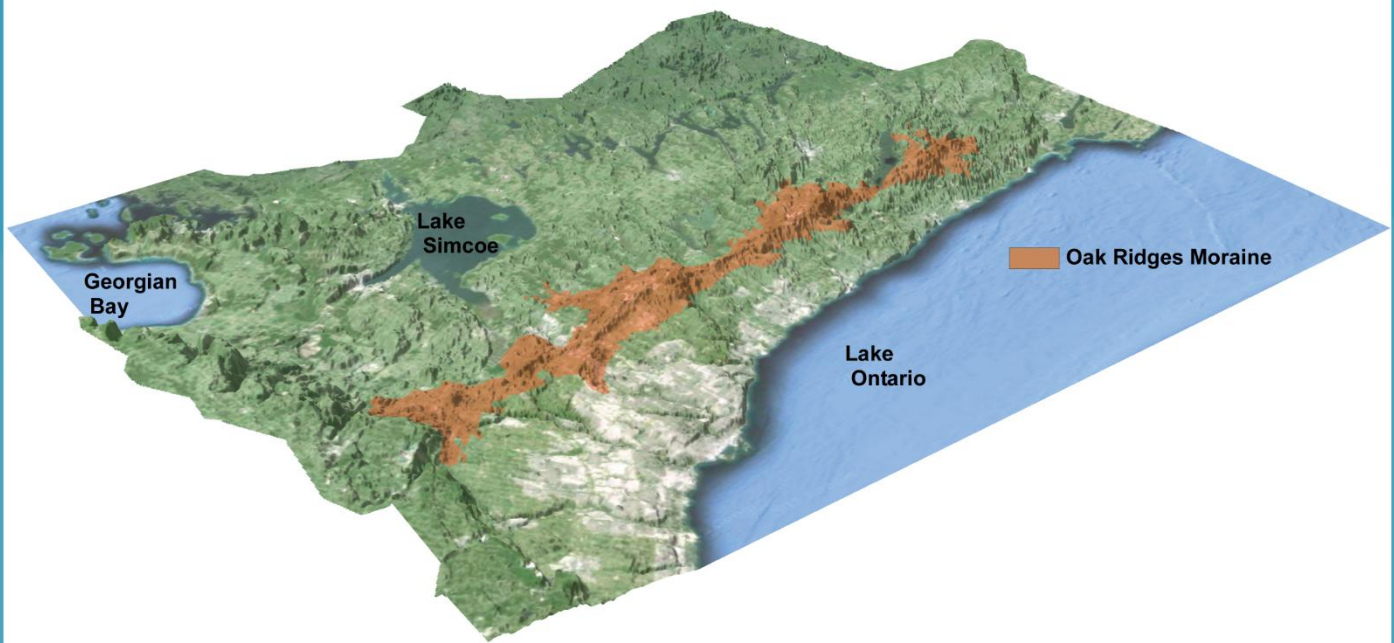




The Oak Ridges Moraine Aquifer System, Canada: Data-driven Collaborative Science for Public Purpose

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The Groundwater Project

i

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Dedication

This book is dedicated to the many scientists and engineers who have studied the geology and hydrogeology of south-central Ontario, particularly those associated with the Oak Ridges Moraine over many decades. Dedication is also extended to the planners and managers who have the foresight and patience to incorporate this knowledge into water-resource management initiatives and policy.

This work is also dedicated by Richard Gerber to his father, Harry Lloyd Gerber, a history teacher who spent his life challenging and nurturing young minds. He impressed upon Richard that geologists are also historians who have a deep understanding of how the earth works, and that it is their duty to disseminate this understanding, particularly lessons learned, to people evaluating many current societal issues.

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The Groundwater Project Foreword

The United Nations (UN)-Water Summit on Groundwater, held from December 7 to 8th 2022 at the UNESCO headquarters in Paris, France, concluded with a call for governments and other stakeholders to scale up their efforts to better manage groundwater. The intent of the call to action was to inform relevant discussions at the UN 2023 Water Conference held from March 22 to 24, 2023 at the UN headquarters in New York City. One of the required actions is *strengthening human and institutional capacity*, for which groundwater education is fundamental.

The [UN-Water website](#)[↗] states that *more than three billion people worldwide depend on water that crosses national borders*. There are 592 transboundary aquifers, yet most do not have an intergovernmental cooperation agreement in place for sharing and managing the aquifer. Moreover, while groundwater plays a key role in global stability and prosperity, it also makes up 99 percent of all liquid freshwater—accordingly, groundwater is at the heart of the freshwater crisis. *Groundwater is an invaluable resource*.

The Groundwater Project (GW-Project), a registered Canadian charity founded in 2018, pioneers in advancing understanding of groundwater and, thus, enables *building the human capacity for the development and management of groundwater*. The GW-Project is not government funded and relies on donations from individuals, organizations, and companies. The GW-Project creates and publishes high-quality books about *all-things-groundwater* that are scientifically significant and/or relevant to societal and ecological needs. Our books synthesize knowledge, are rigorously peer reviewed and translated into many languages. Groundwater is ‘hidden’ and, therefore, our books have a strong emphasis on visualizations essential to support the spatial thinking and conceptualization in space and time of processes, problems, and solutions. Based on *our philosophy that high quality groundwater knowledge should be accessible to everyone*, The GW-Project provides all publications for free.

The GW-Project embodies a new type of global educational endeavor made possible by the contributions of a dedicated international group of over 1000 volunteer professionals from a broad range of disciplines, and from 70 countries on six continents. Academics, practitioners, and retirees contribute by writing and/or reviewing books aimed at diverse levels of readers including children, youth, undergraduate and graduate students, groundwater professionals, and the general public.

The GW-Project started publishing books in August 2020; by the end of 2024, we have published 55 original books and 77 translations (55 languages). Revised editions of the books are published from time to time. In 2024, interactive groundwater education tools and groundwater videos were added to our website, gw-project.org[↗].

We thank our individual and corporate sponsors for their ongoing financial support. Please consider sponsoring the GW-Project so we can continue to publish books free of charge.

The Groundwater Project Board of Directors, January 2025

Foreword

One aim of the Groundwater Project is to publish books that show particular *‘exemplary accomplishments’* related to groundwater from around the world. This book presents an unprecedented accomplishment of human cooperation for the common good. It describes an impressive coming together of a community to bring about four important achievements related to the Oak Ridges Moraine Aquifer.

The first exemplary accomplishment was developing an agreement between all levels of government in the Greater Toronto Area (GTA), Canada’s most populous and mostly urbanized region, that is home to approximately seven million people. The agreement allows for a small, semi-autonomous government agency called the Oak Ridges Moraine Groundwater Program (ORMGP) to work with government agencies to collect and manage subsurface data and information obtained across a broad south-central Ontario geography.

Established two decades ago, the ORMGP was created to receive and manage this information relevant to the Oak Ridges Moraine Aquifer. Its repository includes reports and documentation related to the drilling and completion of boreholes, wells, and piezometers, the results of sample-water analyses, as well as surface and borehole geophysics. The program was founded on a powerful and forward-looking principle: groundwater is a public resource, and therefore all information concerning it should be safeguarded, organized, and made accessible to support its long-term protection and management.

The second accomplishment was development of sophisticated online software that allows users to easily access, manipulate, and visualize the data. This system places an extraordinary resource into the hands of anyone—scientists, policymakers, educators, students, and the public. With just a few steps, users can explore the subsurface, retrieve data of interest, and display it in ways that support inquiry, analysis, and decision-making.

Third, drawing on its substantial hydrogeological expertise and working in close collaboration with the Geological Survey of Canada, the ORMGP developed an advanced geologic and hydrogeological framework of the Oak Ridges Moraine Aquifer. Given the region’s complex geology, this framework is essential. It enables users to extract maximum value from the data and to better understand the intricate architecture of the subsurface.

The fourth accomplishment lies in the system’s exceptional educational value. The diversity of data and the versatility of the software make it ideally suited for all levels of education—from primary school classrooms to graduate seminars. Teachers can use the system to reveal the geology and groundwater conditions beneath their own schools. University instructors can challenge students to develop conceptual models or implement numerical models embedded within the system. In doing so, students are immersed in field

data and engaged in solving authentic problems tailored to their level of study. This is not simply a database—it is a living laboratory.

This comprehensive subsurface data repository with its technologically advanced access system is the brainchild and passion of two visionary hydrogeologists, Steve Holysh and Rick Gerber. They conceived the project and devoted their careers to bringing it to fruition—overcoming the considerable challenges posed by the many layers of government and organizations involved. They built a collaborative team representing diverse expertise, including key staff members Mike Doughty, Mason Marchildon, Britt Smith, and Steve Shikaze; Emeritus Professor Shaun Frape, PhD student Lori Labelle at the University of Waterloo; and Dave Sharpe of the Geological Survey of Canada.

This book will serve for a generation as the principal reference on the hydrogeology of the Oak Ridges Moraine. More than that, it stands as a powerful example of what can be achieved when scientific excellence, public purpose, and sustained collaboration come together. It demonstrates how groundwater science can be mobilized not only to advance knowledge, but also to support practical water management and responsible land-use planning for the benefit of present and future generations.

John Cherry, The Groundwater Project Leader
Guelph, Ontario, Canada, January 2026

Preface

The Oak Ridges Moraine is an upland landform extending for approximately 160 km in an east–west direction over much of south-central Ontario, Canada. Aquifer complexes within and beneath the moraine provide drinking water to hundreds of thousands of people and provide source water to streams with headwaters along the moraine flanks providing key habitat for ecosystem function. The area has historically been dominated by agricultural land use activities interspersed with large urban centers such as the City of Toronto. Challenges to water-resource management and ecosystem protection include: 1) increasing urban population and urbanized areas, 2) climate change with its increased severe weather events including flooding, 3) water quality impairment from the use of chemicals such as road salt, pesticides, nutrients, PFAS, and 4) other anthropogenic activities.

This book describes the geology and hydrogeology of the area as well as the development/refinement of the current conceptual model of the flow system. This information and conceptual model are then used to explain water management initiatives that are underway within the study area. Geologically, the area is characterized by Quaternary-aged sediments deposited over the last 130,000 years overlying Paleozoic bedrock largely consisting of shale and limestone.

The author team has spent decades studying groundwater flow systems and sharing their knowledge, and that of colleagues, with various audiences. Particularly interesting to the lead author is that in many places, much of the historical groundwater knowledge is localized and eventually lost; the result being that society repeatedly encounters the same issues without having knowledge of how those issues were addressed in the past. To this end, the book outlines the ongoing development of a water-resource information and analysis system, and describes a variety of knowledge-transfer initiatives.

Acknowledgments

The current understanding of the geology and hydrogeology of the groundwater flow systems associated with the Oak Ridges Moraine, which covers much of the south-central portion of the province of Ontario, Canada, has evolved over many decades. This understanding has been provided by numerous individuals, agencies, and government scientists including: Geological Survey of Canada; Ontario Geological Survey; Ontario Ministry of Environment, Conservation, and Parks; Ontario Ministry of Natural Resources and Forestry; municipal governments; conservation authorities; university researchers; and private consulting companies. The contributors are too numerous to mention here, but many are listed as references in Section 10.

This book documents existing data and information, but leaves detailed methodology and interpretation to the references cited and to an ongoing website operated by the Oak Ridges Moraine Groundwater Program (ORMGP). References include links to website locations that provide a means to interact further with the information presented in this book. Ongoing funding for this program is provided by the following five municipalities:

- City of Toronto;
- Regional Municipality of Halton;
- Regional Municipality of Peel;
- Regional Municipality of York; and
- Regional Municipality of Durham.

Other program partners are ten conservation authorities with jurisdiction covering parts of the Oak Ridges Moraine and surrounding areas including:

- Conservation Halton;
- Nottawasaga Valley Conservation Authority;
- Credit Valley Conservation;
- Toronto and Region Conservation Authority;
- Lake Simcoe Region Conservation Authority;
- Central Lake Ontario Conservation Authority;
- Ganaraska Region Conservation Authority;
- Kawartha Region Conservation Authority;
- Otonabee Region Conservation Authority; and
- Lower Trent Conservation.

We thank all partners of the ORMGP for access to data and information including, but not limited to, groundwater levels, groundwater chemistry, and field hydrologic testing. These types of data are also generated through the Provincial Groundwater

Monitoring Network (PGMN), a program run by the Ontario Ministry of Environment, Conservation and Parks (MECP), and other conservation authorities.

Water-related information is generated from several sources within the study area, including various levels of government, university researchers, and consultants. Significant government sources of information include Environment Canada, the Geologic Survey of Canada, the Ontario Geological Survey, and the Ontario MECP. The ORMGP collects data from these and other sources and then combines the data into a single database. Hydrogeological interpretations and predictions of future conditions are also developed.

This book makes frequent reference to a website developed and managed by the ORMGP: www.oakridgeswater.ca[↗]. This website allows access to and interaction with all data and information relating to the water resources associated with the Oak Ridges Moraine study area. There are two parts to this website; a public side and a partner side. Due to legal requirements associated with some data sources—for example, private names on water well records cannot be displayed—some of the information is password protected for access by partners only. Access to the partner part of the website can be provided upon request and approval.

Further information regarding the ORMGP can be found on the website, and a brief description of the program is also included in Box 1. Information on the layout, contents, and navigation of the site is included under the ORMGP Support tab. Training videos are also available on ORMGP Support/Website Training at www.oakridgeswater.ca/website-training[↗]. Available resources and information relating to water and geology from other agencies—for example, the Ontario Geological Survey and the Geological Survey of Canada—can be found at www.oakridgeswater.ca/resources[↗].

