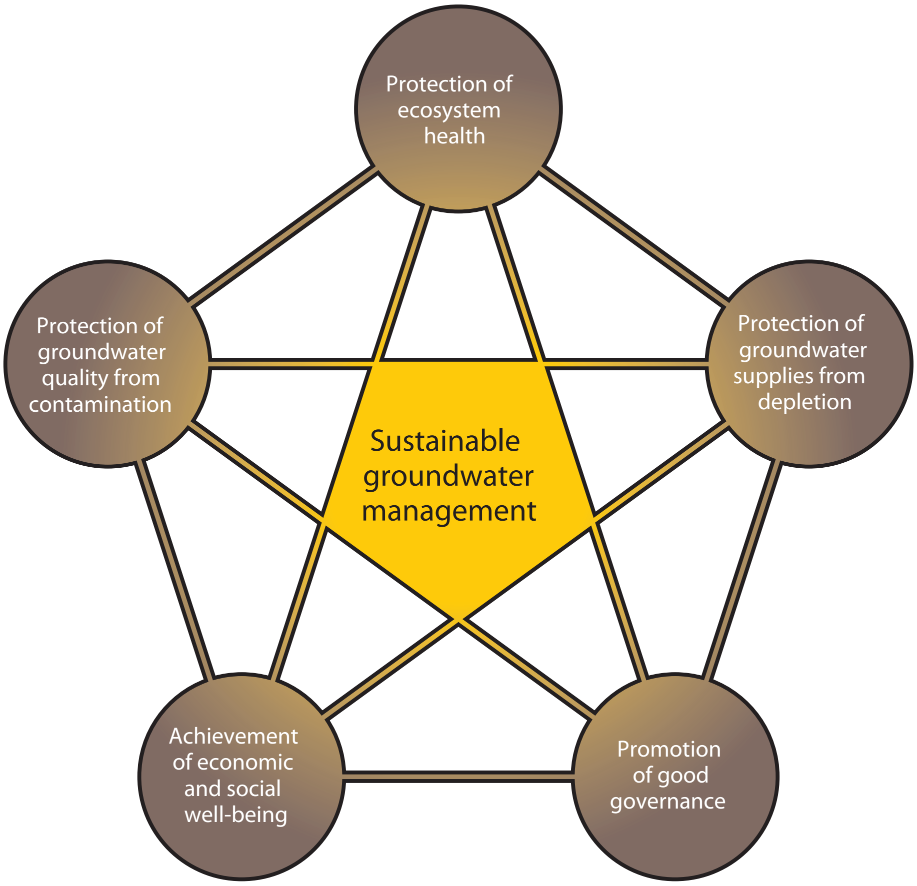


Figure 16.3 Groundwater sustainability pentagons from "The Sustainable Management of Groundwater in Canada" (Council of Canadian Academies, 2009).

Groundwater management in any jurisdiction often includes some or all of the main activities shown in Table 16.5. Readers should note that the activities in the upper portion of this table are regulatory, while the activities in the lower portion are generally non-regulatory (acquisition of science, provision of information, stewardship). There are major differences between the various jurisdictions in how they manage their groundwater resources and the scope of their activities (e.g., style of governance, priorities and agency capacity). Activities that promote good governance and involve public participation include water management planning, wellhead and aquifer protection plans, environmental impact assessments, and undertakings that consider the impacts to groundwater by decision makers of other activities (e.g., land use) not directly related to groundwater but with potential to impact it. Data management activities that make well record data, information and reports readily available to the public through electronic format via the internet also enhance good governance. A summary of some of these activities is presented here—water allocation, environmental and groundwater quality protection, groundwater monitoring networks, and inter-agency cooperation; however, a comprehensive discussion of every activity is beyond the scope of this chapter.

16.5.1 Groundwater supply allocation in the provinces and territories

Allocating groundwater as a water supply is a prime regulatory activity, and includes the regulation of water use and administration of water rights through water-use licences, or water-taking permits. In Canada, the provinces and territories have primary jurisdiction for regulating and allocating quantities of groundwater to various users and for various purposes. All three territories and all provinces, except Ontario and PEI, assert ownership of water to grant water rights or authorizations to others, and to charge royalties or rent for the use of water (Nowlan, 2005). All provinces and territories, with the exception of British Columbia, have developed a groundwater allocation system, although the licensing and permitting processes vary widely between the jurisdictions

TABLE 16.5 GROUNDWATER MANAGEMENT ACTIVITIES

ACTIVITIES	COMMENTS
REGULATORY	
Groundwater supply allocation • Different systems of provincial and territorial approaches within Canada • Water pricing • Water management planning	• Includes regulation of water use and administration of water rights (e.g., water-use licences, water-taking permits) • Fees, water rentals
Regulation of well drilling • Regulating drillers and pump installers • Standards and guidelines for well drilling and testing • Regulating deep wells for oil and gas	• Certification and licensing of water-well drillers and pump installers • Drilling, well construction and testing procedures and materials
Environmental and groundwater quality protection	• Waste permitting, quality standards and objectives • Environmental impact assessments • Source protection, wellhead protection • Land use planning
Enforcement of regulations	• Compliance checking • Fines and other measures
NON-REGULATORY	
Data collection, databases and information systems	• Well record collection and processing, groundwater reports, water quality analyses, geophysical logs, inventories, water level and water quality monitoring networks • Public access to data and reports
Aquifer characterization and modelling	• Aquifer delineation and characterization • Vulnerability to potential contamination at surface from land use activities • Groundwater flow modelling
Public and stakeholder consultation	Policy planning, environmental assessments and water management planning
Water stewardship and public awareness	Workshops, publications, fact sheets, websites, signage

Note: This listing is for illustrative purposes and is not necessarily comprehensive.

(Nowlan, 2007). British Columbia is currently considering regulating groundwater use in all areas of the province (British Columbia Ministry of Environment, 2010).

Water allocation is the process used to decide how water should be shared between industrial, agricultural, municipal, and domestic and conservation uses, including how conflicts between users and uses are to be addressed (Nowlan, 2005). This procedure is normally carried out by issuing a water licence, approval or water-taking permit, all of which allow the holder specific water rights or privileges while setting out certain limiting conditions and responsibilities which need to be met. Water-use licences and permits may specify the rate, quantity, duration, and time of use and purpose for which the specific water supply will be used (Nowlan, 2005). Conditions on licences are routine. In Saskatchewan, for example, licences have a standard requirement wherein the applicant must mitigate any problem that arises between existing users; in Manitoba, each licence includes a reporting requirement on water usage (Nowlan, 2005).

16.5.1.1 Approaches to groundwater allocation

Christensen and Linter (2007), based on Percy (1988), recognize five approaches to water rights in Canada:

(a) Prior allocation
(b) Riparian
(c) Civil code
(d) Public authority management
(e) Aboriginal rights

Prior allocation rights are dominant in the west: British Columbia, Alberta, Saskatchewan and Manitoba. Prior allocation is based on seniority where licence or permit holders acquire the exclusive right to use the water from the date in the licence or permit. Prior allocation is generally referred to as “first in time, first in right” or FITFIR. In BC (with surface water), Alberta, and Manitoba, water licences can be transferred, while in Saskatchewan they cannot. Transfer requires an approval to ensure that the public’s interest in water use continues to be protected.

Riparian rights are common in eastern Canada and subject to regulation (i.e., regulated riparian). They entitle landowners whose land borders on water sources to have certain non-transferable water rights. These rights also give landowners the right to extract groundwater from wells on their property.

In Quebec, water is designated in the Civil Code as a resource “common to all”; the province has responsibility for allocation, regulation, and the establishment of priority use in the public interest.

Public authority management is practiced in the territories: local water boards decide on the allocation and transfer of licences.

Aboriginal rights are guaranteed as existing rights in the 1982 version of the Constitution Act; these rights have priority over other uses in the legislation of Nunavut.

16.5.1.2 Exemptions and terms of licences and permits

Many jurisdictions usually limit licences and permits to terms of <25 years depending upon purpose of use or source of water. The majority of these jurisdictions do not require licences or permits for domestic household and agricultural use under 50,000 L/day (0.58 L/sec). Thresholds for exemption, however, range over several orders of magnitude across the nation, from as low as 3.4 m^3/day in Alberta to 345 m^3/day in PEI. In fact, about a third of jurisdictions do not require any form of reporting of actual water use and only about a half charge fees for groundwater use (Nowlan, 2005).

16.5.1.3 Changing values and water use

Historically, allocation and protection laws in Canada have prioritized settlement, economic development and maximizing resource extraction (Nowlan, 2007). Water allocation has been primarily an administrative function focused on technical and legal concerns (de Loë et al., 2007). Over the years, however, there has been a growing desire to recognize changing values related to water use, the interconnectedness of surface water–groundwater quantity and/or quality, and the role of planning as a guide to allocation. British Columbia developed Water Allocation Plans for Vancouver Island to examine the water budget or water availability in watersheds, so as to establish guidelines for future surface water allocation. Today, integrating and incorporating environmental, social and economic factors are becoming an increasingly important consideration in the decision-making process, e.g., *BC Water Act Modernization* (British Columbia Ministry of Environment, 2010), *Alberta’s Water for Life Action Plan* (Government of Alberta, 2009) and Nova Scotia’s *Water Resource Management Strategy*, *Water for Life* (Province of Nova Scotia, 2010).

Historically the allocation of groundwater use in Canada has not involved an integrated ecosystem and watershed management approach, which draws on sustainable development principles. This includes regulating groundwater and surface water use in a conjunctive manner.

In principle, because all jurisdictions have a single Act that speaks to water, groundwater and surface water should not be managed separately. Nevertheless, this has commonly been the case across Canada. Thus, the challenge faced is to manage surface water and groundwater conjunctively.

Today, we have greater expectations regarding ecological flow needs in streams, as compared to a hundred years ago. There is a recognized need to protect groundwater-dependent ecosystems in the water allocation decision making, including decisions related to groundwater allocation, and, in some jurisdictions (e.g., BC), there is also the requirement to consult with First Nations before making these decisions. The result is there are more considerations and a greater complexity in the decision-making process because interests have broadened over the years.

16.5.2 Environmental and groundwater quality protection

Groundwater quality may be degraded by human activities on or below the land surface. These include industrial and municipal waste discharges, mining, chemical spills, and runoff from agricultural activities. Canadian provinces manage groundwater quality, in part, through

- Regulation of waste discharges to the ground
- Remediation of contaminated sites
- Protection of drinking water sources
- Land use and watershed planning
- Establishment of water quality standards and guidelines

A brief discussion of some of these measures is provided below.