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- ❖ Alfonso Rivera, Emeritus Chief Hydrogeologist, Geological Survey of Canada;
- ❖ Jack Sharp, Dave P. Carlton Professor of Geology, University of Texas, Austin, US;
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The Oak Ridges Moraine Aquifer System, Canada: Richard Gerber, Dave Sharpe, Steve Holysh, Mason Marchildon,
Data-driven Collaborative Science for Public Purpose Mike Doughty, Shaun Frape, Lori Labelle, Britt Smith, Steve Shikaze

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1 The Journey of Managing the Oak Ridges Moraine Aquifer System

An extraordinary coordination of government and industry transpired to create a publicly-accessible groundwater database with an interactive map-based website for the Oak Ridges Moraine (ORM) Aquifer System that serves the Greater Toronto Area (GTA), Canada. The knowledge system provides hydrogeological information that increasingly, is relied upon by public sector agencies, consulting companies, academia, and local citizens for informed water-related work and decision-making (<https://www.oakridgeswater.ca/>). The breadth of the Oak Ridges Moraine Groundwater Program (ORMGP) is extensive because, as for all groundwater systems, a rigorous hydrogeological understanding requires knowledge of how water moves through the subsurface (geology, water levels, water takings, water quality), how much water is available to enter the groundwater system (climate and topographic data), and how much water is leaving the system (streamflow). The complex ORM aquifer system serves more than 7 million people in a region with both highly-urbanized-industrial and agricultural land (Figure 1). The aquifers are important sources of drinking water and stream baseflow. Understanding this multiple-aquifer system is paramount to developing, enacting, and enforcing water-resource-management practices and policies for sustainable use to support a key economic engine of the Canadian economy.

The journey of managing the aquifer system began with the recognition that across south-central Ontario, much groundwater data was regularly being collected but that it was soon thereafter lost or rendered inaccessible due to the absence of any coordinated database management to host this data. Therefore, most data were not available to contribute to future water management decisions. Recognizing an opportunity to help Ontario move forward, the ORMGP stepped up. Database architecture and design was followed by data gathering (Section 1.1), and subsequently regional-scale interpretations and numerical modeling. As technology evolved, the many possible uses for the database and the modeling became recognized, fostering an ever-increasing necessity to incorporate data, knowledge and insights from previous and ongoing investigations and models into the analysis system. This has subsequently led to ever-improving conceptual models and management decisions. Thus, a transition in water-related decision making began and is ongoing (Section 1.2). The resulting important steps that were taken in the building of the ORMGP are presented in Section 1.3. An introduction to the ORM is provided by Section 2, followed by sections that describe the setting (Section 3), an overview of the conceptual flow model (Section 4), the geological framework (Section 5), and the hydrogeology (Section 6). Finally, the monumental evolution of the unparalleled groundwater management and governance of the Oak Ridge Moraine Aquifer System is discussed in Section 7 with a view to the future provided in Section 8.

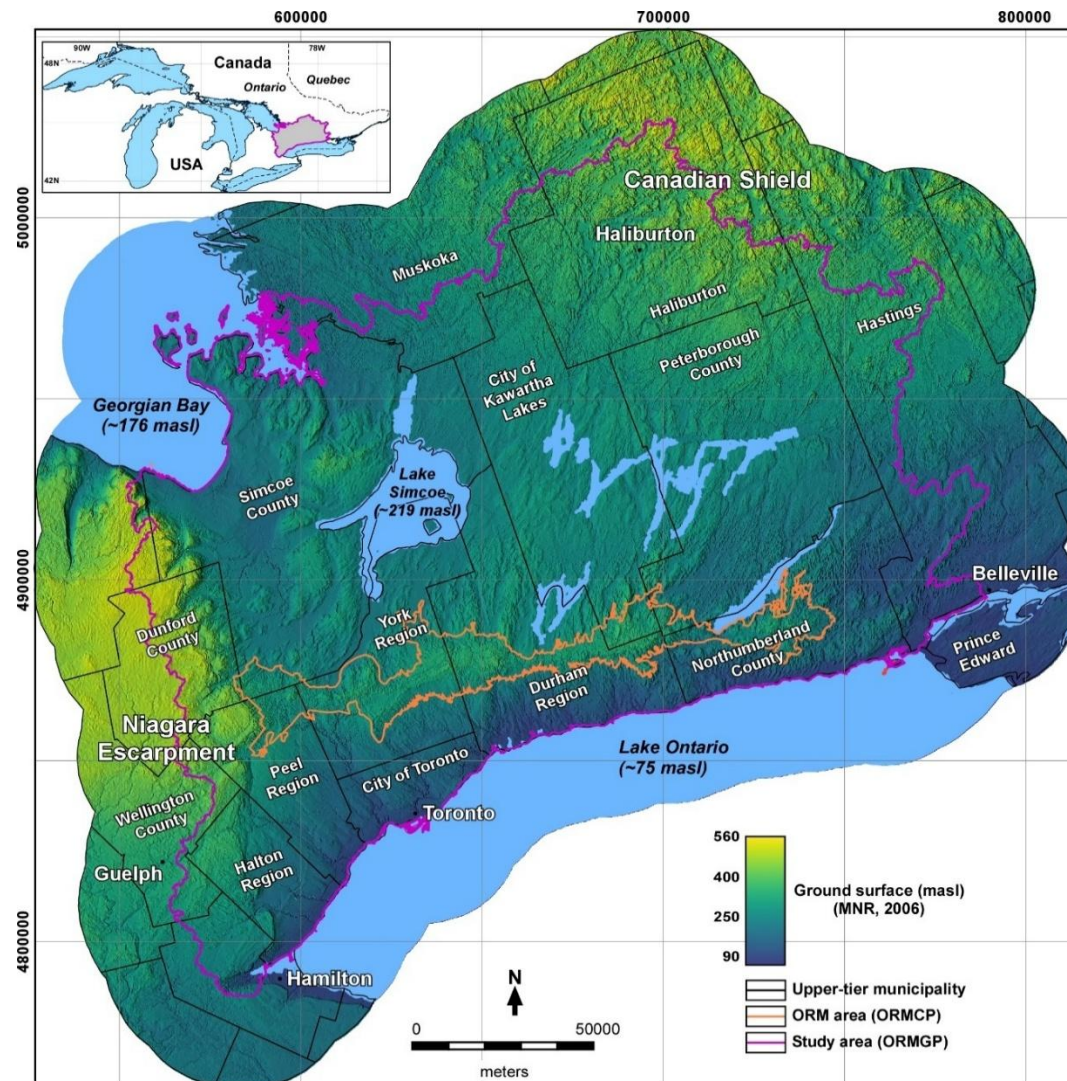


Figure 1 - The Oak Ridges Moraine Groundwater Program (ORMGP) study area. The inset shows the location of the map within the Great Lakes region of Canada. Legend item “Study area (ORMGP)” is the boundary outlining the study area for this book (magenta line). Legend item “ORM area” is the surficial expression of the Oak Ridges Moraine upland and also encapsulates the Oak Ridges Moraine Conservation Plan (ORMCP) boundary (orange line), a planning boundary established by the Province of Ontario to regulate land use across the Oak Ridges Moraine. Black lines indicate municipal boundaries. Coordinates are in meters as per UTM NAD83 Zone 17 projection. Ground surface elevation (MNR, 2006) was provided to the ORMGP by the Ontario Ministry of Natural Resources. It is the 2006 Digital Elevation Model – Version 2.0.0 – Provincial Tiled Dataset (DEM) with a 10m cell resolution for southern Ontario.

1.1 Collecting, Managing, and Using the Data

A robust groundwater management program must be founded on data that is collected and managed consistently with determination and rigor, making use of evolving technology. This requires digital database management, GIS systems, interpretive maps and graphs, and powerful web-based internet accessibility to support projects and decisions that affect and are affected by groundwater resources, such as water management, land use planning, and infrastructure development.

The geological and hydrogeological conceptualization and three-dimensional model of the Oak Ridges Moraine required the collection of high-quality geological, geophysical, and hydrogeological datasets from many collaborators and their integration and analyses alongside all other available data. The integrated data allows for a comprehensive analysis of the moraine's depositional history and geological makeup, how and how much water moves through its subsurface sediments, and how the water quality is affected by natural and anthropogenic influences.

Figure 2 outlines the management system architecture in use by the ORMGP. The strategy can be followed by others to similarly manage and integrate data, build insightful on-line tools and make these accessible to others. As shown in Figure 2, central to the program is a focus on making use of hydrogeological data and interpretations to inform decision making.

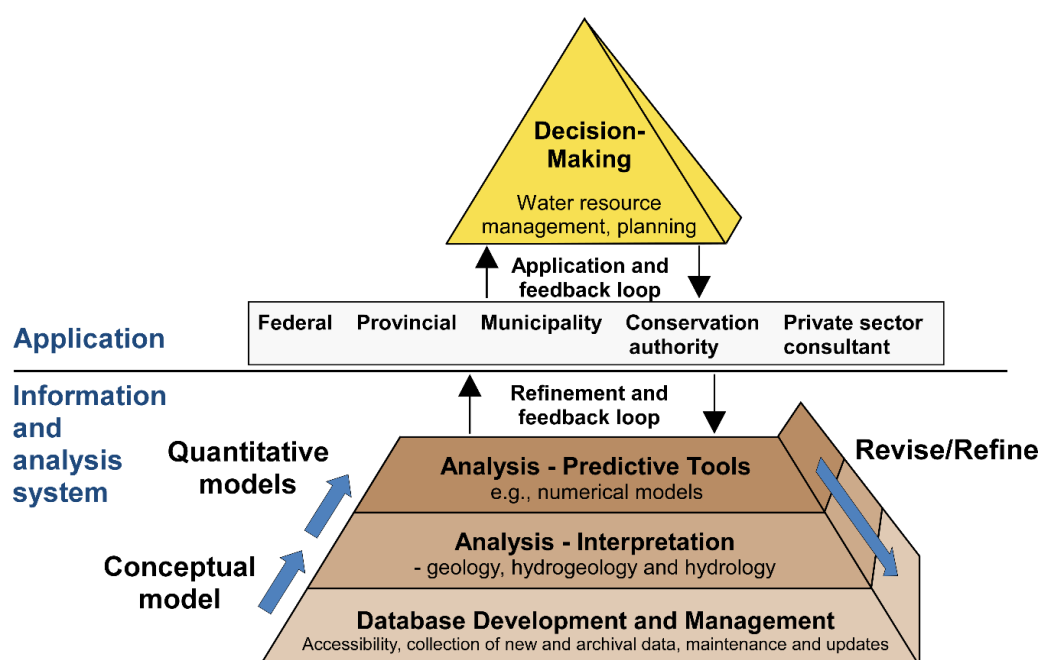


Figure 2 - System utilized by the Oak Ridges Moraine Groundwater Program for analysis and decision-making, and referred to in this book as *the pyramid diagram*. The diagram is modified from Sharpe et al., 2002 and CCA, 2009.

Also key to the system architecture is the pyramid's base, comprised of a robust database and database-management system that allows for the effective storage and retrieval of a wide range of water and subsurface data. There is a never-ending feedback loop that has ORMGP staff always challenging current understandings and perceptions as new data and reports become available and are incorporated into the program's holdings. The pyramid explicitly recognizes the many different players that collect and interpret data, make water management related decisions, and therefore are capable of both contributing to, and benefitting from the ORMGP. The incremental accumulation and synthesis of new data and ideas lead to a methodology that builds upon the overall understanding of the groundwater flow system.

Many societal decisions have long-term consequences for the groundwater flow system. Decisions that potentially impact groundwater resources are routinely made by all levels of government, the private sector, and even individual land and homeowners. These decisions are made at various spatial scales and are of varying importance to Ontario's groundwater resources. They can be made with the full recognition of the potential impacts of the decision on the groundwater system (e.g., water-permitting) or on an ad-hoc basis without due consideration of potential impacts on the resource (e.g., road-salt application). Access to data and information is of critical importance to maximizing the effectiveness of such decisions. Therefore, a key aspect is the evolution of ORMGP's interactive website such that all users, including professionals and decision-makers, have ready access to raw data, interpretations of the data, and additional knowledge they can apply to guide water-resource management and related decisions such as construction, land use change, and ecological management.

The way forward involves applying the data, information, and knowledge held in the ORMGP and bringing it to bear on as many decisions as possible.

1.2 The Transitions in Water-Related Decision Making

As the ORMGP evolves and the potential uses of its technology become recognized, there will be an ever-increasing demand to incorporate knowledge and insights from previous subsurface investigations and sophisticated numerical models into improved conceptual models and management decisions. As demonstrated through the ORMGP, a transition in water-related decision making is underway. Its key elements are summarized in Table 1. The transition is tied to how water-related societal decisions are made and more specifically to how Ontario society, largely through consulting works and reports, undertakes the technical assessments that serve as input to decisions.

Table 1 - The transitions in water-related decision making fostered by ORMGP

Transition away from...	Transition toward...
Technical staff working under tight-time/cost constraints to find paper-format reports holding relevant data/information.	Technical staff being able to readily discover relevant digital data/information/knowledge via the web with limited time and cost.
Data that are repeatedly compiled from multiple sources, checked for errors, and plotted for different investigations.	A single data portal for up-to-date data sets that are organized, verified, and plotted for repeated use in diverse investigations.
Data that are not placed into geological, hydrogeological, or watershed contexts and therefore require further interpretation.	Data and information placed in the context of current geological and hydrogeological conceptual models, thus requiring no, or minimal, interpretation.
Data that are generally of a short-term nature, such as isolated water levels and water chemistry from a report.	Providing better historical context with water level and chemistry data spanning many decades. Data from similar settings can be used to estimate conditions at new sites of interest.
Data that are limited geographically, which can lead to inadvertent omission of relevant data from consideration.	Owing to ease of access, relevant data from a broader geographical area are incorporated into study/decisions.

Transition away from...	Transition toward...
Incomplete technical knowledge through changing personnel with time, loss in accessibility of technical reports, or ignorance of previous work.	Knowledge preservation, creation, and communication.

This book shows how this transition leads to the merging and collectively interpreting disparate data that can then be harnessed to effectively build a more complete and comprehensive subsurface flow–system understanding. Independent of flow system understanding, the transition fosters improved data-driven decision making.

1.3 Important Steps in the Building of the ORMGP

Starting in 2001, a broad coalition of government agencies worked together through the ORMGP, defining a unique pathway that others can follow. This path has expended considerable resources and energy in first assembling and subsequently maintaining a comprehensive subsurface/water-related database that is at the core of the work. Significant steps and perceptions that drove the program are summarized here.

- Initial perceptions/concerns were that subsurface information was insufficient for making informed groundwater-related decisions. In the late 1990s, as urban development encroached onto the ORM, this was a key message. Many technical experts from local governments and watershed managers recognized the fragmentation of groundwater-related data. However, despite lots of discussion, it was thought that developing a coordinated information and analysis system was too daunting.
- Provincial funding to ORMGP in the early 2000s was allocated to data management and regional scale numerical modeling, which led to assembly of data from across much of the ORMGP study area. Data collected at the time, with assistance from partner agencies, was broad-based, including geological information, as well as surface and groundwater quality and quantity data. This required a robust data model to adequately host the information. The initial data-aggregation step took significant time and resources, but it was undertaken with a long-term vision. And it continues to this day. Eventually many bits of information were assembled over time to form a significant database that can now be used for many applications.
- Coincident with the above step was the interpretation of the data to build upon and refine the conceptual model of the groundwater flow system.
- In 2004, a ‘governance’ document was prepared to help guide the long-term continuity of the program. Amongst other things, the document weighed opportunities to leverage the communal ORMGP initiative and also set out responsibilities for both individual agencies as well as for the ORMGP collectively.
- From the beginning, efforts were made to collect new high-quality datasets to assess and further develop the geological and hydrogeological conceptual models.
- In 2008, a Memorandum of Understanding (MOU) was struck between the partner agencies to agree upon methodologies for the sharing and management of

hydrogeological data and information. The MOU has since been renewed on two occasions, with a ten-year duration for each. About 10 years into the program, perceptions began to change. With the assembly of so much data and information in the ORMGP, the question arose, “What does it all mean?” This led to the development of additional maps and graphs to convey knowledge more readily to practitioners.

- Beginning in 2015, the development of a map-based interactive website allowed for easier exploration of the vast data holdings in the ORMGP. This was combined with continued development and website posting of synthesis outreach and guidance products—e.g., water table maps, water budget analyses, graphical analyses of long-term temporal data, groundwater stories, and groundwater *Areas of Concern* memos.
- Continued expansion and refinement of web-based products incorporating additional knowledge such as numerical modeling insights (the [particle tracking](#)  map provides an example) allows users to interact with the ORMGP information, resulting in better-informed water-resource-management decisions.

Underlying the above steps is a critically important program element: making use of data. Many gigabytes of data can be assembled in a database, but a central question is regularly asked: “Can I rely upon the data?” One important QA/QC tenet of the ORMGP is that errors in the data become apparent most readily when making use of the data. Many such errors have been found in the ORMGP database ranging from measurement unit discrepancies, to shallow bedrock wells being incorrectly located in areas of known deep bedrock valleys, to water levels that are out of reasonable range. In all cases, the root of the error is sought by ORMGP staff and either corrected or flagged as unreliable, thus leading to a continually improved database. Importantly, changes are tracked within the database and often displayed on the ORMGP website.

A further strength of the ORMGP is the collaboration and integration of many partner agencies in the program. This includes municipalities, watershed authorities, provincial and federal ministries, and consulting companies. The ORMGP has fostered conversations and links have been strengthened. A greater understanding of the initiatives undertaken by different agencies leads to improved cooperation and allows for the sharing of information and data that over the longer-term leads to efficiencies and savings.

Integration of high-quality local data with all other data and information allows for the construction of regional models that are locally reliable. This data compilation allows the database and its interpretations to be scale independent.

Another important aspect of the ORMGP is development of a numerical model archive. The models can be used to analyze other hydrogeological scenarios for subsequent projects. Equally important, the numerical models serve as tools to test and refine the conceptual models. Model calibration efforts and results are an important part of the feedback loops outlined in the pyramid diagram—information and analysis system—in Figure 2. For example, where numerical models prove difficult to calibrate, this may

suggest needed refinements to interpretations shown on a lower pyramid level, including the necessity of further data collection, which is the foundation of the pyramid. Analysis using numerical models is an important component of ORMGP conceptual model refinement and testing.

The readily available data and knowledge that the ORMGP has assembled and generated can be applied to many local and regional water-resource management related studies and/or projects including, for example, water supply, infrastructure construction, land use change, or ecosystem needs. Avoidance of potential groundwater-related problems—e.g., artesian conditions—can also result.

A core goal of the ORMGP has always been to help foster better water management decisions in Ontario. The assembly, management, interpretation and overall accessibility of the broad-based data held under the program has indeed accomplished this. Associated with this goal is the considerable savings of time and money that comes along with the use of ORMGP data and knowledge.

2 Background

2.1 Rationale – Oak Ridges Moraine Groundwater Program (ORMGP)

The Oak Ridges Moraine (ORM) is a 160-km long, west–east trending ridge with sandy soils in south-central Ontario just north of the City of Toronto and the Lake Ontario shoreline (Figure 1). The ridge rises to a maximum elevation of approximately 400 m above mean sea level (masl), which is 325 m above the average Lake Ontario water level of approximately 75 masl. The ORM area contains a complex multiple-aquifer system within a region containing a mix of highly urbanized–industrial and agricultural land use known as the Greater Toronto Area (GTA), home to more than 7 million people ([Ontario population projections](#)[↗]). The moraine contains an elevated groundwater aquifer system that has often been dubbed the *rain barrel* of southern Ontario in recognition of how it provides baseflow to the many streams that emerge from its flanks. Aquifers associated with the ORM serve as important sources of drinking water and for maintaining stream baseflows. Understanding how this multiple-aquifer system functions is paramount to developing and enacting future sustainable water-resource-management policies, and for supporting a key economic engine of the Canadian economy.

The general area of interest, shown in Figure 1, encompasses a 30,000 km² area bounded by: large lakes to the south (Lake Ontario) and northwest (Georgian Bay of Lake Huron), uplands to the west (the Niagara Escarpment) and north (the Canadian Shield), and a lower elevation area (Hastings Municipality) to the east. The magenta boundary in the figure shows the extent of the Oak Ridges Moraine Groundwater Program (ORMGP) and is referred to as the “study area” for the remainder of this book. The study area extends well beyond the ORM upland landform (ORM area) in order to include all aspects of the flow system associated with the moraine including aquifers extending beneath and beyond the moraine area, and the entirety of stream networks emanating from the ORM upland. The ORMGP boundary has expanded over the years due to partner agency requests. The orange boundary shows the ORM upland and the extent of the Oak Ridges Moraine Conservation Plan (ORMCP, an area subjected to specific land use planning restrictions), which in this book is referred to as the “ORM area.” (Figure 1). Figures in this book frequently show both of these boundaries for ease of reference.

Sound conceptual models are necessary to support water-resource protection and management (Hinton et al., 2007). A groundwater conceptual model is a qualitative description of how the groundwater system operates (LeGrand & Rosen, 2000; Tóth, 1970) and incorporates an understanding of the topography as a driver of groundwater flow. It includes the source of groundwater, its movement through geologic materials, how it is stored, and where it discharges to surface water or the atmosphere. Also important is the

complex depositional setting and the distribution of the glacial water-bearing sediments that host the flow system. A sound conceptual model is key to understanding a flow system. This book describes the development of conceptual models for the study area (or portions of it), which are anchored by high-quality data that include borehole cores, surface geophysics, borehole geophysics, surficial geologic mapping, field hydrologic testing, and long-term groundwater level and groundwater quality records. Under the program, these data have been integrated and used to develop conceptual flow models for varying scales of investigation; from local to watershed to regional. The conceptual models, along with mathematical predictive models, allows management strategies to be evaluated and modified prior to implementation.

To plan for and enable effective water management, a high-quality, actively managed hydrogeological database provides a foundation for decision making as shown in Figure 2 (National Round Table on the Environment and the Economy, 2010). Referred to in the book as the *pyramid diagram*, the premise is that all elements of the water-resource-management system benefit from a solid foundation of information. The approach moves progressively from early database development at the base of the pyramid through interpretation and predictive/analysis tools at subsequent steps higher in the pyramid, including collation of collective groundwater knowledge. These steps lead to the development of a conceptual model which in turn, is subsequently “quantified” by developing analytical/numerical quantitative models of groundwater flow used to make predictions. Robust groundwater management should utilize some or all of the components shown in Figure 2. The models are always being tested and refined as new information becomes available. Adaptive management of water resources (decision-making) may lead to feedback loops requiring additional information and/or analysis to further refine the conceptual and quantitative flow models.

Recognizing the historical lack of a coordinated approach to collecting/managing data and establishing a hydrogeological framework, a leading-edge groundwater management program has been built over the past 20 years.

As a water-resource management program, the ORMGP was established in 2001 by a coalition of municipalities and conservation authorities (Georgieff et al., 2001; Holysh & Gerber, 2014). The program’s mandate is to collect, manage, interpret, and disseminate water-resource-related data and information as a basis for effective water resource stewardship. Program staff also build, maintain, and provide to partnered agencies the regional geological and hydrogeological context for ongoing groundwater studies and management initiatives within the study area. ORMGP staff compile information and refine the understanding of the groundwater flow system for the study area, while providing support to partner-led, water-related endeavors. A key strength of the ORMGP is that it provides a platform for ongoing water-resource management collaboration

between various federal, provincial, municipal government agencies, and those conservation authorities operating within the study area (Figure 1).

The systematic management of this knowledge is undertaken within a structure or template that provides this part of Ontario with a highly effective groundwater-decision support system. When used to support land use, water allocation, or other related decisions, the ORMGP data, interpretations, and knowledge base will lead to the maintenance of healthy and resilient groundwater resources and groundwater-affected ecosystems as the population increases and the climate changes. Further information on the ORMGP is provided in [Box 1](#) .

Perhaps most unique to this book, and of significant importance, is that the reader can interact with over 100 gigabytes of geological, hydrogeological, and hydrological data, and associated interpretations on the ORMGP website (www.oakridgeswater.ca ). The ORMGP website can be viewed as a living laboratory that can, and should be, used as a teaching resource. The site allows for instructors and students to work with real world data on real world problems.

2.2 Canadian Context

Prior to delving into the hydrogeology of the study area, let's look briefly at the Canadian context regarding water resources ([Exercise 1](#) ). Canada is the second largest country in the world by area (approximately 10 million km²) with a population reaching 40 million (Statistics Canada, estimate as of June 2023). The highest population density occurs in the south along its shared border with the United States, whereas much of the northern part of Canada is sparsely populated (Figure 3). Canada is divided politically into ten provinces and three territories. The provinces have significant power according to Canada's Constitution Act, while the territories negotiated with the federal government to have partial legislative authority. The management of water resources falls under a variety of legislative frameworks, leading to significant differences across the country (Rivera, 2014). For example, it is common for some provinces to delegate, at least in part, groundwater-management responsibilities to local municipal governments or other stakeholder groups. The management of groundwater resources in Canada is therefore fragmented among various agencies (Council of Canadian Academies, 2009).