16.5.2.1 Waste discharges and contaminated sites

Waste discharges are commonly regulated through permitting and approval processes which consider the nature of the potential contaminants and the environment's ability to assimilate these pollutants (e.g., *BC Environmental Management Act, Quebec Environmental Quality Act, Yukon Environment Act*). Land sites that may contain hazardous chemicals are mandated to remove or contain contaminants that threaten groundwater quality (e.g., *BC Contaminated Sites Regulation, Ontario Environmental Protection Act, Nova Scotia Environment Act*). Management of contaminated sites in Canada is risk-based and standards and practices vary from province to province (Council of Canadian Academies, 2009). A key feature of this risk-based approach is the fact that remediation or treatment is triggered only when there is an identifiable on-site or off-site risk, where risk refers to the likelihood of exposure of a hypothetical human or ecological receptor to specific contaminants present at levels exceeding maximum acceptable concentrations (Council of Canadian Academies, 2009).

16.5.2.2 Protection of drinking water sources

Canada's provinces and territories regulate the quality of groundwater used by most water supply systems across the country, with the exception of individual domestic wells. Hill et al. (2007) have outlined some key aspects of drinking water protection (e.g., water treatment requirements and monitoring) currently being implemented. The federal government works with the provinces and territories through the Federal-Provincial-Territorial Committee on Drinking Water (CDW) to establish *Guidelines for Canadian Drinking Water Quality.* These guidelines set out levels of microbiological, chemical and radiological parameters that every water system should strive to achieve in order to provide the cleanest, safest and most reliable drinking water possible (Federal-Provincial-Territorial Committee on Drinking Water, 2013), although use of these guidelines varies by jurisdiction. Ontario, for example, has adopted drinking water quality standards for 161 parameters and requires monitoring for 57 organics, 13 inorganics, and three microbiological contaminants. British Columbia requires the monitoring of bacteriological contaminants only and leaves additional contaminants to the discretion of the Drinking Water Officer (Hill et al., 2007).

All jurisdictions support the multi-barrier approach, which prevents or reduces contamination of drinking water supplies from source to tap (CCME, 2002). This method evaluates and implements measures for ensuring high-quality drinking water in every component of the water-supply system, from broad environment to supply aquifer or reservoir, to water treatment facility and finally to the distribution system (Council of Canadian Academies, 2009). One key aspect of this multi-barrier approach is source or watershed planning and source water protection.

Source protection, more specifically called wellhead protection, involves identifying capture zones and time-of-travel zones around water supply systems or community wells, assessing potential sources of contaminants in these zones, and developing measures that reduce or eliminate contamination risks from these sources. New Brunswick, for example, has implemented a wellfield protection program for all municipal wellfields (covering 20% of the population) under the *Wellfield Protected Area Designation Order* (Crowe et al., 2003).

In 2000, British Columbia developed a guidance document entitled *The Well Protection Toolkit* to assist water purveyors and communities throughout the province in their development of well protection plans. The toolkit outlines a six-step process for preparing and implementing a wellhead protection plan. While these plans are voluntary in British Columbia, some local health authorities require their preparation for large, new well water supply sources. Ontario requires the preparation of source protection plans under the *Clean Water Act* to ensure activities carried out near municipal wells do not threaten the quality and quantity of the drinking water supply.

16.5.2.3 Land use and watershed planning

Local governments make land use decisions, which can impact on both groundwater quantity and quality. Accordingly, this level of government has an important role in groundwater management. Quantity is affected by local governments' supply of water to local users on a central system (e.g., industrial or domestic users within a municipality), which usually requires that local government obtain a permit from the province to supply their own systems. Land development may be restricted by the availability of groundwater (Nowlan, 2007). Quality is affected by many things (local government's decisions on polluting industries, control of urban runoff, and pavement limits, to name a few), which can impair groundwater recharge.

Although most jurisdictions do not have

comprehensive watershed regulations, important examples for watershed planning and protection do exist (Hill et al., 2007). Nova Scotia and New Brunswick, for example, regulate specific activities in entire watersheds, while Newfoundland and Labrador, and Prince Edward Island have designated buffer zones around wells (Hill et al., 2007). In Ontario, communities are required to develop source protection plans in order to protect municipal sources of drinking water. These plans aim to identify risks to local drinking water sources and to develop strategies to reduce or eliminate these risks. British Columbia's *Water Act* and *Drinking Water Protection Act* enable the designation of water management planning areas and drinking water protection plans, respectively. Such plans will address risks to water quality, or prevent threats to drinking water. In 2007, the Regional District of Nanaimo on Vancouver Island was one of the first local governments in British Columbia to develop a *Drinking Water and Watershed Protection Action Plan*. Although not strictly prepared under the above legislative processes, the plan was developed through the participation of a number of provincial ministries, water districts, municipal, private, public and industry organizations (Lanarc Consultants Ltd., 2007).

16.5.3 Best management practices and standards

Best management practices, codes of practice, standards, and guidelines are important management tools for sustaining and protecting both water quality and quantity. Agriculture and Agri-Food Canada (2000), for example, have developed *Agricultural Best Management Practices* to address the potential negative impacts agriculture can have on soil and water quality, by stressing those farming practices which minimize such impacts.

One particularly challenging groundwater quality issue is contamination derived from diffuse or non-point sources. Nitrate contamination from septic systems, or from agricultural activities, is a particular example of this problem. Sources of contamination tend to be small and localized, but in number can exert a measurable impact on groundwater quality. The challenge with non-point source contamination is that effective solutions to the problem require remedial actions which affect and involve many landowners (e.g., provide septic servicing or adopt best management practices for fertilizer application).

16.5.4 Groundwater monitoring networks

All Canadian provinces maintain active regional groundwater monitoring networks (commonly referred to as observation well networks), to monitor long-term (seasonal and annual) fluctuations in groundwater levels and, in many cases, water quality. Maathuis (2005) compiled a comprehensive survey of groundwater level networks (Figure 16.4). The number of wells in these networks range from 25 in Prince Edward Island, to over 500 in Manitoba (Council of Canadian Academies, 2009). Many of these wells are located in important aquifers where they monitor stresses caused by aquifer withdrawals and/or climatic variations (see for instance Figures 9.1, 10.27, 10.32, 10.34, 12.26 and 13.20).

These monitoring networks also provide an important indication of the magnitude of groundwater recharge taking place, as well as when aquifers are being depleted. These monitoring networks play a key role in gauging aquifer sustainability, especially as limited data is available on actual water use in many areas. The BC Ministry

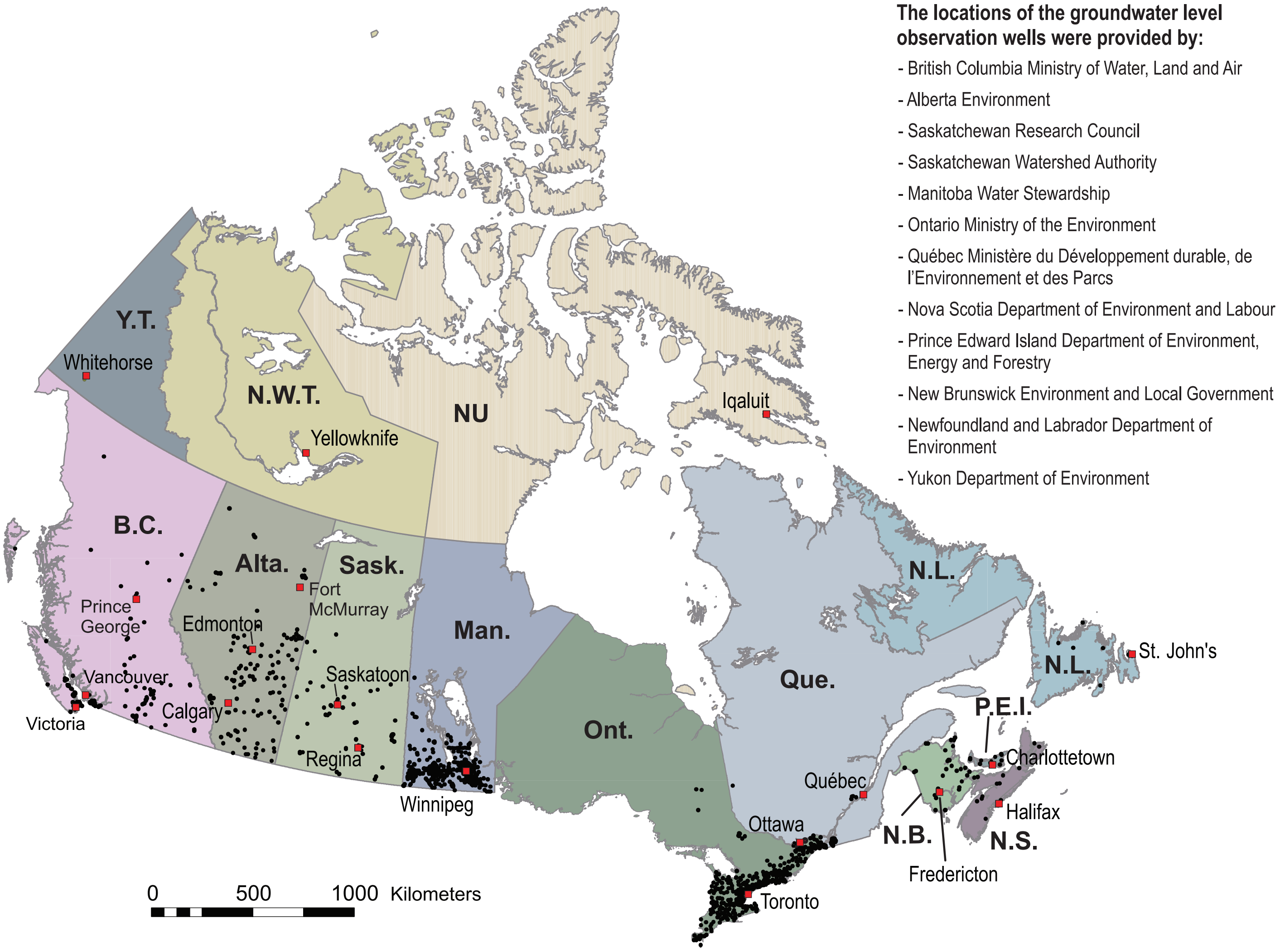


Figure 16.4 Observation wells in Canada in 2005 (after Maathuis, 2005).

of Environment (2007), for example, reported an increase in the percentage of observation wells showing declining water levels due to human activities during the period 2000–2005.

Water quality is also monitored. Environment Canada and the BC Ministry of Environment have tracked groundwater quality in the Abbotsford-Sumas aquifer, British Columbia, since the early 1970s (see Box 9-2).

16.5.5 Inter-agency cooperation

Although much is made of jurisdictional fragmentation, in practice there exists a high level of inter-jurisdictional coordination, particularly on issues of data collection and database maintenance, yet even here, significant gaps and overlaps exist (Dunn and Baker, 2011). A good example of a groundwater study involving inter-agency partnerships, which brought funding sources to the table, focused on the Okanagan Basin in British Columbia. Here, local governments, provincial officials, federal and academic researchers, water districts, groundwater associations, and the Okanagan Basin Water Board participated in the Groundwater Assessment of the Okanagan Basin (GAOB). This large-scale research effort was initiated in 2004 by the Geological Survey of Canada (GSC) and the BC Ministry of Environment to bring together and guide groundwater studies in the Okanagan, as part of the Okanagan Water Supply & Demand Study. The goal was to give local governments the information they need to balance water needs and availability into the future. A comprehensive overview covering the scope of the project has been prepared by Carmichael (2006). Other similar examples of groundwater studies and aquifer assessments with inter-agency cooperation exist across Canada; descriptions of some of these projects can be found at: http://www.nrcan.gc.ca/earth-sciences/about/current-program/groundwater-geoscience/4106.