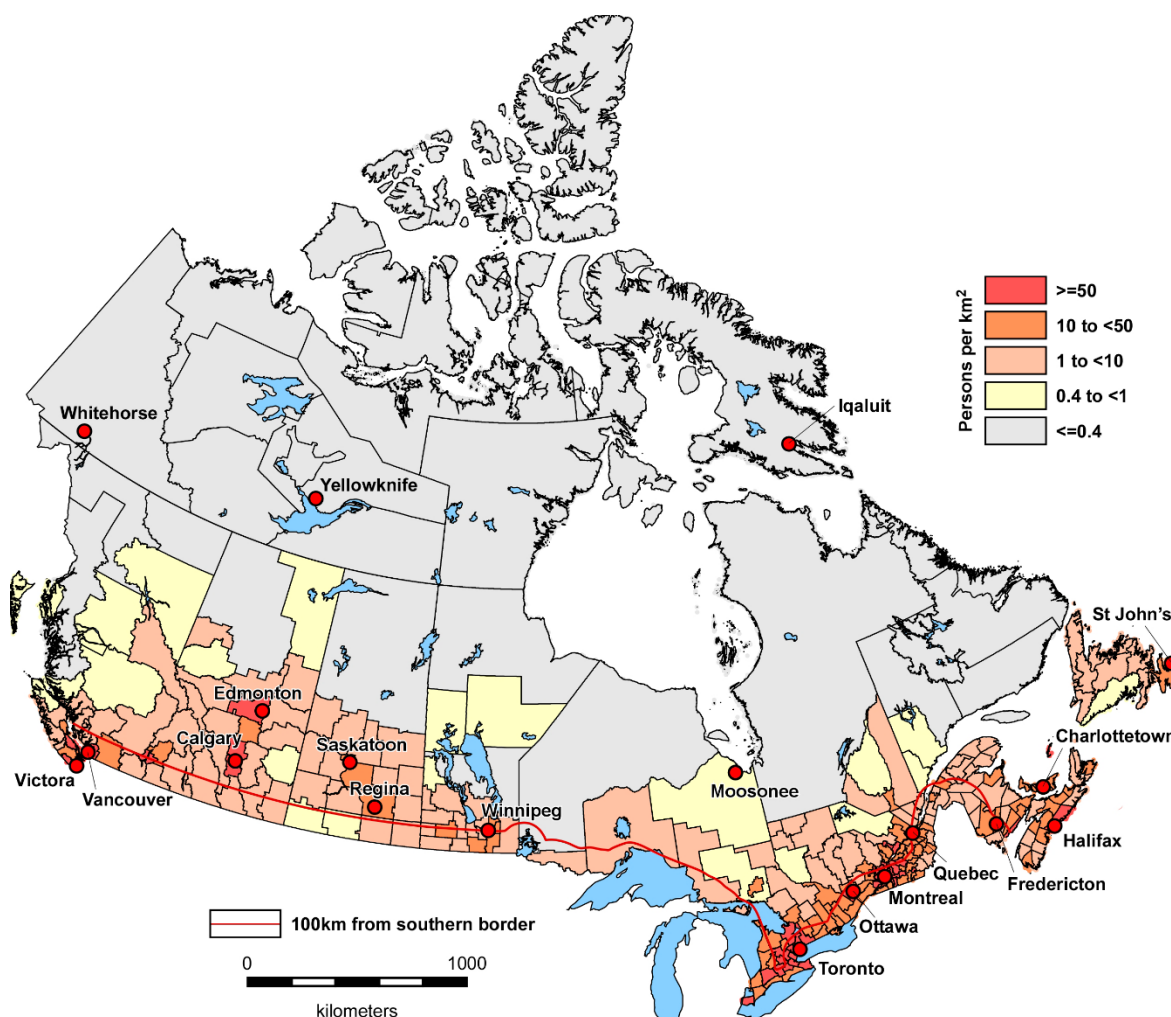


Figure 3 - Canada's population density (2016) by Census Division. Source: [Statistics Canada census](#)⁷. Boundary Files are from the 2016 census. Statistics Canada Catalogue no. 92-160-X; Geographic attribute file from the 2016 census—Statistics Canada Catalogue no. 92-151-X. The study area for this book (Figure 1) surrounds Toronto.

Canada's climate varies widely depending on geographic location. For example, much of the far north has frozen ground for most or all of the year (permafrost), whereas four distinct seasons occur in the south. Also, proximity to mountain ranges in western Canada and the Great Lakes in central Canada affect climate significantly. Across many parts of the country, precipitation exceeds evapotranspiration, leading to an abundance of freshwater resources in the form of lakes, rivers, and groundwater. Other areas, such as the interior of British Columbia, the southern prairies of Alberta, Saskatchewan and Manitoba, and the high Arctic, have arid or semi-arid climates where evapotranspiration exceeds precipitation ([Water in Canada](#)⁷).

Power generation, industrial/manufacturing, mining, and agricultural users are large consumers of water in Canada (Council of Canadian Academies, 2013; Rivera, 2014). While most Canadian water supplies come from surface water bodies and reservoirs, it is estimated that approximately 30 percent of country's population currently relies on groundwater for home use, including more than 80 percent of the rural population (Council

of Canadian Academies, 2009; Rivera, 2014). By comparison, in 1970 it was estimated that only 10 percent of the Canadian population relied on groundwater (Brown, 1967; Rivera, 2014). Figure 4 shows that groundwater use is significant in all of the Canadian Provinces and Territories, varying from 21 percent in Alberta and the Northwest Territories to 100 percent in Prince Edward Island (Rivera, 2014). Approximately 29 percent of Ontario's population relies on groundwater for their water supply.

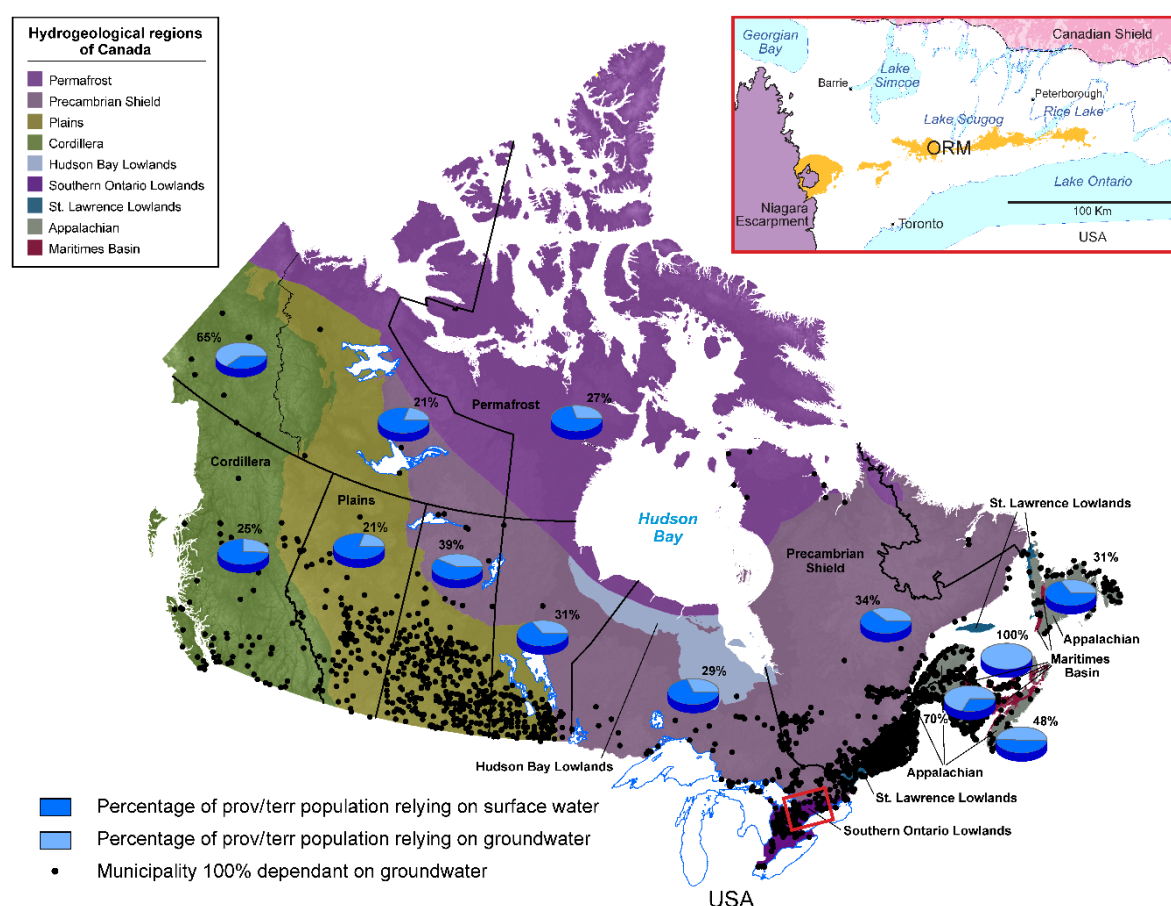


Figure 4 - Hydrogeological regions of Canada and estimated groundwater use in Canadian provinces (prov) and territories (terr). The red rectangle outlines the inset region showing the approximate location of the ORM. The study area for this book is shown in Figure 1. Background colors represent nine hydrogeological regions of Canada. This figure is modified from Rivera (2014).

2.3 Background – Historical Study Area Context

For the last 250 years, settlement area and population (Figure 5) have been expanding northward from the Lake Ontario shoreline in the Toronto area. In the 1780s, the British reassigned the Great Lakes Basin to be potential farming territory. In the 1790s, the first lieutenant governor of Ontario—then, Upper Canada—surveyed and cleared along Yonge Street in Toronto to make it a main artery for northward expansion from Lake Ontario. By the mid to late 1800s, much of the moraine area had been deforested for agricultural purposes, leading to soil erosion, groundwater level declines, reduced flow to springs, and flooding in downstream areas (Wood, 1991). In the late 1800s and early 1900s,

the provincial government began encouraging the planting of trees to alleviate erosion and flooding problems (Bacher, 2011; Carman, 1941); however, subsequent reforestation efforts were limited, and deforestation activity and its associated problems continued into the mid-1900s (Kuhlberg, 1998). Figure 6 shows the land cover distribution for the study area. Within the study area, agriculture covers 43 percent of the area, mixed coniferous–deciduous forests presently cover about 38 percent, urban settlement and roads covers 12 percent, and wetlands and lakes cover 7 percent.

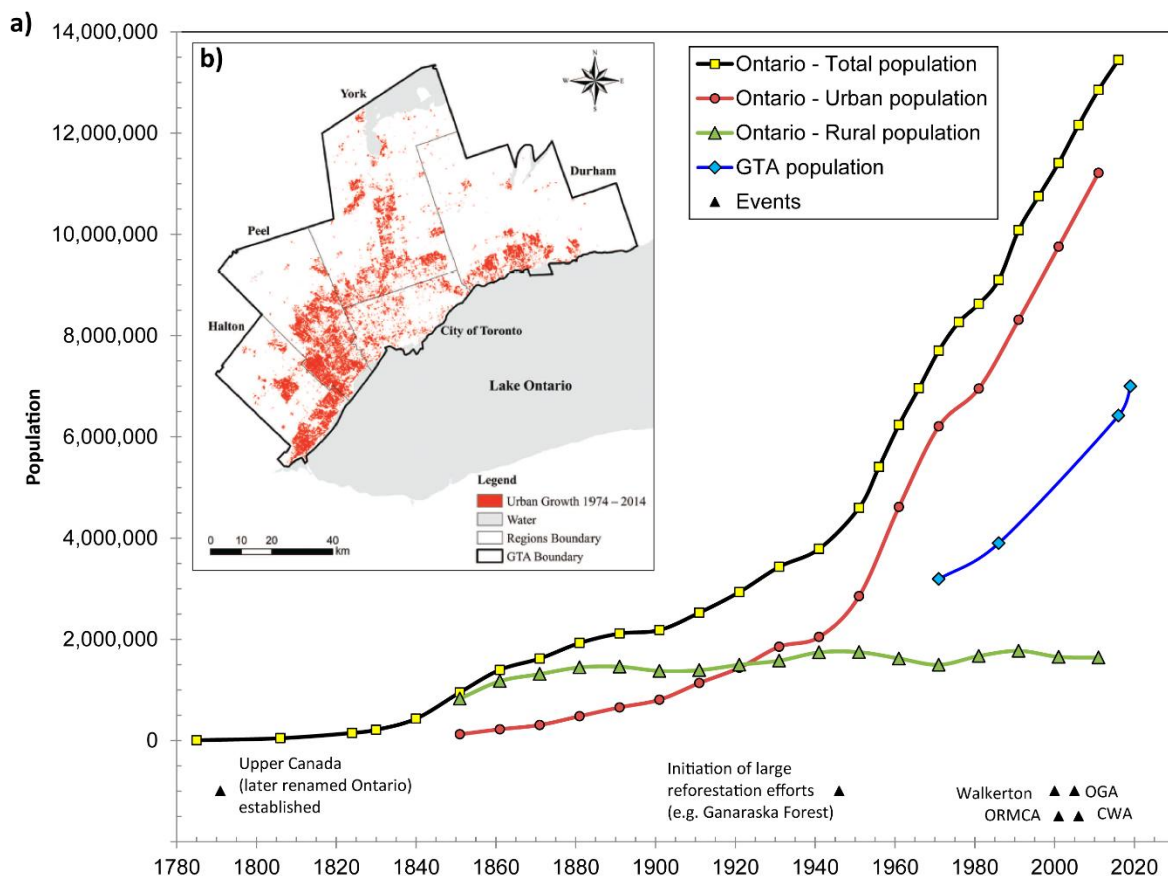


Figure 5 - a) Ontario Province and Greater Toronto Area (GTA) population trends (Source: Statistics Canada). **b)** GTA map area showing urban growth emanating north from Lake Ontario and the City of Toronto (inset figure from Wang et al., 2015).