In 2003, a National Ad Hoc Committee on Groundwater comprised of stakeholders from a number of federal and provincial agencies, along with academic researchers and individuals from the groundwater industry, developed the *Canadian Framework for Collaboration on Groundwater* (Rivera et al., 2003). Their document recognizes and emphasizes the need to address the groundwater issues of Canada through close co-operation between federal, provincial, territorial, municipal, and First Nations governments.

Most jurisdictions in Canada currently regulate groundwater and surface water without much consideration as to the type of source. This may be because surface water–groundwater interactions are not well understood. (For a discussion of surface water and groundwater interaction, see Chapter 5). In some provinces (e.g., Alberta, Ontario) surface water and groundwater are managed conjunctively. Groundwater, however, is not always considered in many land and other resource use decision-making processes. New water management strategies under development are aimed at providing a more holistic and integrated approach for natural resource management, by involving groundwater–surface water interactions, protecting in-stream flows and ecosystems (ecological flows), requiring more efficient use of water, and using economic instruments and incentives.

There is also an increasing trend for provinces to involve local governments, watershed agencies (such as Ontario's Conservation Authorities) and multi-stakeholder bodies in managing and protecting groundwater (Council of Canadian Academies, 2009). Examples of such activities include groundwater monitoring, conducting joint studies, protecting sensitive recharge areas in land use planning, considering groundwater availability in planning growth, and helping raise local awareness. In many jurisdictions, local governments such as municipalities, regional districts, counties and conservation authorities are playing an increased and more proactive role in groundwater management activities. They are often involved in groundwater management where groundwater is the source of municipal water supply, and/or indirectly, through land use decisions that have groundwater contamination potential (Council of Canadian Academies, 2009). Local government has a broad mandate, which includes authority over land use that might impact groundwater, planning growth, water demand, and the servicing of water supply and sewerage.

In Quebec, the Municipality of Chelsea collaborated with the University of Ottawa's Institute of Environment, and with Action Chelsea for the Respect of the Environment (ACRE), a local non-government organization, in developing a policy that requires land developers to conduct pumping tests to demonstrate that there is sufficient available water to support the number of homes planned for the development (Nowlan, 2007). Elsewhere in Quebec, several municipalities recently collaborated with the provincial government and academic researchers to examine groundwater resources of the Abitibi-Temiskaming region (Société de l'eau souterraine Abitibi-Témiscamingue, 2010).

In Ontario, the Grand River Basin Water Management Study provides a solid example of collaborative work between the local conservation authority, several municipalities, residents of the area, and several provincial ministries in the investigation of water resources within the basin (Grand River Implementation Committee, 1982).

In British Columbia, the Township of Langley developed its *Water Management Plan (Part 4 of the Water Act*) in collaboration with the province (Township of Langley, 2009). The plan proposes policies and regulations to protect local groundwater resources for community use, in addition to promoting healthy aquatic habitats. Proposed new regulatory tools include expanded water conservation initiatives and water quality protective measures, including stopping and controlling artesian flow, well sitting requirements and the initiation of a nutrient management plan. These procedures have yet to be approved by the provincial government.

B.C's Smart Growth on the Ground (SGOG) initiative involved development of a team where elected officials and staff from local government, community members, experts and representatives of key agencies worked together to create plans for land use, transportation and other designs. The team in Oliver, BC, a community in the southern Okanagan Basin dependent upon community wells, coordinated research in a number of areas, including climate change and water resources (Smart Growth on the Ground, 2006). Other water stewardship initiatives have also been implemented, including the Royal Bank of Canada (RBC) Blue Water Project aimed at fostering a culture of water stewardship across Canada.

16.6 ISSUES IN GROUNDWATER MANAGEMENT IN CANADA

During the last decade, a number of authors including Rivera et al. (2003), Nowlan (2005, 2007), Council of Canadian Academies (2009), and CCME (2010), identified several existing and emerging issues for groundwater management in Canada. A listing of the main issues, which can be categorized as being concerns about quantity, quality and other, is provided in Table 16.6. Aquifers with both quantity and quality issues are common. Many of the concerns in the other column of Table 16.6 may simply reflect poor governance due to a lack of appreciation for, and understanding of, groundwater resources and their importance in sustaining aquatic ecosystems; such oversights resulted in a lack of priority, investment, and insufficient legal authority for the jurisdiction to act.

Some of the issues in Table 16.6 may merely reflect symptoms of other problems: the real issue may be that funding allocation for groundwater study has not kept pace with current demands, as has been reported by the Council of Canadian Academies (2009). There is a strong need for fundamental groundwater assessments and characterization to be undertaken now, before specific problems develop.

16.6.1 Quantity issues

16.6.1.1 Aquifer depletion

While many of the quantity issues are significant on a local scale, there are a few examples of excessive groundwater depletion on a large scale

TABLE 16.6 CURRENT AND EMERGING GROUNDWATER ISSUES

CURRENT AND EMERGING ISSUES		
QUANTITY	**QUALITY**	**OTHER**
Growing water demand and limited water availability leading to conflicts and competing priorities among agriculture, municipal, recreation and natural habitats • Aquifer depletion in local areas (e.g., over-pumping, uncontrolled flowing artesian wells) • Local well interference • Groundwater–surface water interaction, wells affecting in-stream flows	Water quality concerns from human activities (diffuse) • Nitrate, bacteriological and pesticide contamination from various agricultural and septic disposal sources • Degradation due to road salts • Localized saltwater intrusion from seawater and saline aquifers (e.g., PEI, Gulf Islands, BC) • Improperly constructed or closed wells posing a risk of cross connection of aquifers with different water quality • Degradation from unidentified chemicals (e.g., synthetic organic compounds and volatile organic compounds)	Limited enforcement of laws and regulations
Increasing resource extraction • Increased demand from growing population and resource extraction (e.g., oil sands development in AB) • Aquifer depletion due to coal-bed methane extraction and dewatering • Demand for high water volumes for fracking of shale formations in northeast BC	Water quality concerns from human activities (point source) • Contamination from acid mine drainage from metal mining • Local contamination from chemical leaks and spills (e.g., hydrocarbons) • Contamination from petroleum activities (e.g., oil sands development) • Degradation at contaminated sites • Thermal degradation from geothermal activities Potential contamination due to hydrofracking	Limited resources for data collection, maintenance and management (both regional and place-based assessments) • Effectiveness of groundwater monitoring networks for quantity and quality • Few indicators of groundwater quality and quantity • Limited number of aquifer characterization studies (recharge rates, groundwater use, quality)
	Naturally occurring water quality concerns—elevated levels (e.g., metals, nonmetals —arsenic, chloride, radioactive elements)	Aboriginal and Treaty Rights to water
		Effects of climate variability and changes

(Council of Canadian Academies, 2009). One such case involves deep buried-valley aquifers located in southern Saskatchewan (see Box 10-2); heavy pumping from these aquifers has led to significant drawdowns, extending tens of kilometres from the pumping centre. Recovery of water levels to the aquifers' original static levels may take decades or even centuries (Maathuis and van der Kamp, 2003).

There is also a general shortage of data on actual use of groundwater in Canada. Most jurisdictions have some data available on groundwater volume allocations (under a permit or licensing regime), but few jurisdictions have available data to confirm the *actual* volume used (Rutherford, 2004). This severely restricts assessments of available water supply versus actual demand investigations and assessments of aquifer sustainability. Two emerging quantity issues of interest are oil sands development and transboundary aquifers.

16.6.1.2 Oil sands development

The long-term cumulative impact of oil sands development on groundwater is insufficiently understood (Council of Canadian Academies, 2009), given the magnitude of these projects over several decades. Oil sands, which are accessed through open-pit mining operations and *in situ* operations, involve extensive land areas, and the extraction of large volumes of both ground and surface water. *In situ* operations are projected to have the greatest impact, because of their much larger extraction areas and, because non-saline and saline groundwater is used, at the majority of sites, to provide steam for the oil extraction process.

Production of bitumen is expected to triple by 2020, resulting in more water withdrawals, declining wetlands and expanding tailings ponds. Most companies already recycle their water, so new policies and technologies are necessary to insure that water use does not grow at the same rate (Griffiths et al., 2006).

There are some 5,000 licenced wells in the Athabasca River, with groundwater allocations in the order of 120 Mm^3/year (Rosenberg International Forum, 2006). Allocations for the Peace River and the Cold Lake-Beaver River are 30 Mm^3/year and 20 Mm^3/year, respectively. Not all allocations, however, are for oil sands developments: it is estimated that some 79% of the allocations in the Athabasca River are for oil sands, 57% in the Peace River, and 86% in the Cold Lake-Beaver River.

16.6.1.3 Transboundary aquifers

When an aquifer extends beneath the border of two or more jurisdictions, there is shared interest in the quantity and quality of groundwater available. Canada's interest in transboundary groundwater issues (both between provinces and territories, and between Canada and the U.S.) has increased sharply over the recent past.

The most important cases of transboundary aquifers within this country are located in Alberta, Saskatchewan and Manitoba, but no disputes have been reported. The equitable and "reasonable" use of shared waters is the most essential principle considered when negotiating a groundwater apportionment method. Other factors considered are: the priority use, the sustainable yield of the aquifer, and the joint apportionment of surface water and groundwater. To ensure water resources are shared fairly in the Prairie Provinces, the provincial governments of Alberta, Saskatchewan, and Manitoba, working with the Government of Canada, created the Prairie Provinces Water Board in 1948 to manage inter-provincial transboundary waters. A Master Agreement on Apportionment shares water equitably between the Prairie provinces, in addition to protecting interprovincial surface water quality and groundwater aquifers (Prairie Provinces Water Board, 2011). The Mackenzie River Basin Master Agreement (British Columbia-Alberta-Saskatchewan, Yukon and Northwest Territories, in conjunction with the federal government) is another interprovincial coordinating agreement involving groundwater.

There are over 20 million Canadians living in watersheds that cross the Canada-US border (over 17 million people of them reside in the Great Lakes-St Lawrence watershed). Figure 16.5 is a map of Canada containing identified transboundary aquifers along the Canada-US border as per 2011.