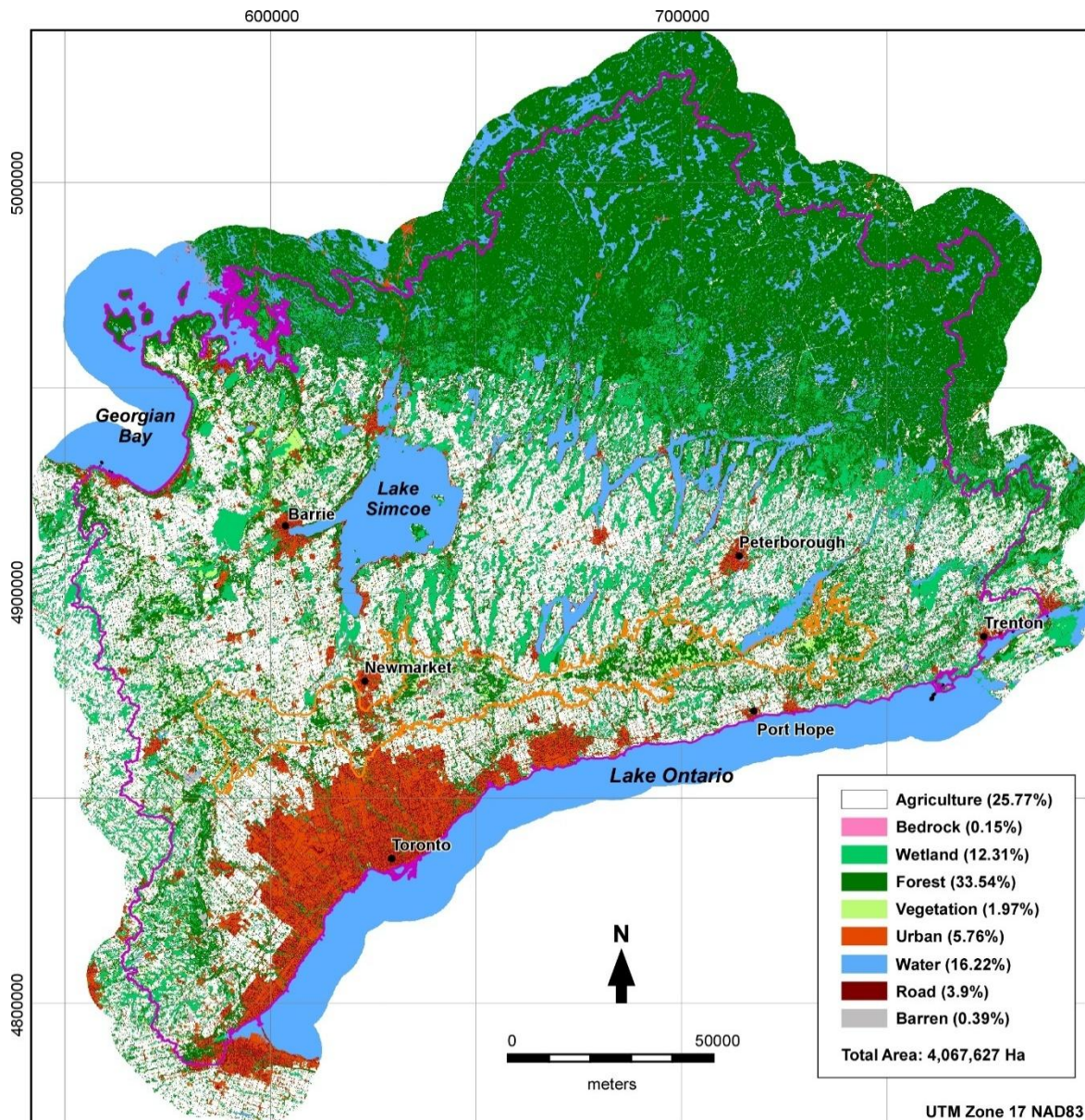


Figure 6 - Land cover within the study area. Data from the Southern Ontario Land Resource Information System, available from the Province of Ontario; SOLRIS v1.2, 2008, Ontario Ministry of Natural Resources and Forestry, 2008. Orange line delineates the surficial expression of the ORM upland and is also utilized as the ORMCP boundary, a planning boundary with policies aimed at controlling land use across the moraine. The magenta line is the boundary of the study area.

In 1946, Ontario implemented the Conservation Authority Act, which led to the formation of conservation authorities, watershed-linked government bodies that were charged with managing flooding and ecosystem loss (Shrubsole, 1990). The conservation authority mandate included soil and water conservation, forest management and reforestation, pollution abatement, and wildlife protection. Flood plain management and flood forecasting/warnings were added to the mandate following Hurricane Hazel in 1954. The current political climate is leading to a reassessment of conservation authority duties and core mandate (Mitchell et al., 2021; Mitchell et al., 2022).

Historical groundwater-resource investigations provide an early foundation for the development of the hydrogeological conceptual model for the study area. Early groundwater-resource inventories were conducted in the mid-1940s on a county or township basis by the federal government (Caley et al., 1947a, 1947b; Haefeli, 1970, 1972; Hainstock et al., 1948a, 1948b, 1948c, 1948d, 1948e; Hainstock et al., 1952). Subsequently, in the mid-1950s, the Ontario Water Resources Commission (OWRC) was established by the Province to manage water resources under a single government body (Scott, 1970). The OWRC evolved into the current provincial environment ministry in 1972. Key groundwater contributions from the OWRC and the subsequent provincial environment ministry for the study area were a series of major aquifer maps (Turner, 1977, 1978) and water-resource investigations on a watershed basis (Fligg, 1983; Funk, 1977; Ostry, 1979a; Sibul & Choo-Ying, 1971; Sibul et al., 1977; Singer, 1974, 1981; Vallery et al., 1982). Other key foundations in understanding the groundwater flow system relate to studies for: municipal groundwater supplies (International Water Consultants Ltd., 1991), proposed development applications, landfill investigations (Interim Waste Authority, 1994a, 1994b, 1994c, 1994d, 1994e, 1994f, 1994g, 1994h, 1994i), and infrastructure construction.

During the 1980s, large infrastructure expansion allowed for rapid urban growth toward and north of the ORM. Urban expansion often entailed associated localized groundwater quantity and quality issues. This expansion was accompanied by increased concern about threats to water resources in general and within the ORM in particular. A provincial environmental assessment advisory committee suggested there was a need for regional-scale planning that would take into consideration the ORM and surrounding areas. The committee advised that the ORM should be considered a provincial resource and managed as a single land use unit comparable to the Niagara Escarpment or the Lake Ontario waterfront (Wood, 1991). Recognizing the fragmented planning across the 14 local municipalities situated within and adjacent to the ORM, the Province ordered an intensive future land use study in 1989 that recommended the following (Kanter, 1990):

- a regional greenlands system of valleys, moraine, and other areas of natural significance, linked by a series of valley and ridge trails, should be established;
- extensive study of the ORM should be pursued; and
- planning for the ORM should be linked across municipalities and Ontario provincial ministries to limit urban development and the cutting of trees.

At that time, documented land use concerns related to water resources included: aggregate extraction, urban/suburban area expansion, golf course development, road salt application, waste disposal sites, and agricultural applications. Concerns were also expressed over the lack of environmental data and monitoring to evaluate potential impacts on the groundwater system (Intera Kenting Ltd., 1990).

Building upon these early background reports, the 1990s saw many regional groundwater investigations conducted utilizing both federal government funding by the

Geological Survey of Canada (Sharpe, Hinton et al., 2002) and provincial funding (Howard & Eyles, 1996; Howard et al., 1995; Hunter and Associates with Raven Beck Environmental Ltd., 1996). Considerable public debate regarding the role of groundwater in development planning on the ORM took place during hearings held by the Ontario Municipal Board in 2000. Provincial policy efforts culminated in new provincial legislation, including the Oak Ridges Moraine Conservation Act and Plan (<https://www.ontario.ca/page/oak-ridges-moraine-conservation-plan>) in 2001, and the subsequent overarching Greenbelt Plan in 2005 (OMMAH, 2005). The Oak Ridges Moraine Conservation Plan (ORMCP) was originally released in 2001 and updated in 2017 (OMMAH, 2017). The Greenbelt Plan covers a significant land area, encompassing both the ORMCP area and the Niagara Escarpment Plan area (Figure 7). The ORMGP was established in 2001 to collect and provide groundwater-related information to inform the above planning initiatives.

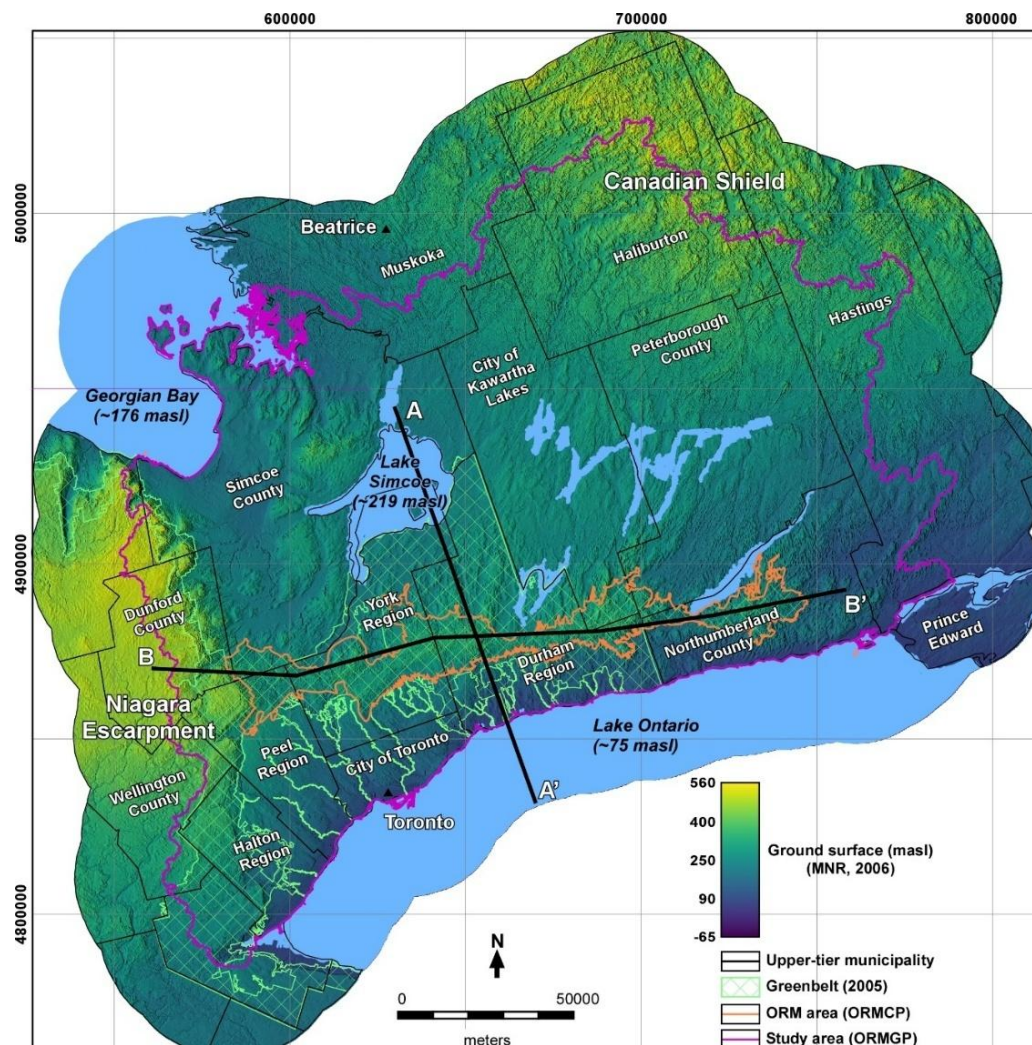


Figure 7 - Ground elevation (DEM) for the study area. The greenbelt (green hatch) includes the Oak Ridges Moraine Conservation Plan (ORMCP) and the Niagara Escarpment Plan areas. The Greater Toronto Area (GTA) includes the municipalities of Halton, Peel, York, Durham, and Toronto along the western half of Lake Ontario. The coordinates shown on the boundary are UTM NAD83 Zone 17. ORMCP is the Oak Ridges Moraine Conservation Plan boundary outlining the surficial expression of the Oak Ridges Moraine. The study area boundary is shown as a magenta line.

Recent and renewed efforts to protect Ontario's drinking water at the source were tied to an infamous drinking-water contamination event, a bacteria outbreak that resulted in seven deaths and over 2,000 illnesses in the town of Walkerton, Ontario, Canada, in May of 2000 (O'Connor, 2002). An inquiry into this event led to the establishment of the Provincial Clean Water Act of 2006 and the Source Water Protection (SWP) program, where the province and conservation authority partners work collaboratively to prepare and implement SWP plans aimed at protecting drinking-water supplies on a watershed basis.

In this rapidly urbanizing area of Ontario, municipal water supplies continue to shift from groundwater toward large lake-based surface water supplies, such as Lake Ontario, Lake Huron, and Lake Simcoe (Holysh & Gerber, 2014). However, there is recognition that groundwater remains an important resource for drinking water, agriculture, and industry, resulting in a continued need to understand, manage, and protect groundwater resources. Groundwater issues occurring within south-central Ontario and along the ORM emanate from increasing population and population density, along with an associated increase in urban area expansion. With this increasing urbanization, research activities and policy frameworks to better manage groundwater resources need to move forward in lockstep. While much has been done to alleviate data gaps within the study area, additional work is required. The effects of urbanization on groundwater resources are discussed further in Howard and Gerber (2018).

2.4 Book Overview

This book builds upon regional studies related to the Oak Ridges Moraine aquifer system. The major focus is on the key elements of the conceptual model—geology and hydrogeology—necessary to understand the groundwater flow system and to inform water-resource management decisions. All the water movements and exchanges encapsulated within the hydrologic cycle are described in this book, including those:

- to and upon the ground surface (precipitation and surface runoff);
- into the ground surface (infiltration/groundwater recharge);
- through the subsurface (groundwater flow); and
- discharging to surface water (mostly wetlands and streams) or by evapotranspiration to the atmosphere.

We describe methodologies that have been used to understand the groundwater flow system. These often have incorporated previous works (e.g., from some of the 15,000+ documents in the ORMGP library and from more than 100 groundwater numerical flow models documented in the ORMGP numerical model archive). The hydrogeologic function of the moraine flow system is then cast in the light of groundwater use, groundwater knowledge dissemination, and management initiatives aimed at protecting the resource.

Throughout the book, ample reference is made to further detail in publications (Section 10) and to the online data, interpretations, graphics, and mapping that constitute the foundation of the ORMGP (www.oakridgeswater.ca[↗]).

3 Setting

The general area of interest (Figure 1) encompasses a 30,000 km² area bounded by: large lakes to the south (Lake Ontario) and northwest (Georgian Bay/Lake Huron), uplands to the west (the Niagara Escarpment), uplands to the north and northeast (the Canadian Shield), and a lower elevation area (Hastings Municipality) to the east.

3.1 Physiography

Ground elevation of the study area is shown in Figure 7. The ORM upland is bounded by extensive plains of glacial till to the north and south, with uplands covered by till deposits and lowlands often containing a veneer of glaciolacustrine sediments.

Many physiographic regions including the ORM (Chapman & Putnam, 1984) have been mapped within the study area as shown in Figure 8. The use of physiographic mapping, while informative, is of lesser importance as detailed geologic mapping and digital elevation products such as LiDAR become available. The ORM region forms an upland separating the Lake Ontario drainage basin in the south from the Georgian Bay and Trent River drainage basins in the north and is the source area for many rivers and streams.

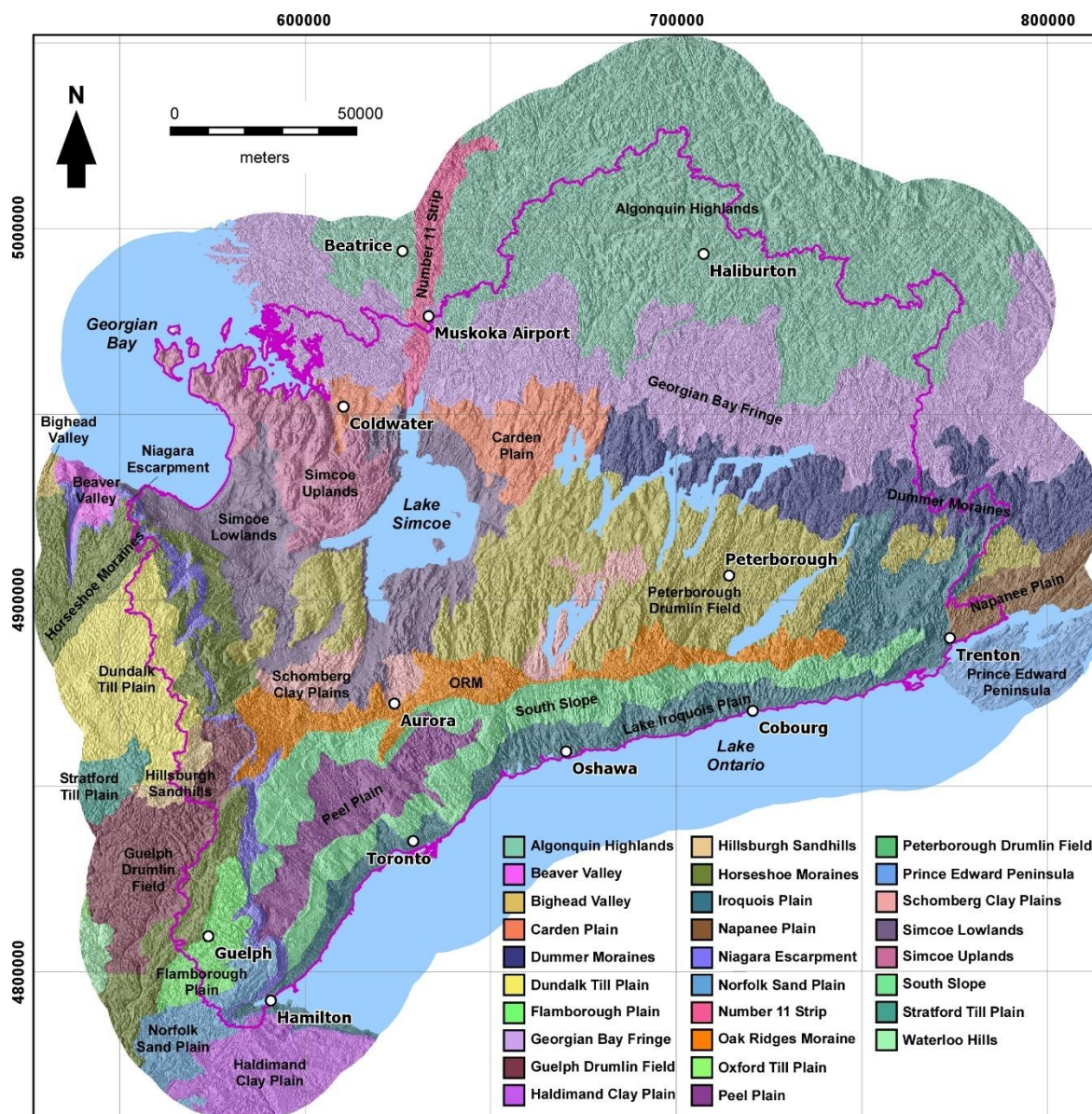


Figure 8 - Historic physiographic regions within the study area (map from Chapman & Putnam, 2007). The physiography of the study area can be further explored at www.oakridgeswater.ca within the Geology mapping theme. The boundary of the study area is shown as a magenta line. The ORM upland (orange) is flanked to the north by till plains including the Peterborough Drumlin Field and the Schomberg Clay Plains. The ORM upland is flanked to the south by till plains referred to as the South Slope. Lowlands on the flanking till plains are covered with a veneer of glaciolacustrine deposits (Peel Plain, Lake Iroquois Plain, Schomberg Clay Plain, and Simcoe Lowlands). Coordinates are in m as per UTM NAD83 Zone 17 projection.

On much of the ORM, the soils are mainly sandy loam, sand, or gravelly sand. As shown in Figure 8, northeast of the ORM is a rolling drumlinized till plain called the Peterborough Drumlin Field. To the northwest are the Schomberg Clay Plain and Simcoe Lowlands deposits, which overlay the tills and consist of stratified clay and silt within basins and river valleys. These soils are mainly fine sandy loam, reflecting the varied parent materials, which are carbonate rich. Many eskers and stream valleys trend north from the moraine. Till-covered uplands and glaciolacustrine lowlands surround Lake Simcoe.

Three physiographic regions occur south of the ORM between the moraine and Lake Ontario. Adjacent to the south boundary of the ORM is the extensive south-slope till plain that is locally overlain by glaciolacustrine veneer deposits of glacial lakes Iroquois and Peel. Lake Iroquois deposits occur along the Lake Ontario shoreline and consist of sands and silts with localized till islands. To the southwest, in an area between the ORM and Lake Ontario, are the Peel deposits that consist of silt and clay.

3.2 Climate

The study area climate is influenced by large lakes including Lake Huron and Georgian Bay to the west and Lake Ontario to the south, and by large elevated landforms including the Niagara Escarpment to the west, the ORM, and the Canadian Shield which is shown as Algonquin Highlands in Figure 8 to the north (Brown et al., 1980). Climate data across southern Ontario have not been summarized in quite some time; however, previous summaries are provided by Brown and others (1980), the Ontario Ministry of Natural Resources (1984), and Phillips and McCulloch (1972). Long-term climate data are available from [Environment Canada](#)[↗]. These data are readily accessible in graphical format, along with statistical analyses on the ORMGP web site (www.oakridgeswater.ca[↗]). The ORMGP website summarizes long-term temperature and precipitation data for stations with long-term climate data ([ORMGP-Data Snapshot-climate summary](#)[↗]) and are generally current within a week of the search date.

The ORMGP climate summary Data Snapshot shows that the mean annual air temperature for the study area varies from around 5 °C at the northerly stations inland from Georgian Bay—Beatrice, Muskoka Airport, Haliburton—to 9.9 °C in the south at the Hamilton station, located at the west end of Lake Ontario. This compares reasonably well to earlier reports of mean annual air temperature ranging from 5 to 9 °C (Farvolden & Cherry, 1988; Sharpe, Russell et al., 2014). Monthly average temperatures for an urban climate station (Toronto) and a rural climate station (Beatrice) are shown in Figure 9, illustrating the moderating influence of Lake Ontario toward the south and temperature regime differences between urban and rural areas. In general, stations nearer to Lake Ontario, especially in urbanized areas, have higher mean monthly temperatures and smaller daily fluctuations compared to northern rural areas. Average annual temperatures are slightly cooler to the west, east, and north, away from Lake Ontario.

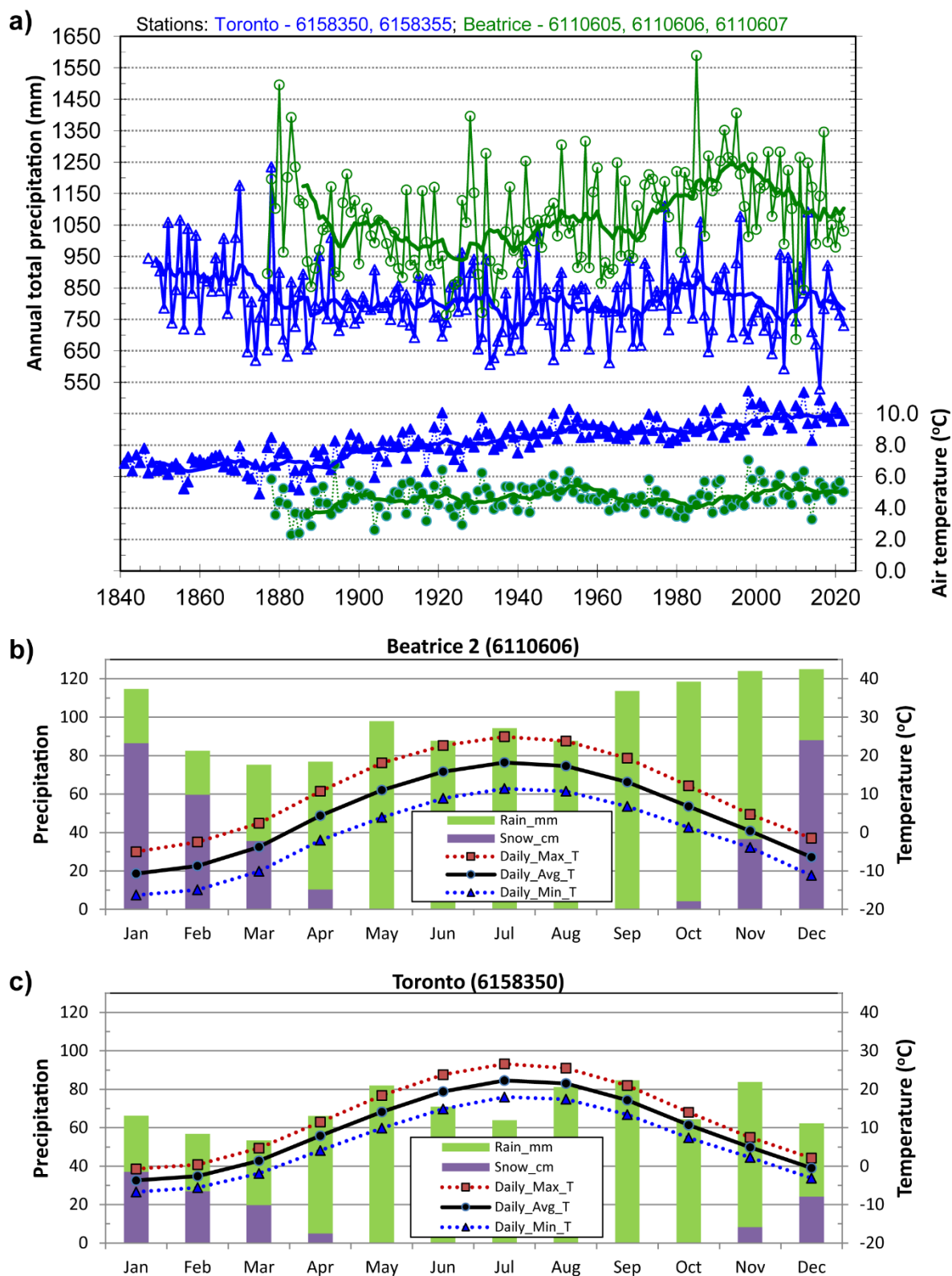


Figure 9 - Toronto and Beatrice 2 climate station observations. a) Historical annual precipitation and annual average air temperature for Toronto (urban, in blue) and Beatrice (rural, in green). Ten-year moving average lines for Toronto (blue) and Beatrice (green). Canadian climate normals 1981–2010 for b) Beatrice 2 (rural) and c) Toronto (urban). Data from Environment Canada. Station locations are shown in Figure 8. Climate data for the study area are available at [ORMGP-Data Snapshot-climate summary](#). The variability of the number of climate stations occurring over time can be evaluated at [ORMGP-Data Snapshot-Periods of Record – Climate/SW/GW](#).

The ORMGP climate summary Data Snapshot indicates the greatest annual average precipitation across the study area is 1,135 mm/year at the Coldwater Warminster station toward the north end of Lake Simcoe, and the lowest average annual precipitation of 710 mm/year occurs at the Oshawa Station to the east of Toronto. This compares favorably with earlier reported numbers of 700 to 1,100 mm/year (Brown et al., 1980; Farvolden & Cherry, 1988; Ontario Ministry of Natural Resources, 1984; Phillips & McCulloch, 1972; Sharpe, Russell et al., 2014). The Data Snapshot shows that higher annual total precipitation generally occurs to the north of the ORM as well as toward the west of the study area where the influence of the Great Lakes is greater. In general, stations closer to Lake Ontario tend to have annual precipitation amounts of less than 900 mm/year, whereas stations farther inland are frequently above 900 mm/year. Snowfall is lowest at stations along Lake Ontario, with Cobourg reporting an average of only 104.6 mm/year precipitation as snow, whereas Haliburton to the north reports an average snowfall precipitation of 285 mm/year. Readers are encouraged to go to the website and explore the graphs and statistical analyses available for various climate stations. Many charts and graphs, as well as the raw data, can be downloaded and/or printed (www.oakridgeswater.ca; [ORMGP-hydrograph explorer](#)).