16.6.2 Quality issues

16.6.2.1 Nitrate contamination

Contamination of groundwater and wells due to agricultural activities is common in all agricultural regions of Canada with elevated levels of nitrate the main concern. In fact, nitrate contamination is a major global contamination issue leading to

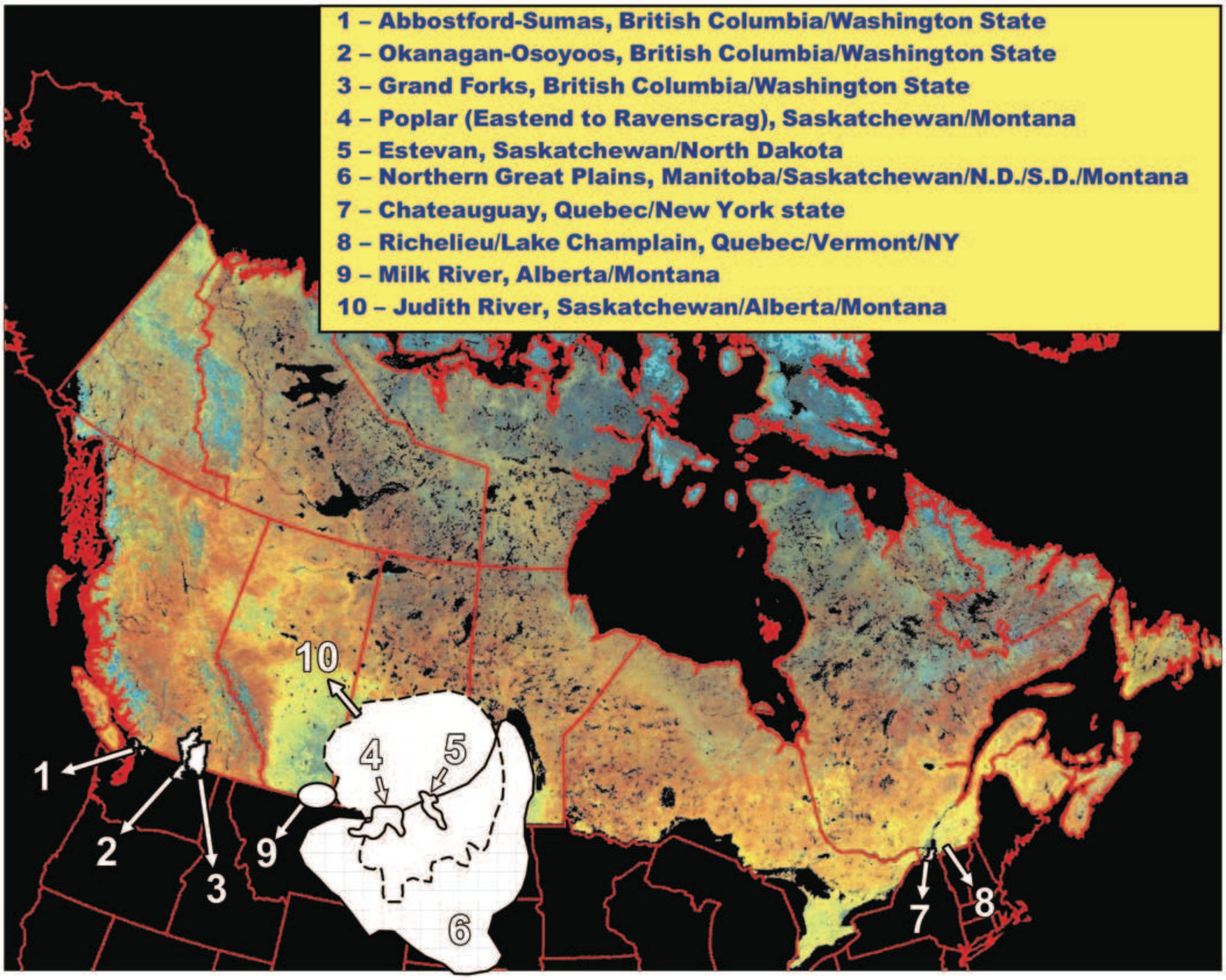


Figure 16.5 Some transboundary aquifers that have been identified along the Canada-US border (after Rivera, 2011).

water quality degradation in rivers, lakes, groundwater and coastal areas. Unconfined, shallow sand and gravel or sandstone aquifers with relatively high water tables are particularly susceptible (e.g., Abbotsford-Sumas Aquifer, BC; Environment Canada, 2004; and the Prince Edward Island sandstone aquifer; Savard and Somers, 2007). The behaviour of nitrates in groundwater is generally well understood, but information linking agriculture sources is inadequate. Nutrient applications related to agricultural land use raises particular challenges in balancing societal needs for both food and water; hence Canada needs to have more effective strategies for the containment and/or elimination of nitrates in agricultural areas (CCME, 2010). Part of the solution involves federal-provincial programs such as the National Farm Stewardship Program and Best Management Practices for minimizing contamination of groundwater; these procedures have not yet been widely adopted by agricultural producers (Council of Canadian Academies, 2009). In 2008, the Province of Prince Edward Island appointed an independent Commission on Nitrates in Groundwater to identify issues and find solutions to specific problems within their jurisdiction (Government of PEI, 2008). Other provincial guidelines have been enacted in BC (e.g., Guidelines and Best Management Practices; BC Ministry of Agriculture and Lands), Saskatchewan and Alberta.

16.6.3 Other issues

16.6.3.1 Aboriginal and treaty rights to water

Aboriginal peoples in Canada comprise First Nations, Inuit and Métis groups. Aboriginal rights are those that many of Canada's Aboriginal nations hold as a result of their ancestors' long-standing use and occupancy of the land: the right to hunt, trap and fish on ancestral lands are some examples. Aboriginal rights vary from society to society, depending on custom, practice and tradition (Indian and Northern Affairs Canada, 2011).

Aboriginal and Treaty Rights to water are a complex and unresolved issue in this country. The Supreme Court of Canada (SCC) has brought down rulings on the nature and extent of Aboriginal title and Aboriginal rights in a number of cases: some land claims and treaty settlements, in the Canadian North and other regions of the country (Nowlan, 2005), have partly addressed this issue as well. The Council of Canadian Academies (2009) reports that groundwater jurisdiction is complicated by unresolved Aboriginal water interests, which include legally recognized rights such as treaty rights, and unresolved claims of Aboriginal rights and title. In 2004, the SCC held that government had a duty to consult and accommodate Aboriginal interests before Aboriginal rights and title were finally determined. As reported by de Loë et al. (2007), some provinces and territories recognize and address Aboriginal rights in their legislation. Examples include

- The Northwest Territories' *Water Resources Agreement Act* which states in section 6 that "Nothing in this Act shall be interpreted so as to affect or diminish Aboriginal rights."
- In Nunavut, the *Nunavut Waters and Nunavut Surface Rights Tribunal Act* was formulated to be respectful of Aboriginal customary allocation boundaries and traditions.
- In Newfoundland, the *Water Resources Act* is to be applied in conjunction with the Labrador Inuit Land Claims Agreement, which includes provisions for Inuit water rights, allocation and management.

Water governance issues for First Nations communities were examined in 2010 at a workshop entitled *Sharing Water Challenges and Solutions: Experiences of First Nations Communities* (von der Porten and de Loë, 2010). Some of the outcomes included the following: the need for Aboriginal peoples taking the lead on water governance or other resource-related initiatives within their jurisdictions, incorporating Indigenous knowledge in decision making, asserting water rights, pooling common resources, and sharing among First Nations communities. Further aspects of this issue, including the quality of drinking water in First Nations communities, are examined by Phare (2009) and von der Porten and de Loë (2010).

16.6.3.2 Effects of climate change

Canada's climate is changing and projections show that it will continue to change in the future, with gradual shifts in average temperature and precipitation, changes in temperature and precipitation extremes, and changes in sea level (Lemmen et al., 2008).

Some of the most significant and pervasive impacts of climate change in this country will be related to water resources. Water-stressed areas will expand as runoff in many areas decreases as a result of precipitation changes and increased evapotranspiration. Reduced water quality and quantity will be experienced on a seasonal basis in every region of Canada. Observed water impacts include a trend toward earlier spring runoff and, in the Prairie Provinces, a decline in summer and fall runoff, leading to lower lake and river levels during those seasons. Increasing demands on water resources for agriculture, energy production, communities and recreation will need to be managed in conjunction with ecosystem needs. A number of processes suggest that spring recharge of groundwater regimes from snowmelt may decline, except in those regions where frozen soils thaw due to warmer winters (Council of Canadian Academies, 2009). Reduced groundwater recharge under climate change is anticipated in some areas of the country, while rising sea levels pose an increasing threat of saltwater intrusion into groundwater along coastal regions (Council of Canadian Academies, 2009). Groundwater withdrawals are expected to increase under warmer conditions, and during extended periods of drought, producing added pressures on both groundwater and surface water resources.

16.6.3.3 Limited place-based knowledge of the resource

Much of what is currently known about the groundwater resources of Canada is limited to those populated areas and corridors, such as along, and within, a few hundred kilometres of the Canada-United States border, or along major transportation routes. Vast areas of the country are unpopulated, as a result, little is known about the full extent, availability and quality of groundwater resources in these regions. Characterization of known aquifers remains very limited, even in settled areas of the country.

Dunn and Bakker (2011) suggest that managers and policy makers do not share common points of reference when using freshwater indicators of water quality and quantity to assess the state of water security. This, they suggest, impedes decision making on cross-cutting issues. They note that, while the challenges imposed by regional (climatic, topographical and hydrological) diversity are recognized, there remains a need for more standardized, integrated approaches to enable place-based assessments, which could then be compared at a broader scale.

As Canada's population continues to grow, and water demands for resource-based industries, such as oil and gas drilling, coal-bed methane production, oil sands development and mining activities continue to increase, there will be added pressures to improve the scientific knowledge of aquifers and their groundwater flow systems. Although Canada has a history of mapping aquifers (Betcher, 2011), there is growing consensus that this work needs to be emphasized and advanced in order to support informed decision making.

The Standing Senate Committee on Energy, the Environment and Natural Resources, acknowledged this issue in 2005 by recommending that the Government of Canada take necessary steps to ensure that all of Canada's major aquifers be mapped by 2010. It also recommended that the resultant data be made available in the national groundwater database, supported by a summary document assessing the risks to groundwater quality and quantity (Senate of Canada, 2005).