The estimated mean annual potential evapotranspiration (PET) ranges from 560 mm along the moraine to 610 mm along the shore of Lake Ontario (Brown et al., 1980; Phillips & McCulloch, 1972). The mean annual actual evapotranspiration (AET) for the study area, is approximately 530 to 560 mm, reflecting areal variability in climate, vegetation types, and plant density (Brown et al., 1980; Phillips & McCulloch, 1972). Estimates of water surplus during periods of excess soil moisture range from 280 mm along the moraine highlands to 330 mm along the north and south flanks of the moraine. This water surplus reflects water that is available as surface runoff and/or groundwater recharge (Brown et al., 1980).

Greenland (1977) presents a more detailed analysis of the climate for the study area, including radiation and energy budgets for the period 1968–1970. The Great Lakes moderate the climate of the study area, cooling summer temperatures and increasing winter temperatures. Increases in precipitation are also observed downwind from the various Great Lakes (Scott & Huff, 1996). The increase in urbanization over the last few decades has contributed to an increase in annual mean temperatures within the western part of the study area (Mohsin & Gough, 2010), particularly in the Toronto area (Anderson et al., 2018) as shown in Figure 9. The anticipated impacts of climate change for Canada and Ontario are described further in Bush and Lemmen (2019) and Columbo and others (2007). Over the next few decades, it is estimated that southern Ontario will receive up to 10 percent less precipitation during the spring, summer, and fall, and up to 20 percent less precipitation during the winter (Columbo et al., 2007). As with many climate change projections, discrepancies exist between estimates of future precipitation trends. For

example, McDermid and others (2015), suggest that winter precipitation within the Great Lakes basin may increase.

4 Overview of Current Conceptual Flow Model

The large-scale architecture of the current, conceptual, flow-system model is illustrated by cross-sectional schematics (Figure 10) using a large vertical exaggeration (100:1). Figure 7 shows the ground elevations as well as the section lines for the cross sections shown in Figure 10.

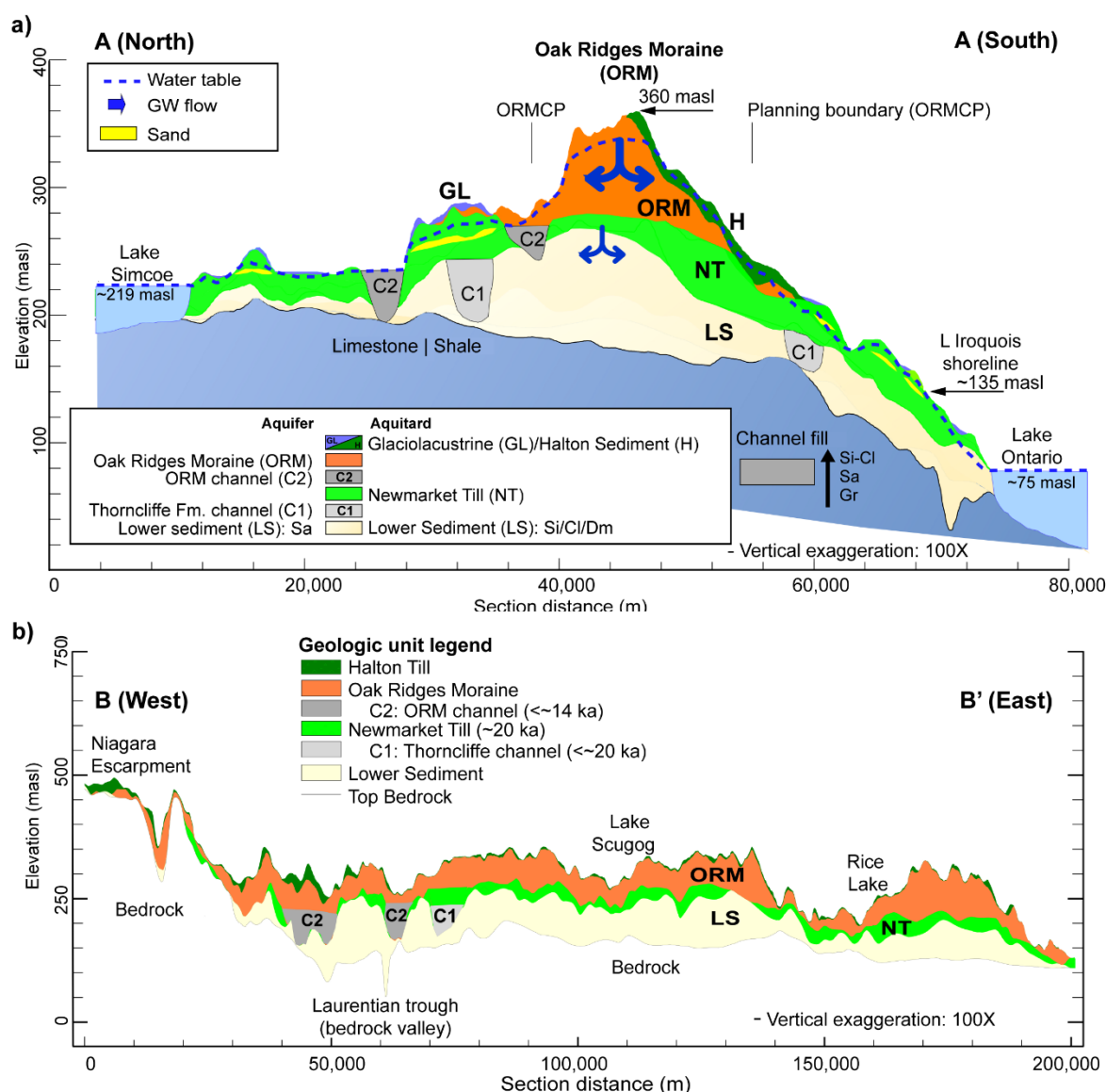


Figure 10 - Schematic cross sections illustrating major geologic units of the Oak Ridges Moraine hydrogeologic conceptual model. a) north-south cross section A-A'; b) west-east cross section B-B'. Cross section locations are shown in Figure 7. The sections are presented at different scales. Buried channels trend approximately north-south and are perpendicular to cross section B-B' and at an angle to A-A'. C1 channels were formed approximately 25,000 years ago and C2 channels are younger with an estimated age of 14,000 years. Bedrock in the study area mostly consists of gently dipping, unfolded Paleozoic sedimentary rocks. Overlying the bedrock are unconsolidated Quaternary glacial and interglacial sediments that can exceed 200 m in thickness, particularly beneath moraines and in buried bedrock valleys. Along river valleys closer to Lake Ontario, on the limestone plain to the east of Lake Simcoe (Figure 8), and in the uplands west of the Niagara Escarpment, glacial sediments can be locally absent with bedrock exposed at the surface. The blue dashed line in (a) is the trace of the water-table surface. Blue arrows show the general direction of groundwater flow and indicate that the ORM highland coincides with a regional west-east surface water and groundwater divide.

Physiographic/climatic, geologic, and hydrogeologic details are provided in Sections 3, 5, and 6, respectively. In this section, we briefly outline key components of the flow system which provide context for the details described in subsequent sections. Sound conceptual hydrogeologic models are necessary to support predictive analytical/numerical quantitative models used for decision making related to water-resource protection and management (Hinton et al., 2007).

Quaternary aquifer systems are subdivided into hydrogeologic terrains of *lower* to *higher* complexity based on sediment thickness and degree of heterogeneity (Haj et al., 2018; Yager et al., 2019). The ORM area is a higher complexity aquifer system based on its thick and stratified moraine sediment package. Stratified moraines are rare in glaciated terrain yet are common in southern Ontario (Sharpe & Russell, 2023). The stratified ORM is unusual in that it contains extensive, high-permeability sand and gravel aquifers surrounded by lower permeability sediments (Farvolden & Cherry, 1988). The lower permeability sediments include till deposits such as the Newmarket Till, and silt, clay, and diamict layers within the Lower Sediment unit (Figure 10).

The ORM functions as an elevated reservoir. It stores and distributes water from sandy uplands, via surface and subsurface flow, to Georgian Bay, Lake Simcoe, and the Trent River system in the north and to Lake Ontario in the south (Figure 10a). The water-table surface tends to be a subdued reflection of the overlying land surface and regional groundwater flow directions are typically in the direction downward topographic slopes.

A simplified hydrogeologic characterization of the moraine consists of aquifer and aquitard complexes that control the ORM flow system. These hydrogeologic units occur within the Quaternary-aged sediments deposited over the last approximately 135,000 years. The major shallow aquifer complex includes the ORM landform and associated higher-permeability ORM channels. The ORM ridge landform contributes flow to headwater streams and, together with the underlying ORM buried channels, forms an integrated complex of aquifers and streams that convey water flow away from the ORM uplands (Sharpe et al., 2007). The upper aquifer complex is separated from the deeper aquifers by the Newmarket Till aquitard, which forms a regionally continuous, thick marker bed deposited during the last glacial maximum approximately 20,000 years ago.

The Lower Sediment is thickest in the western part of the study area within the Laurentian bedrock trough and in uplands west of Lake Simcoe (Figure 10b). It contains extensive silt and clay sediments across the study area, with some areas having more silty sand—e.g., the uplands west of Lake Simcoe; the eastern half of the study area—typical of facies changes associated with subaqueous fan deposition emanating from surrounding upland source areas (Gerber et al., 2018; Sharpe et al., 2024). The Lower Sediment muds, together with the Newmarket Till, generally restricts vertical groundwater flow.

Within and beneath the Newmarket Till are important aquifers associated with glacio-lacustrine and/or glacio-fluvial Lower Sediment deposits (Figure 10). The most important and highest permeability zones (gravel) occur within buried glacial channels, which serve as significant water-supply aquifers. An extensive north–south trending deep bedrock valley—the Laurentian Trough—stretches more than 100 km between Georgian Bay and Lake Ontario and contains a multitiered glacial sediment package with high permeability gravel aquifers.

Three regionally extensive aquitards control groundwater flow to the identified aquifers (Figure 10): 1) Halton sediment (muddy till) and surficial glaciolacustrine deposits; 2) Newmarket Till; and 3) silt, clay, and diamict sediments present within the Lower Sediment package. The Halton sediment complex laps onto and partly confines flow in the upper ORM aquifer, helping to produce springs at the topographic break on the moraine flanks. Newmarket Till forms a regional aquitard below the ORM landform and generally restricts downward groundwater flow. However, at some locations, buried channels breach this aquitard and provide possible hydraulic connections from the upper ORM aquifer to deeper aquifers within the Lower Sediment. The Lower Sediment aquitard is composed of low permeability silt and clay deposits, older tills in the north, and glacio-lacustrine muds and muddy diamictos.

There can be enhanced permeability at the contact zone between thick sediment and bedrock, which is more common in the north where the bedrock is limestone compared with the south where the bedrock is shale ([Exercise 2](#) .

Further development and refinement of the study area conceptual flow model are provided in subsequent sections (Sections 5 and 6).

5 Geological Framework

5.1 Introduction

A sound geologic framework is an essential component of the conceptual model of a groundwater flow system. ORM groundwater stakeholders first met in 1993 to form an open partnership and collaboration to assess the geologic framework and groundwater resources for ongoing stewardship and development. From this initial meeting over 30 years ago, the geological framework, research methods, and knowledge accumulation have evolved significantly with contributions from the Geological Survey of Canada (GSC), the Ontario Geological Survey, university researchers, consultants, and since 2001, the ORMGP. As part of this collaboration, the GSC initiated a regional hydrogeological study and a detailed geological mapping program—part of the National Mapping project—to investigate the ORM (Sharpe et al., 1999). The GSC initiative encouraged interested parties to collaborate, fund, develop methods, characterize the terrain, and contribute understanding on the origin and hydrologic function of the ORM landscape (Robertson, 2017).

A preliminary geological model presented at the 1993 inaugural ORM groundwater stakeholders meeting signaled the need to develop a geological framework to support groundwater studies across the ORM region (Sharpe et al., 1994). Early versions of the geological framework were tested during a series of field trips (Sharpe & Barnett 1997; Sharpe et al., 1994; Sharpe et al., 1998). In this section, we trace the progression of the geological framework, highlighting the importance of Great Lakes glaciation in the formation of the ORM, and the significance of glacial geology and basin analysis methods to groundwater studies. We present an overview of basin analysis methods followed by the introduction and evolution of the stratigraphic sequence that provides the backbone of an evolving geological framework for the ORM ([Exercise 3](#), [Exercise 4](#)).

5.1.1 Importance of Glacial Geology and Basin Analysis to Groundwater Management

Managing Canada's groundwater resources in a sustainable manner requires regional knowledge of geological systems (Rivera, 2014). To obtain this knowledge, basin analyses were undertaken, which employed multiple approaches and scales to map, characterize (Sharpe, Hinton et al., 2002), and improve the understanding of groundwater systems in the ORM (Gerber et al., 2018). Geological models were developed by integrating high-resolution surficial and subsurface geophysical, geochemical, and geological data. The application of basin analysis methods helped to identify a network of large surface and buried channels that dissect the landscape (Sharpe et al., 2018) and provided data to formulate new geological concepts of the ORM glaciated terrain (Barnett et al., 1998; Pugin et al., 1999). Furthermore, the improved geological understanding led to hydrostratigraphic

frameworks and associated hydrogeological models that support groundwater management (Section 6). This geoscience approach and significant interagency coordination contributed to the development of new legislation for water and land resources planning in the ORM area, such as the Oak Ridges Moraine Conservation Act of 2001.