Previously in 2003, the *National Ad Hoc Committee on Groundwater* recommended the need to characterize and inventory, within 10 years, the groundwater resource in the settled areas of Canada, in

TABLE 16.7 LIST OF THE GEOLOGICAL SURVEY OF CANADA'S TOP 30 PRIORITY AQUIFERS ACROSS CANADA (FROM RIVERA, 2005)

NAME OF AQUIFER OR AQUIFER SYSTEM (LOCATION IN BRACKETS)	JURISDICTION(S)
Fraser Lowlands (east of Vancouver)	British Columbia
Nanaimo Lowland (east coast of Vancouver Island)	British Columbia
Okanagan Valley (southern interior of B.C.)	British Columbia
Fractured aquifers-Gulf Islands (Strait of Georgia)	British Columbia
Shuswap Highlands (Shuswap Lake)	British Columbia
Paskapoo (north of Calgary)	Alberta
Buried-valley/blanket aquifers (southern Manitoba)	Alberta, Saskatchewan, Manitoba
Upper Cretaceous sands (central east to northwest of Alberta)	Alberta, Saskatchewan
Milk River (southern Alberta)	Alberta
Judith River (southwestern Saskatchewan)	Saskatchewan, Alberta
Eastend-Ravenscrag (southeastern Saskatchewan)	Saskatchewan
Inter-till aquifers (southeast-northwest Saskatchewan	Alberta, Saskatchewan, Manitoba
Carbonate rock (south, east and northwest of Winnipeg)	Manitoba
Basal clastic unit (Winnipeg)	Manitoba
Odanah shale (southwestern Manitoba)	Manitoba
Sandilands (southeastern Manitoba)	Manitoba
Assiniboine delta (between east of Brandon and west of Lake Winnipegosis)	Manitoba
Oak Ridges Moraine (north of Toronto)	Ontario
Grand River Basin (south Hamilton)	Ontario
Credit River (between Brampton and Mississauga)	Ontario
Waterloo Moraine (Waterloo region)	Ontario
Upper Thames (centered in London, ON)	Ontario
Mirabel (north of Montreal)	Quebec
Chateauguay (south of Montreal)	Quebec
Richelieu (between east of Montreal and southwest Trois Rivières)	Quebec
Chaudière (south of Quebec City)	Quebec
Maurice (north of Trois Rivières)	Quebec
Portneuf (west of Quebec City)	Quebec
Annapolis-Cornwallis valleys (northeast-southwest line from Wolfville to Bridgetown)	Nova Scotia
Carboniferous basin (centered in Moncton)	Prince Edward Island, New Brunswick, Nova Scotia

terms of its quantity, quality, vulnerability, and sustainability, with areas selected depending upon jurisdictional priorities. *The Groundwater Mapping Program* managed by the Geological Survey of Canada has undertaken the task of assessing 30 key regional aquifers across the nation (Rivera, 2003, 2005; Table 16.7). It is evident that the ultimate task is a significant one that will likely require the combined resources and collaboration of governments at all levels, with assistance from all private and public sectors (academia, industry and organizations) that benefit from the use of groundwater resources.

16.7 CONCLUSIONS AND RECOMMENDATIONS

Canada's federation of provinces and territories occupies a large land mass. The country's groundwater has been managed more or less independently by the provinces and territories. The effectiveness of groundwater management within Canada may be more practically evaluated by examining how each of these jurisdictions manages its own groundwater resource. We will not do this here, because the scope of this chapter is limited to a national overview. Our recommendations in this chapter are necessarily broad, conceptual and overarching. They are also more or less common to all provincial and territorial jurisdictions:

1. Allocation of use of groundwater needs to be carried out using an integrated ecosystem and watershed management approach that draws on sustainable development principles. This includes regulating groundwater and surface water use in an integrated manner.
2. The science of groundwater hydrology is mature, yet the knowledge and understanding of groundwater in many basins in Canada is lacking.
3. Knowledge of groundwater is place-based. A systematic program to map and characterize aquifers or groundwater in a basin, beginning with the most important ones is necessary. Use of this information will be invaluable in mitigating the variety of groundwater issues that exist in any particular place: such work cannot be done when an issue is imminent.
4. A specific purpose for groundwater studies is to help jurisdictions establish goals for the aquifers. To achieve this, these studies must be done in partnership with provincial (allocation) and local (quality protection) agencies.
5. Stable and adequate base funding is required for provincial and territorial agencies to keep on top of collecting high-quality and spatially comprehensive groundwater data (e.g., collecting and processing well records, operating, groundwater monitoring networks). Such procedures would ensure that legacy groundwater data problems, which are costly to address later, are avoided.
6. There should be an integration of regulatory activities (allocation) with non-regulatory activities (groundwater science) to increase knowledge in support of decision making. Scientific knowledge and new research with groundwater management policies should be linked, and those agencies responsible for groundwater management should make groundwater information readily available to the public via the internet.
7. The role of local government in groundwater management and protection needs to be advanced. Strengthening and clarifying local government mandates in this area will improve groundwater governance by increasing local-scale government initiatives such as well protection planning by water suppliers, planning growth with consideration of basin water availability, and helping to address non-point source contamination problems through increased public awareness and smart land use.

8. Promoting water stewardship in the broadest sense.
9. Promote the sharing of data, which will increase transparency and relevancy of available groundwater information using modern tools.
10. The growing demand for groundwater, coupled with the greater complexity of problems related to its use, has compelled many different federal, provincial and territorial agencies, as well as universities and industry, to work together, collaborating their knowledge and expertise to address common groundwater issues and to achieve common goals for this valuable resource.
11. Despite the fact that management and protection of groundwater is a provincial or territorial responsibility, scientific leadership and dedicated coordination at the federal level is needed to promote meaningful dialogue and consistency in practice; collaboration on groundwater is more important than ever.

GLOSSARY

Alluvial

Applying to environments, processes, and sediments of rivers or streams.

Alluvial fan

A low, relatively flat to gently-sloping mass of loose sediment, shaped like an open fan or cone deposited by a stream where it issues from a narrow mountain valley.

Anisotropy

A condition in which properties depend on direction (e.g., differing hydraulic conductivity of an aquifer in different directions).

Aquifer

Any water-saturated body of geological material from which enough water can be drawn at a reasonable cost for the purpose required. An aquifer is only a relative term and is best illustrated by extreme examples. An aquifer in an arid prairie area required to supply water to a single farm, for example, may be adequate if it can supply 1 m^3/day. Such an aquifer would not be considered sufficient by any industry looking for cooling water in the order of 10,000 m^3/day. An aquifer is commonly thought of as water-bearing material from which water is most easily extracted. An aquifer is by no means equivalent to a single geologic, lithographic, or stratigraphic unit; in fact, two contiguous layers of sand and limestone, may form a *single* aquifer.

Aquitard

A water-saturated sediment or rock whose permeability is so low it cannot transmit any useful amount of water. An aquitard allows some measure of leakage between the aquifer intervals it separates.

Artesian

A condition which applies to aquifers confined by layers of low-permeability where the aquifer hydraulic head is higher than the top of the aquifer. If the hydraulic head is higher than the ground surface, the well will flow at the surface without pumping.

Artesian condition

(See **Artesian**)

Bank storage

Surface water that flows into the banks (shores) of a stream, reservoir or lake when surface water levels increase above groundwater in the bank. When surface water levels remain high, most water is stored as groundwater. As surface water levels decline below those of groundwater, water will flow back to the stream.

Bedrock

Solid rock exposed at ground surface (as outcrop) or that which underlies unconsolidated surficial sediments.

Bedrock aquifer

Bedrock having the ability to transmit a sufficient quantity of water to a well completed within it, or to a surface water body. The permeability of bedrock aquifers is due to either primary porosity or secondary porosity (fractures and solution cavities).

Brackish
Water that is saltier than fresh water but not as salty as ocean water.

Brine
A solution of salt (usually sodium chloride) in water.

Buried valley
Any channel-form depression which was initially formed on the Earth's surface, but is now buried by sediment or rock. These valleys may be filled with sediment of significant permeability (e.g., sand), or low permeability (e.g., till, clay).

Catchment
Watershed or drainage area of flowing surface water.

CGCM1
The first version of the Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model.

Channel
An eroded depression in sediment or bedrock into which stream (alluvial) deposits may accumulate (i.e., gravel, sands, silt, clay).

Climate change
A trend in climate that persists over long periods (decades and longer).

Climate variability
Variations in climate generally observed on short time scales (few years to decades).

Cone of depression
The lowering of the water table in an unconfined aquifer due to pumping. This term can also be used to describe lowering of the potentiometric surface in a confined aquifer due to pumping.

Cone of under-pressuring
The lowering of the potentiometric surface in a confined aquifer due to pumping. Often used interchangeably with the term cone of depression.

Confined aquifer
An aquifer bounded from above and below by impervious formations. Such aquifers usually occur where the hydraulic head of the water is higher than the elevation of aquifer's upper limit.

Consumptive use
Water used that is not returned to aquifers, rivers or seas, but is either incorporated in products or organisms, or discharged as vapour into the atmosphere.

Contaminant
A substance present in an environmental medium in excess of background concentration (natural baseline).

Crystalline bedrock
Igneous or metamorphic rocks, such as granites, basalts, metaquartzites or gneisses, where the inter-granular pore spaces are poorly connected and where almost all groundwater flow occurs through cracks and fractures in the rocks.

Deep Geologic Repository (DGR)
A deeply buried geological unit that can be used effectively to isolate the spread of contaminants. Ontario Power Generation (Canada), for example, has proposed construction and operation of a deep geologic repository (DGR) which would safely isolate and contain low and intermediate level nuclear waste. The proposed DGR would be located 680 metres below ground at the Bruce nuclear generating station, in sedimentary rock formations over 450 million years old.

Depressurization
The lowering of the groundwater potentiometric surface over an area by means of pumping.

Dewatering
Removal of groundwater from a geological formation using wells or a drainage ditch system.

Discharge area

An area or specific point (e.g., spring) where the net direction of groundwater flow is upward (e.g., groundwater leaves the aquifer and flows to the surface).

DRASTIC—Fm

A modified form of the DRASTIC vulnerability mapping method that takes into account the nature of fractured media (**Fm**) (Denny et al., 2007). DRASTIC itself is a composite rating of the **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography slope, **I**mpact of the vadose zone and the hydraulic **C**onductivity of the aquifer.

Drawdown

Lowering of the groundwater level or piezometric surface caused by abstraction of groundwater, including pumping, as well as outflow from an artesian well, or discharge from a spring.

Ecotone

Boundary or transition zone between two ecosystems exhibiting characteristics of both ecosystems. The hyporheic zone is an example of a transition zone between surface water and groundwater ecosystems.

Effective porosity

Within a given mass of soil or rock, the percentage of total volume consisting of interconnected void spaces.

Equipotential

Points of equal potential, which can be joined as lines (in 2D) or surfaces (in 3D). In hydrogeology, equipotential is often applied to point locations of equal hydraulic head and referred to as equipotential or piezometric lines and surfaces.

Esker

A long, narrow, low-relief, sinuous, steep-sided, or flat-topped ridge composed of sand and gravel. Such formations have been deposited by subglacial or englacial streams flowing between ice walls, or in an ice tunnel.

Evapotranspiration

The process by which water is returned to the atmosphere as a result of evaporation from the soil, surface-water bodies, or plant transpiration. Transpiration is the process by which water passes through living organisms, primarily plants, into the atmosphere.

Fault

A surface or zone of rock fracture along which displacement, ranging in scale from a few centimetres to a few kilometres, has occurred.

Fen

Minerotropic peat-forming wetlands which receive surface moisture from precipitation and groundwater. Fens are less acidic than bogs, and derive most of their water from groundwater rich in calcium and magnesium.

Fluvial deposits

Mineral or rock sediments which are transported by a river and deposited along its valley.

Fracture

A general term for any break in a rock due to mechanical failure by stress, whether or not displacement occurs.

Gaining

(See **Gaining streams**)

Gaining streams

A gaining or effluent stream receives groundwater discharge along its length, which provides baseflow for the stream.

Glacial outwash

Stratified sediment (mainly sand and gravel) "washed out" from a glacier by meltwater streams and deposited in front of, or beyond, the ice margin.

Glacial sediment

Any sediment laid down by, or in association with, the activity of glaciers and ice sheets.

Glaciation

Interval of time (thousands of years) of an ice age that is marked by colder temperatures and glacier advances. Inter-glacials, on the other hand, are periods of warmer climate between glacial intervals. The last glaciation ended about 10,000 years ago.

Glaciofluvial

Pertaining to meltwater streams flowing from melting glacier ice, and especially to deposits produced by such flows (e.g., eskers, outwash plains, terraces).

Great Lakes

Five large (total surface, 244,106 km^2; total volume of water, 22,671 km^3) freshwater lakes located on the east-central Canada–United States border. They (Lakes Superior, Michigan, Huron, Erie, and Ontario) drain eastward to the Atlantic Ocean through the Saint Lawrence River. The Great Lakes form the largest group of freshwater lakes on Earth, containing 21% of the world's surface fresh water.

Groundwater

All water contained in pores/voids within unconsolidated sediments or consolidated rocks (i.e., bedrock). Groundwater is the subsurface water where pressure is equal to or higher than the local atmospheric pressure. In other words, water below the water table or phreatic level.

Groundwater sustainability

(See **Sustainable use of groundwater**)

GW-SW exchange

Occurs where surface water (SW) enters the subsurface, flows as and mixes with groundwater (GW) along or beneath a stream or river and then discharges back to the surface water.

GW-SW interaction

Physical, chemical, biological and ecological processes associated with the transfer or mixing of water between groundwater (GW) and surface water (SW) reservoirs, as well as the interactions among these processes.

HELP

Hydrologic Evaluation of Landfill Performance software developed by the United States Environmental Protection Agency (US EPA) and used for simulating infiltration for landfill design. The model has also been used to simulate recharge in several Canadian studies.

Hydraulic conductivity

Commonly refers to the ease with which soil or rock allows groundwater to move through it. Symbolized as "K", hydraulic conductivity depends on the physical properties of formation and the fluid (groundwater) in that formation. "K" is the rate of flow per unit cross-sectional area under the influence of a unit gradient: it has the dimension of length^3/length^2 × time or length/time (e.g., m/s).

Hydraulic gradient

The change in groundwater elevation (or potentiometric head) per unit of distance in a given direction. When not specified, direction generally is understood to be that of the maximum rate of decrease in head. The hydraulic gradient is the main driving force for groundwater flow. This coefficient is dimensionless (metres/metres).

Hydraulic head

A measure of the potential energy of a fluid, divided by the weight of the fluid (in this case, groundwater). For groundwater, the hydraulic head at any point is the level to which groundwater would rise above a fixed datum (usually sea level) in a well.

Hydrochemical type

A chemical composition definition of groundwater based on the relative percentages of major cation and anion concentrations.

Hydrogeological region

Area exhibiting common regional geological, topopgraphical, hydrological, and climatic characteristics which makes it distinct from other regions. The delineation of hydrogeological regions in Canada is based on major geological provinces and rock formations (Table 8.1). Fundamental water-bearing openings and rock matrix properties help determine the quantity (storage), flux (transmission), and composition (quality) of formation waters (see section 8.2 for more details).

Hydrogeological terrain

Geological setting with similar hydrogeological characteristics. For example, groundwater systems in southern Ontario, Canada, are described as four simple geological settings: 1) Sediment, 2) Sediment-bedrock interface (i.e., contact zone), 3) Exposed or thin sediment-covered bedrock, and 4) Deep bedrock (see BOX 12-2 in Chapter 12 for more details).

Hydrogeology

The science that relates geology, fluid movement (i.e., groundwater) and geochemistry to gain an understanding of water residing under the Earth's surface. Groundwater, as used here, includes all water in the zone of saturation beneath the Earth's surface, but not water chemically combined in minerals.

Hydrological integrity

The ability of a landscape to maintain proper drainage and groundwater-surface water interaction, and to support healthy ecological functioning and aquatic habitat.

Hyporheic zone

A transitional zone between surface water and groundwater ecosystems. This is a subsurface zone adjacent to or beneath surface waters in which surface water and groundwater mix.

Infiltration

The process by which surface water enters the soil. Infiltration is governed by gravity and capillary forces.

Integrated resource management

An inter-disciplinary and comprehensive approach to decision making. Integrated resource management recognizes the interrelationships between resources and incorporates decisions, legislation, policies, programs and activities across resource sectors to gain the best overall long-term benefits for society and the environment while minimizing conflicts.

In-stream Flow Needs (IFN)

Amount of river water required to sustain a healthy aquatic ecosystem, and/or meet human needs (such as recreation, navigation, waste assimilation or aesthetics).

Isopach map

A map depicting the variations in thickness of a stratigraphic unit throughout a geographic area.

Isotropic or isotropy

A condition in which properties do not depend on direction (e.g., hydraulic conductivity of an aquifer is the same in all directions).

Karst

A topography caused by slow dissolution of carbonate and evaporite (gypsum, halite) bedrock by surface and groundwater over time. This dissolution produces fissures, sinkholes, underground streams, and caverns that together create a karstic terrain.

Karstic

(See **Karst**)

Land cover

Physical material at the Earth's surface; this material may include a range of vegetation types, trees, grasslands, croplands, wetlands, water, ice/snow and urban areas, etc. Land cover information is captured by field surveys and through analysis of remotely sensed imagery.

Laurentide Ice Sheet

A massive ice sheet which covered most of Canada and a large portion of the northern United States at several times during Pleistocene glacial epochs.

Lithify

To change from loose sediment to solid rock.

Lithology

Mineral composition and texture of sediment or rock.

MAC

MAC or **M**aximum **A**cceptable **C**oncentration is the concentration limit set for a particular substance in water for a particular water use. A MAC for a substance in water is usually set as a guideline or a standard (enforceable). For example, Health Canada's guideline for the Maximum Acceptable Concentration for potable drinking water is 45 mg/L for nitrate, and 10 mg/L for nitrate-nitrogen.

Metamorphic rock

Rocks altered (change of form) by heat and pressure when mountain-building forces pressurized and heated them. These rocks which previous were sedimentary or igneous changed form, or size, shape and mineral arrangement (e.g., limestone changing to marble, and shale changing to slate).

Mineralized groundwater

Groundwater containing dissolved natural constituents. Measurement usually reported as a concentration of total dissolved solids (TDS) (typically reported in mg/L).

Monitoring well

A constructed well which allows groundwater observations. Small diameter observation wells used to monitor groundwater levels are often called piezometers.

Moraine

A ridge of unsorted till and sorted sand and gravel deposited at the margin of a glacier.

Niagara Escarpment

A prominent escarpment or cuesta formed by differential erosion of sedimentary rocks. It extends from northern New York State west and northwest through Ontario, Michigan, Wisconsin and Illinois. The Niagara River plunges over the escarpment at Niagara Falls.

Oak Ridges Moraine

A prominent glacial landform and height of land located north of Lake Ontario, extending from the Niagara Escarpment eastward beyond Rice Lake, Ontario. Its sandy hills, rising more than 200 m above Lake Ontario, capture considerable precipitation which is directed as ground and surface water flow south to Lake Ontario and north to Lake Simcoe.

Outcrop

A portion of bedrock or other rock stratum protruding above the soil as rock formations. Outcropping bedrock is very useful because it allows geologists to determine local geology, and helps them assemble Earth's geologic history.

Overpressure

In geologic terms, a condition wherein pressure at the point of interest in the subsurface exceeds the lithostatic pressure thereby creating artesian conditions for water flow.

Permafrost (or perennially frozen ground)

A thermal condition in which rock or soil remains continuously below 0°C for two or more years.

Permeability

A physical property of a porous medium which reflects that medium's ability to allow fluid flow through it. Symbolized as "k", permeability has dimensions of Length^2. When measured in cm^2, the numerical value of permeability is very small. Consequently more practical units, such as the darcy (D) or millidarcy (mD), are commonly used especially in the petroleum engineering industry. One darcy is equivalent to 9.86923×10^{-9} cm^2.

Phreatic surface

A term that refers to the water table, located in an unconfined aquifer as the boundary between saturated and unsaturated conditions where the water is at atmospheric pressure. Phreatic water is groundwater located within the saturated zone of an unconfined aquifer.

Physiography

The topography, soil, sediment and rock at the Earth's surface. The related field of geomorphology (earth forms) is concerned with understanding the Earth's surface and the processes (past and present) by which it is shaped.

Piezometer

(See **Monitoring well**)

Piezometric

(See **Equipotential**)

Pinch out

A reduction in thickness (tapering) of geologic strata as a result of on-lapping rock or sediment sequences. Pinch out can form good reservoirs for ground fluids/gases, including water and/or oil and gas.

Piper, Stiff or radial diagrams

Different diagram types designed to help visualize variations in the major ion composition of differing water samples and to aid in the classification of distinct water types.

Pleistocene

An epoch of the Cenozoic era covering the span of time between about 1.8 million and 11,000 years ago during which a number of glacial episodes occurred; also, the corresponding system of unconsolidated deposits.

Polygons

An area or 2-dimensional (2D) shape of many sides. A polygon, in reference to an aquifer or geological unit, is the area of an aquifer or geological unit as it appears on a map. The area is referred to as a polygon because the areal boundary these features has been digitized as a series of short straight lines to capture its areal extent or shape.

Porosity

The ratio of the aggregate volume of pore space in rock or sediment to its total volume.

Potentiometric surface

An imaginary surface which coincides everywhere with the static water level in a given water bearing formation. The surface to which the water from a given interval will rise under its full hydraulic head.

Precautionary principle

Within science-based risk management, the precautionary principle recognizes that the absence of full scientific certainty shall not be used as a reason to postpone decisions when faced with the threat of serious or irreversible harm.

Quaternary

An epoch of the Cenozoic era between about 1.8 million years ago and the present, in which a number of glacial episodes occurred. Quaternary includes the last 11,000 years of time, which had no continental glacial episodes; it also includes related unconsolidated deposits.

Recharge

The process by which groundwater beneath the water table is replenished. Recharge occurs both naturally and through anthropogenic processes (e.g., via managed aquifer recharge).

Recharge area

An area where the net direction of groundwater flow is downward, thereby contributing to groundwater storage in the aquifer.

Residence time

The amount of time groundwater spends in the ground. Residence times span from days to millions of years, depending on geology and physiographic setting.

Riffles and pools

Small scale changes in elevation along the length of a stream result in shallower, faster flowing, more turbulent stream sections with coarser sediment (called riffles) and deeper, slower, flatter sections with finer sediment (called pools).

Riparian

Located adjacent to a surface water body, riparian zone generally refers to the area of an ecotone transitional between aquatic and terrestrial ecosystems, for example along river banks and floodplains.

Road salt

Either sodium chloride or calcium chloride which is applied to roads for the purpose of melting ice and snow in winter, or for dust control in summer.

Seawater intrusion

The incursion of seawater into freshwater aquifers located in coastal areas.

Sediment

Unconsolidated material overlying bedrock (e.g., Quaternary sediment and/or surficial deposits).

Sedimentary basin

A low area in the Earth's crust, often of tectonic origin, in which sediments have accumulated.

Shear zone

A tabular zone of deformation in which strain is noticeably higher than in the surrounding rock. Brittle shear zones often include a core zone, where crushed material is located, surrounded by damage zones, which are made more permeable by the higher fracture density.

Sinkhole

Also known as doline in geological terms. A sinkhole is a natural depression or hole in a land surface formed by the dissolution and collapse of a cavern roof. Such collapse may have various causes including karst processes, the chemical dissolution of carbonate rocks in limestone regions, or evaporite rocks (such as gypsum or halite), and are connected to subterranean passages.

Source water protection

Safeguarding those lakes, rivers and aquifers utilized for drinking water and other human uses. This activity is part of Ontario's *Clean Water Act* and is designed to help protect drinking water at source, as part of an overall commitment to safeguard human health and the environment (see figure 12.7 for SWP areas in Ontario).

Specific capacity

Rate of discharge from a well per unit decline in drawdown. It is calculated by dividing the pumping rate by the stable drawdown in the well during continued pumping.

Specific storage

Specific storage, Ss, for a saturated aquifer is the volume of water that a unit volume of aquifer releases from storage per unit decline in hydraulic head (l/m).

Specific yield

The volume of water that an unconfined aquifer releases from storage due to gravity drainage per unit surface area, per unit change in head.

Storativity

The volume of water a confined aquifer releases from or takes into storage per unit surface area, per unit change in head. Storativity is equal to the product of specific storage and aquifer thickness (dimensionless).

Stratigraphy

The geological study of the sequence of (sedimentary) rocks in terms of time and space.

Stream order

Part of a classification system determining the relative size of streams and rivers. Stream order is a numerical value assigned to a stream segment based on the order (or number) of upstream tributaries flowing into it. Stream order increases downstream such that low-order streams are generally small streams near their source, whereas high-order streams are generally rivers which occur farther downstream, and drain much larger watershed areas.

Subcrop bedrock

Geological unit occurring at the bedrock surface but covered by surficial deposits.

Submarine groundwater discharge

Any flow of water across the sea floor which includes both fresh groundwater and recirculated sea water. Such discharge not only includes topography-driven groundwater flow, but also considers additional processes such as ocean dynamics (tides, waves, currents, storms), density gradients and geothermal gradients, leading to groundwater flow and mixing.

Surficial deposits

(See **Sediment**)

Sustainable use of groundwater

Use of groundwater in such a manner that it can be maintained for an indefinite time without causing unacceptable environmental, economic or social consequences.

TDS

(See **Total Dissolved Solids**)

Thalweg

Line defining the lowest point (flow path) along the length of a river bed. Also the line defining the central (long) axis of a buried channel or valley; may coincide with the location of the thickest sedimentary deposits.

Till

A poorly-sorted, glacial-originating heterogeneous sediment (mixture of boulders, gravel, sand and mud), deposited directly by a glacier. Although till usually forms aquitards, it may yield water for domestic use when interbedded with sand and/or gravel.

Total Dissolved Solids (TDS)

Concentration of all chemicals dissolved in water (solids remaining after evaporation of a water sample).

Transmissivity

The product of hydraulic conductivity and aquifer thickness. Transmissivity is the rate of flow under a unit hydraulic gradient through a cross-section of unit width over the whole aquifer thickness. It is designated by the symbol “T”, and has the dimension of length^2/time (e.g., m^2/day).

Trend

The relationship between a series of data points (e.g., Mann Kendall test for trend).

Unconfined aquifer

Also called phreatic aquifer or water-table aquifer. An aquifer having a water table (phreatic surface) which serves as its upper boundary wherein pore pressure is equal to atmospheric pressure. Water in a well penetrating an unconfined aquifer does not, in general, rise above the water surface.

Valley fill

The unconsolidated sediment deposited by any agent, which fills or partially fills a valley.

Vulnerability (of an aquifer)

A measure of the intrinsic susceptibility of an aquifer representing the "tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer".

Walkerton

A small rural town in southwestern Ontario, Canada, in which a series of events accompanied the contamination of the town's water supply by *Escherichia coli* bacteria in May 2000 (see Box 12-1 in Chapter 12 for more details).

Water balance

An accounting of the inputs and outputs of the various components of the hydrological cycle (precipitation, evapotranspiration, surface runoff, groundwater recharge, and changes in storage). Water balance calculations are normally carried out annually at the catchment scale.

Water-bearing

Containing water within the spaces of a sediment or a rock and between sediment grains or fractures.

Water Quality Check Program

A subsidized program for residents in British Columbia, Canada, to have their water quality tested and analyzed. A resident could collect a water sample from his or her water supply source (e.g., well, spring, lake or stream) and send it to the analytical laboratory to have the water sample analyzed at a reduced cost. The program existed between 1977 and 1993 and generated up to over 11,000 water quality sample results.

Well capture zone

The two-dimensional (2D) projection to the land surface of the aquifer volume containing all the groundwater that may flow toward a pumping well over an infinite time period.

Wellhead Protection Area (WHPA)

Location immediately surrounding a well that must be protected from potential sources of surface contamination. Defined by the U.S. Environmental Protection Agency (US EPA) as "the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field." (see BOX 6-4 in Chapter 6 for more details)

Wetland

An area where the ground is permanently or seasonally saturated with water (e.g., swamp, marsh, peatland).

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CHAPTER 10

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CHAPTER 11

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Charles LAMONTAGNE, *M.Sc. Ing.* Directeur par intérim, Bureau de coordination sur les évaluations stratégiques. Min. Développement Durable, de l'Environnement, de la Faune et des Parcs.

Charles received his BA, geological engineering at UQ Chicoutimi in 1979 and an M. Sc. in hydrogeology in 1995 at U Laval. Between his degrees, he carried out mineral exploration for uranium and gold in northern Saskatchewan. Since 2001, he has been working at Environment Quebec on regional groundwater assessments, notably the Chateauguay Basin, on large scale groundwater contamination cases and has been involved with modernising the environmental regulations on groundwater for the province of Quebec.

Denis LAVOIE, *Ph.D., Research Scientist,*Geological Survey of Canada.

Dr. Lavoie's main research interests include Eastern Canada regional geology and basin analyses, evaluation of the conventional hydrocarbon potential of eastern and northern Canada, and unconventional hydrocarbon systems of southern Canada. He has recently been involved in different projects related to environmental impacts of shale oil and gas development, notably on groundwater.

Harm MAATHUIS, *Hydrogeologist M.Sc, P.Geo, P. Eng.*, Saskatoon, SK.

Harm Maathuis worked for over 30 years at the Saskatchewan Research Council dealing with regional and local geological and hydrogeological site characterizations, contaminant hydrogeology and groundwater monitoring networks.

Kerry T. B. MacQUARRIE, *Ph.D., P.Eng., Professor,* Department of Civil Engineering & Canadian Rivers Institute, University of New Brunswick, Fredericton, NB.

Dr. MacQuarrie's research interests include the transport and fate of contaminants in the subsurface and the use of hydraulic, thermal, and geochemical information to understand groundwater–surface water interactions. A particular area of focus has been the development and application of numerical models for the simulation of solute mass transport and reactions. He has recently served as a member of expert committees for organizations such as NSERC and the Council of Canadian Academies.

Scott M. MacRITCHIE, *P.Geo. Senior Hydrogeologist.* Climate Change Vulnerability Specialist. Ministry of the Environment, Toronto, Ontario.

Scott began his earth science career as a geophysicist in 1981 and has been a hydrogeologist working in Ontario since 1992. Since 2005 he has been employed by the Ontario Ministry of the Environment working on the Provincial Groundwater Monitoring Network and on various projects involving climate change adaptation and water resources.

Richard MARTEL, *P.Eng., Ph.D. Professor,* Université du Québec, Centre Eau Terre et Environnement, Institut national de la recherche scientifique.

Professor Martel's research interests are related to the characterization of groundwater flow systems, contaminant fate, behaviour and transport, the in situ remediation of contaminated soils and aquifers using surfactant-alcohol-polymer solutions, the aquifer mapping and protection and, the subsidence prediction in relationship to groundwater extraction.

Renald McCORMACK, *géo., hydrogéologue;* ENVIR'EAU PUITS INC.: Founder and President, Levis, Quebec. Ministry of Natural Resources from 1972 to 1980 (Groundwater Regional Mapping). Chief, Groundwater Branch-Quebec Groundwater Legislation and Policy- Groundwater Vulnerability Mapping with the Ministry of Environment: 1980–1997.

Yves MICHAUD, *Ph.D., Geoscience Manager,* Geological Survey of Canada, Quebec.

Yves Michaud joined the GSC in 1990 as research scientist. His work has focused on the dynamic of geomorphic processes in permafrost areas and on regional hydrogeological mapping and characterization of three key Canadian aquifers (Laurentian Piedmont, Maritimes Carboniferous Basin and Annapolis Valley aquifers). Yves is now the manager of the Groundwater Geoscience Program at NRCan.

Frederick A. MICHEL, *Ph.D., P. Geo., Associate Professor;* Carleton University, Ottawa, ON.

Dr. Michel is cross-appointed between the Dept. of Earth Sciences and the Institute of Environmental Science at Carleton University, where his research has focused on permafrost regimes, groundwater as a resource, and low temperature geothermal energy systems.

Miroslav NASTEV, *Ph.D., Research Scientist*. Geological Survey of Canada, Quebec (QC).

Miroslav Nastev has a broad-ranging expertise related to earthquake engineering, environmental assessments and groundwater resources. Currently, his research interests are focused on the risk assessment from natural hazards and he leads the Hazus Canada project.

Linda NOWLAN is Director of Pacific Conservation at WWF-Canada in Vancouver. An environmental lawyer for more than twenty years, Nowlan is a former Executive Director of West Coast Environmental Law, a UBC Faculty Research Associate at the Program on Water Governance and an advisor to the Environment Department of the UK Foreign Office. She is on the Board of the Fraser Basin Council, a member of the Canadian Council of Academies' Expert Panel on Groundwater, and has served on the BC Independent Drinking Water Review Panel. She has written widely on groundwater, water and environmental law.

Michel PARENT, *Ph.D., Research Scientist* Geological Survey of Canada, Quebec (QC).

Michel Parent joined the GSC in 1988 as a research scientist specialized in Quaternary geology. He has been engaged in drift exploration projects in northern Quebec and Labrador during most of that period; he has continued to carry out and supervise surficial geology and hydrostratigraphy research in diverse Quaternary settings of southeastern Canada.

Andrew PIGGOTT, *Senior hydrogeologist*, formerly Environment Canada.

Andrew Piggott has educational and employment backgrounds in geotechnical, mining, petroleum, and water resources engineering. Much of his research has focused on the characterization and modelling of groundwater conditions at regional scales, largely within the Great Lakes basin and often with an emphasis on the impacts of climate on groundwater.

Christine RIVARD, *Ph.D., Research Scientist* Geological Survey of Canada.

Dr. Rivard has been working at the GSC since 2001. She has participated in and managed three regional hydrogeological characterization projects in Eastern Canada. She has also been studying potential impacts of shale gas development and climate change on groundwater resources.

Alfonso RIVERA is the Chief Hydrogeologist of the Geological Survey of Canada.

Dr. Rivera obtained his Ph.D. degree with honours at the National School of Mines of Paris, France. He worked for 14 years in Europe, France, Switzerland, Germany and Spain before he immigrated to Canada. He designed and implemented the GSC's Groundwater Program and was its Manager from 2002 to 2012. He is adjunct professor INRS-ETE and Université de Laval. Over the last years, Dr. Rivera has been scientific advisor to UNESCO, OAS, GEF, RAMSAR, and IAEA; and a few provincial governments in Canada. In 2013, he was inducted as member of the Académie de l'Eau, France.

Kevin RONNESETH, *M.Sc., P.Geo.*

Kevin, recently retired from the Ministry's Groundwater and Aquifer Science Section, was with the Ministry of Environment for 25 years, providing technical expertise and, more recently, managing the provincial aquifer mapping program to help the province of British Columbia manage and protect its valuable groundwater resource. Kevin holds a Master of Science in Geography from the University of Victoria (1994) and a Bachelor of Science (Honours) in Geography from the University of Victoria (1981).

Alain ROULEAU, *Ing., Ph.D., Professor.*

Alain is a geological engineer and professor at Université du Québec à Chicoutimi. He completed his graduate studies at Université Laval and at the University of Waterloo. He has worked for more than 30 years in hydrogeology, particularly in fractured rock aquifers, as a consultant and a researcher, in Canada and in many other countries.

Denis W., ROY, *Ph.D., Emeritus Professor,* Université du Québec à Chicoutimi.

Denis W. Roy received a Ph. D. in Geology from Princeton University (NJ, USA) in 1978. He taught Structural Geology, Tectonics and Geomorphology à Université du Québec à Chicoutimi (QC, Canada) from 1971 to 2009. Impacts craters (Manicouagan and Charlevoix), Grenvillian Geology, local Phanerozoic and Quaternary geology of the Saguenay–Lac-Saint-Jean area, rock fractures and lineaments surveys applied to the 1988 Saguenay Earthquake and to fractured aquifers are his main research topics.

Hazen A. J. RUSSELL, *Ph.D., Sedimentologist,* Geological Survey of Canada, Natural Resources Canada.

Hazen has a Ph.D. from the University of Ottawa and applies basin analysis techniques to understanding the origin of sedimentary deposits in glacial basins. For 20 years he has worked on groundwater studies, surficial geological mapping, and mineral exploration questions at the Geological Survey of Canada. He is part of a multidisciplinary team employing sedimentology, geophysics, and hydrogeology techniques to improve regional groundwater understanding across Canada.

Martine M. SAVARD, *Ph.D., Research Scientist (Isotope Geochemistry),* Geological Survey of Canada, Quebec (QC).

Dr. Savard received her Ph.D. in 1991 from U. of Ottawa. After joining the GSC, she built the Delta-Lab, a stable isotope laboratory, and led several large research projects. Her main scientific interest is in addressing priority-environmental issues on the sustainable development of natural resources. She has organized major international symposia, been a member of several grant selection committees, and received numerous governmental awards.

Dave R. SHARPE, *Ph.D., Research Scientist,* Geological Survey of Canada.

Dave is a sedimentologist, a project leader for the Groundwater Mapping Program of the Geological Survey of Canada, and an Adjunct Professor at the Universities of Ottawa and Waterloo. He holds degrees in Earth Sciences from Toronto (B. Sc.), Colorado (M.Sc.) and Ottawa (Ph.D.). His current interests include basin analysis assessment of glacial aquifer systems in Ontario and the Canadian prairies and mineral exploration in glaciated barren land terrains. He works in a team with geophysical, sedimentological and hydrogeological specialists.

George SOMERS, *Hydrogeologist, Manager,* Drinking Water and Wastewater Management section, Charlottetown, PEI.

Mr. Somers holds an M.Sc. (Geology) from the University of Western Ontario (1984) and an M.B.A. from Dalhousie University (1988). He has worked in the field of groundwater for 25 years, in Prince Edward Island and northern Nova Scotia. His interests have focused on regional groundwater resources, nitrate contamination and saltwater intrusion.

Sonja STRYNATKA, *Hydrogeologist*, Grand River Conservation Authority, Cambridge, Ontario.

Sonja has been a hydrogeologist with the Grand River Conservation Authority for the past 10 years. She holds a Master of Science degree in Geology from Western University. Her interests are in groundwater chemistry, and watershed-scale monitoring and modelling. Sonja is a member of the Association of Professional Geoscientists of Ontario and is also actively involved within the Association.

René THERRIEN, Ing., *Ph.D., Professor;* Département de géologie et de genie géologique, Université Laval.

Dr. Therrien has been a professor of hydrogeology at Université Laval since 1994. His research programme focuses on quantitative hydrogeology with an emphasis on the development and application of hydrogeological models to address various issues related to water resources. He has recently served as a member on expert committees for the Natural Sciences and Engineering Research Council of Canada (NSERC), the Council of Canadian Academies and the Royal Society of Canada.

Bob TURNER, *Ph.D.,* Geological Survey of Canada, Vancouver.

Bob has coauthored two popular science books on geoscience issues in the Vancouver region, *Vancouver, City on the Edge*, which was nominated for the City of Vancouver Book Award in 2003, and *At Risk, Earthquakes and Tsunami hazards of the Pacific Northwest*. Bob won the Geological Association of Canada's award for earth science education in 2002 for his ongoing outreach work that includes numerous public education posters and guides on geoscience, water resources, and climate change for communities in BC and across Canada. From 2006 to 2011, Bob was the Mayor of Bowen Island Municipality near Vancouver, where he lives.

Garth VAN DER KAMP, *Ph.D., Research Scientist,* Water Science and Technology, Environment Canada, Saskatoon, SK.

Dr. van der Kamp's work deals with the role of groundwater in the hydrological cycle, with focus on the interactions between groundwater and surface water in upland recharge areas as well as in wetlands and lakes.

Robert O. VAN EVERDINGEN, *Ph.D., Research Associate and Fellow,* Arctic Institute of North America, Calgary, AB.

Robert van Everdingen received the Robert N. Farvolden Award from the International Association of Hydrogeologists (Canadian National Chapter) and the Canadian Geotechnical Society (Hydrogeology Division) in 2010 for “outstanding contributions to the disciplines of earth science and engineering that emphasize the role and importance of groundwater”.

Mike WEI, *P. Eng.,* British Columbia Ministry of Environment, Victoria, BC.

Mike is the Head of the Ministry’s Groundwater and Aquifer Science Section and has been with the Ministry of Environment for over 30 years, providing technical and, more recently, policy expertise to help the province of British Columbia manage and protect its valuable groundwater resource. Mike has also been an associate faculty member at Royal Roads University since 1999. Mike holds a Master of Science in Hydrology from the New Mexico Institute of Mining and Technology (1991) and a Bachelor of Applied Science in Geological Engineering from the University of British Columbia (1982).

Gilles WENDLING, *Ph.D., P.Eng., Hydrogeologist*, GW Solutions Inc., Nanaimo, BC.

Dr. Gilles Wendling focuses his consulting activities on identifying groundwater sources, characterising aquifers and watersheds, and providing tools to water users and managers for a better understanding, characterisation, management and protection of the groundwater resources. He is particularly interested by surface water and groundwater interaction, and by the water-food-energy nexus.

Ming-ko WOO, *Ph.D., Professor Emeritus,* McMaster University, Hamilton, ON.

Ming-ko (Hok) Woo is a Professor Emeritus in the School of Geography and Earth Sciences at McMaster University. He is a Professional Hydrologist of the American Institute of Hydrology, a Fellow of the Arctic Institute of North America and of the Royal Canadian Geographical Society. His primary research relates to the hydrology of permafrost, snow and wetlands.

Paul R. J. WOZNIAK, *M.Sc. Geology,* Geological Survey of Canada.

Paul contributed to GSC Groundwater Program projects and data management starting in 2003 and completed a M.Sc. degree in 2011. Interests include: sedimentology and fluvial environments; conceptual aquifer characterization; groundwater flow modeling; aquifer testing; GIS analytics; and data mining.

Gregg ZWIERS, *M.Sc., P.Geo., Senior Hydrogeologist*, Grand River Conservation Authority, Fellow of Geoscientists Canada.

Gregg is the Senior Hydrogeologist at the Grand River Conservation Authority and has about 18 years of experience in hydrogeology. He holds a Bachelor of Science degree in geology from Brock University and a Master of Science degree in hydrogeology from the University of British Columbia. Gregg is very active with the Association of Professional Geoscientists of Ontario and sits on Science Advisory Committees at both the University of Guelph and the University of Waterloo.

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Notes: Page numbers in italic indicate an illustration or table. In subheadings, GW refers to groundwater and SW refers to surface water.

I'm sure it will become a standard reference in Canadian water resource circles, and will meet your expectations for use by scientists, engineers, consultants, managers, regulators, decision makers, and all others who have need of information on groundwater conditions in Canada.

—Allan Freeze, Professor

Ira Brown's Groundwater in Canada *appeared in 1967—the age of Meyboom, Tóth and Farvolden on the Prairies. My weathered copy of this Old Testament of Canadian hydrogeology now acts like a time capsule, establishing how little we knew. Just how much has been accomplished in the meantime becomes apparent with the revision of* Canada's Groundwater Resources, *again courtesy of the GSC. This New Testament is for all scientifically inquisitive Canadians with an interest in their environment, a fascination with their country and a willingness to learn about it. It is exceptionally well illustrated and written in a style that is concise yet informative. It's all here from the Gulf Islands to the Annapolis Valley, from Darcy to Deuterium.*

—Dick Jackson, Geofirma Engineering, Heidelberg, Ontario

From mountains to plains, geothermal springs to permafrost, this ambitious and long overdue volume describes Canada's rich hydrogeological heritage. A must-read and reference for hydrogeology students, teachers and practitioners.

—Bob Leech, Senior Scientist, AECOM

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