5.1.2 Glaciation and the Great Lakes Basin

During the last approximately 2.6 million years (Quaternary period), continental glaciers advanced and retreated over numerous cycles, affecting all of Canada and the northern portions of the U.S. (Fulton & Prest, 1987). Continental glaciers eroded, transported, and deposited glacial sediment across the landscape (Alley et al., 1997). The ORM, for example, formed ~13.5 ka years ago (Barnett et al., 1998) near the southern extent of a continental ice sheet (Prest et al., 1968) with influence from the complex geological and topographic setting of the Great Lakes Basin (Hough, 1958; Eyles, 2002). Glacial dynamic forces in the Great Lakes Basin were influenced by bedrock geology and physiography, such that large lake depressions and escarpments affected glacial flow and water routing across the region. Sediment thickness, distribution, and composition were also influenced by ice flow across differing geology—i.e., metamorphic versus sedimentary rocks—as well as by the role of blocked and released drainage from the large Great Lakes watershed. The effects of glaciation present a progression of regional basin, landform, and sediment scales of investigation. For example, at the regional scale, basin geometry, topography, lithologic provenance, and sediment thickness are important elements that are shown to influence groundwater flow systems (Anderson et al., 1999; Tóth, 1963).

5.1.3 Study Approach in Glacial Landscapes

The variability in scales of Great Lakes glacial landscapes calls for a regional approach to geological and hydrogeological investigations that promotes integrated geological analysis of a basin (Fogg, 1986; Freeze & Witherspoon, 1967). Capturing regional patterns of landscape and sediment variability traditionally requires information specific to depositional successions within bounded strata – lithostratigraphy (Walker, 1992). Equally important yet often missing, is information on the extent and geometry of erosional discontinuities (Shanmugam, 1988) highlighted in sequence stratigraphy (Brookfield & Martini, 1999; Martini & Brookfield, 1995). These stratigraphic elements control the architecture and continuity of geological units and the regional patterns of sediment permeability. These primary elements of the geological framework need to be considered for geological model development and hydrogeological study. Basin analysis methods can be implemented to address the geological hierarchy in glacial landscapes and they have enhanced the characterization of the range, structure, and properties of ORM stratigraphic elements.

5.2 Basin Analysis Approach

5.2.1 Methods

Basin analysis is a well-developed multidisciplinary, multi-scaled approach that integrates diverse geological elements in investigations of complex sedimentary environments (Eyles et al., 1985; Miall, 2000). This approach encourages researchers to describe the sediment, processes, and history of the basin. It also provides consistent mapping, stratigraphic correlation, and nomenclature across the required basin scale. The approach combines stratigraphic architecture, landform patterns, and sediment facies with paleocurrent analysis and provenance trends, key components in characterizing a basin (Sharpe, Hinton et al., 2002).

The basin analysis approach of the Oak Ridges Moraine supports the progression from data collection and compilation to geological conceptualization and the development of a regional geological model (as shown in Figure 3 of Sharpe, Hinton et al., 2002) and a pyramid strategy for water-resource management as shown in Figure 2. Meaningful steps in the geological progression relate to database assembly, map compilation, conceptualization, and demonstration of how basin-analysis methods were used to advance primary stratigraphic, architectural, and depositional models for the ORM area.

ORM data were assembled and organized in a comprehensive database (Logan et al., 2006). Both archival and new high-resolution surface and subsurface geological, geophysical, and geochemical data were gathered and integrated within a reference digital elevation model (DEM). A DEM provides accurate coordinates to all land surface observations and map units, and elevations that can then be extended to all stratigraphic layers, which are key steps in producing a three-dimensional geological model. These data components were stratigraphically coded within the ORM database to allow for ease of review, editing, and updating as data collection progressed (Logan et al., 2006). The resultant analysis and early conceptual geological models guided strategic data capture that targeted newly revealed subsurface geometry, sediment architecture, and facies trends. Of significance, the data collection focused on the identification and characterization of a network of erosional meltwater channels and their sediment infill, hypothesized to have scoured the study area (Brennand & Shaw, 1994). As data collection proceeded (Barnett et al., 1998; Pugin et al., 1999), new glacial process models of the regional landscape and landform patterns were developed, incorporating site-specific sediment data and observations at a range of scales. These concepts fundamentally altered the geological understanding and methods of studying ORM glaciated terrain (Barnett et al., 1998), advances that were later shown to have significant hydrogeological implications (Gerber et al., 2018).

ORM basin analysis workflow progressed from surface geological mapping to subsurface geophysical surveys—seismic profiles and borehole probes—to

continuous-core drilling and sediment logging, complemented by laboratory testing and analysis of sediment properties. We introduce the main methods and then provide a detailed description of ORM geology in Sections 5.3 and 5.4, leading to model construction. Interpretation of the data was completed within a knowledge framework developed from modern analog sedimentary basins (Russell et al., 2007) and specific glacial processes from active Icelandic glaciers that experience catastrophic flooding (Roberts, 2005). These essential components were used to build a stratigraphic framework and a geological model of the glaciated basin containing the ORM.

5.2.2 Basin Analysis Development for the ORM Region

The following basin analysis methods were used to develop the geological framework for the ORM region.

Geological mapping

Traditional geological maps are two-dimensional descriptions of land surfaces, which can provide a basis for conceptualizing the processes that produced those surfaces. Due to the sparsity of data in many areas and the need for interpretation, maps are created by field researchers who can visualize geology and create conceptual models.¹ Thus, geological maps effectively provide a spatial summary that builds and communicates information on physiography, landforms, lithology, and stratigraphy, map attributes that can be combined to build a conceptual geological model of a glaciated basin (Sharpe & Barnett, 1997). These traditional maps—those prior to the 1990s—were often developed from roadside surveys (Chapman & Putnam, 1943, 1984, 2007) combined with visual interpretation of aerial stereophotography (Barnett et al., 1998). More recently, the use of digital elevation models has allowed for enhanced terrain analysis and feature identification in a digital form (Kenny et al., 1999), resulting in the production of improved digital terrain models. These models often incorporate field probing and sampling to 1-m depth to add soil, textural, and sediment data to the tonal patterns on photo-imagery and to the detailed digital topography.

Figure 11 from Sharpe and others (1997) is a simplified surficial geologic map of the ORM area based on data collected at a density to support a 1:20,000 to 1:50,000 map resolution, but is shown on the figure at a base map scale of approximately 1:250,000. This new scalable sediment-landform map is based on approximately 25,000 field observations

¹ Each geological unit has an implied model of formation, or an explicit conceptual process model. Such models, when tested, support the extrapolation of unit properties and variability across a study area. Consider some basic examples: till units result from erosion and deposition of rock particles by glaciers to produce a mix of fine to coarse materials; sand and gravel units originate mainly from water flowing in stream channels; glaciofluvial sediment originates from glacial meltwater.

and sampling sites linked to coordinate-referenced field locations. The digital map set provides the densest observational record of sediment properties and surface geological information available continuously across the ORM area. Hence, the map represents the best supported regional stratigraphic and hydro-stratigraphic layer. The page or printed map obscures unit variability; however, queries of the field site database capture and allow quantification of unit heterogeneity. Site data also include soil descriptions and weathering features that affect geological and hydrogeological unit properties. Given the high geological variability regarding glacial landscapes (Cummings et al., 2011), this high-density map data helps to develop a comprehensive geological framework.



Figure 11 - Simplified surficial geology map of the ORM area. The map is set on an elevation model of the ORM region and shows the main geological units that can be linked to landforms, soils, and surface hydrology. The surficial geology layer (1-2 m) also forms a building block for the ORM stratigraphic model (Figure 12) through links to subsurface structures such as buried channels. Dashed lines show where meltwater channels eroded through or into the Newmarket Till exposed to north and south of the ORM. The ORM is associated with four main sediment wedges—Albion, Bloomington, Pontypool, and Rice Lake, which are located on the map. Each wedge consists of esker-fan sediment bodies. B: Brighton; CB: Cook's Bay; HM: Holland Marsh; SB: Scarborough Bluffs; HV: Humber Valley. Drumlins are identified with short dashes. Red lines and orange dots mark the sites of seismic profiles and cored boreholes. The black line from CB to SB and the orange from the Niagara Escarpment to the Nobleton area locate cross sections shown in subsequent figures. The dashed red line is the post-glacial Lake Iroquois shoreline.

Geological mapping is guided by an evolving stratigraphic model. Hence, the ORM geology map offers a stratigraphic prototype. The set of geological map units in Figure 11 are listed from oldest (1) to youngest (5) on the stratigraphic section shown in Figure 12a. The map (Figure 11) indicates that the once-continuous Newmarket Till is truncated regionally by channels (dashed margins) that result in drumlinized uplands adjacent to channel lowlands. In turn, ORM sandy sediment overlies channels and straddles Newmarket Till uplands (e.g., near Rice Lake); this indicates that ORM sediment overlies, and is younger than both channels and eroded Newmarket Till, that together form a regional unconformity (Figure 12a). These stratigraphic relationships present evolving

geological concepts, such as channel erosion, fill, and till sheet dissection that alter sediment continuity, architecture, and unit geometry.

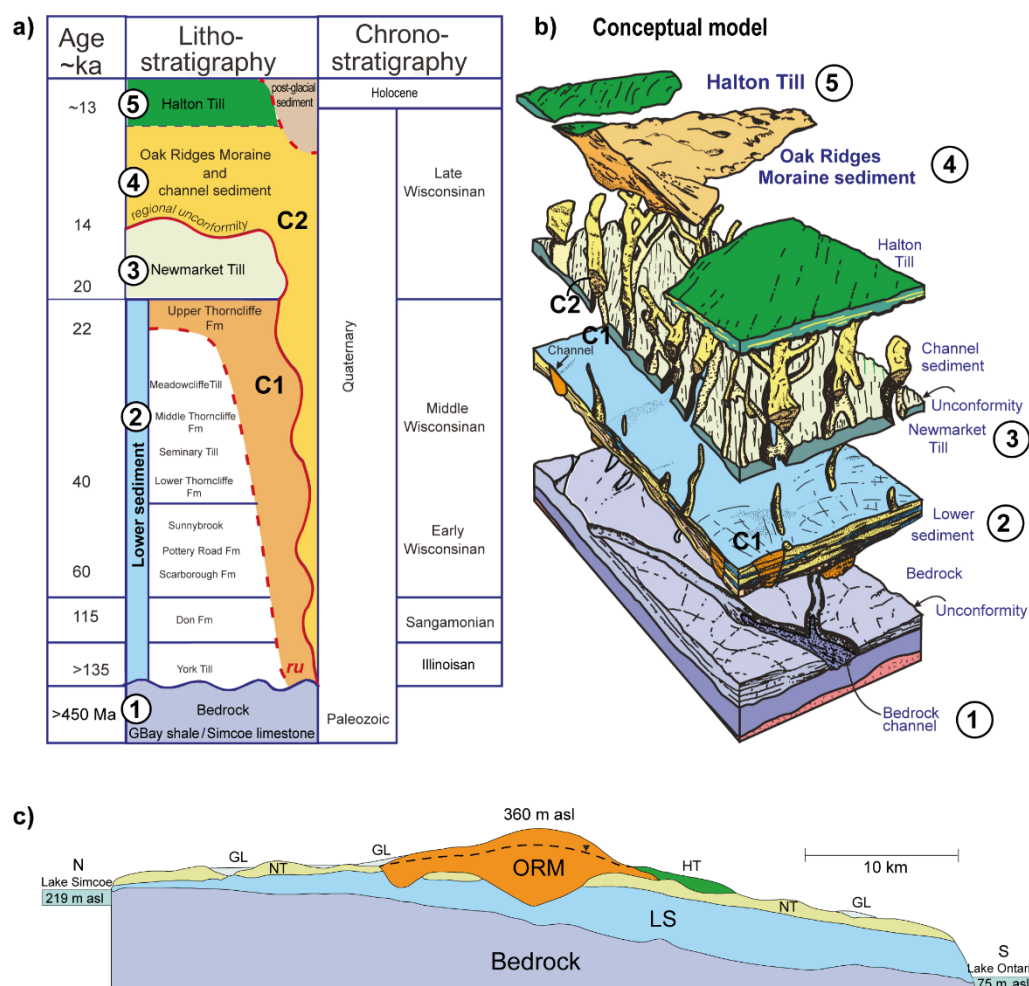


Figure 12 - Conceptual geological model of the ORM area. a) Stratigraphic column compiled by stacking the map units in order from oldest (1) to youngest (5). The approximate ages are listed in the left-hand column (Barnett, 1992; Berger & Eyles, 1994). Lower Sediment subunits (2) are listed under litho-stratigraphy and mainly occur at or near the Scarborough Bluffs (Karrow, 1967). There are two ages of channel fill; Thorncliffe (C1) sediments approximately 21 ka and ORM (C2) sediments approximately 13.5 ka. The stratigraphic section shows diagrammatically that these buried channels are eroded into underlying stratigraphic units and can extend down to bedrock. The unconformities are shown as solid and dashed red lines. b) three-dimensional perspective conceptual geological model of the ORM region. c) Simplified N-S cross section of the four main units between Lakes Simcoe and Ontario (section location N-S in Figure 11). HT: Halton Till; NT: Newmarket Till; ORM: Oak Ridges Moraine; LS: Lower Sediment. The Halton Till equivalent north of the ORM is locally called Kettleby Till (not discussed). Not shown are local buried channels with glacial-fluvial fills (C1 and C2) that can extend downward as deep as bedrock. Data sources are summarized in Sharpe et al., 2018.

Surface geology maps expand the stratigraphic record through links to subsurface data. This includes observations from measured sections at river and lake bluffs, and from borehole records (discussed in a later section). Appropriate depth information on the Newmarket Till map unit, for example, turns a two-dimensional aerial model layer into a three-dimensional model volume. Figure 13 is a set of regional maps showing bedrock geology, bedrock topography, and sediment thickness that can be derived from merging surface-subsurface geological data. These maps portray a first order stratigraphy.

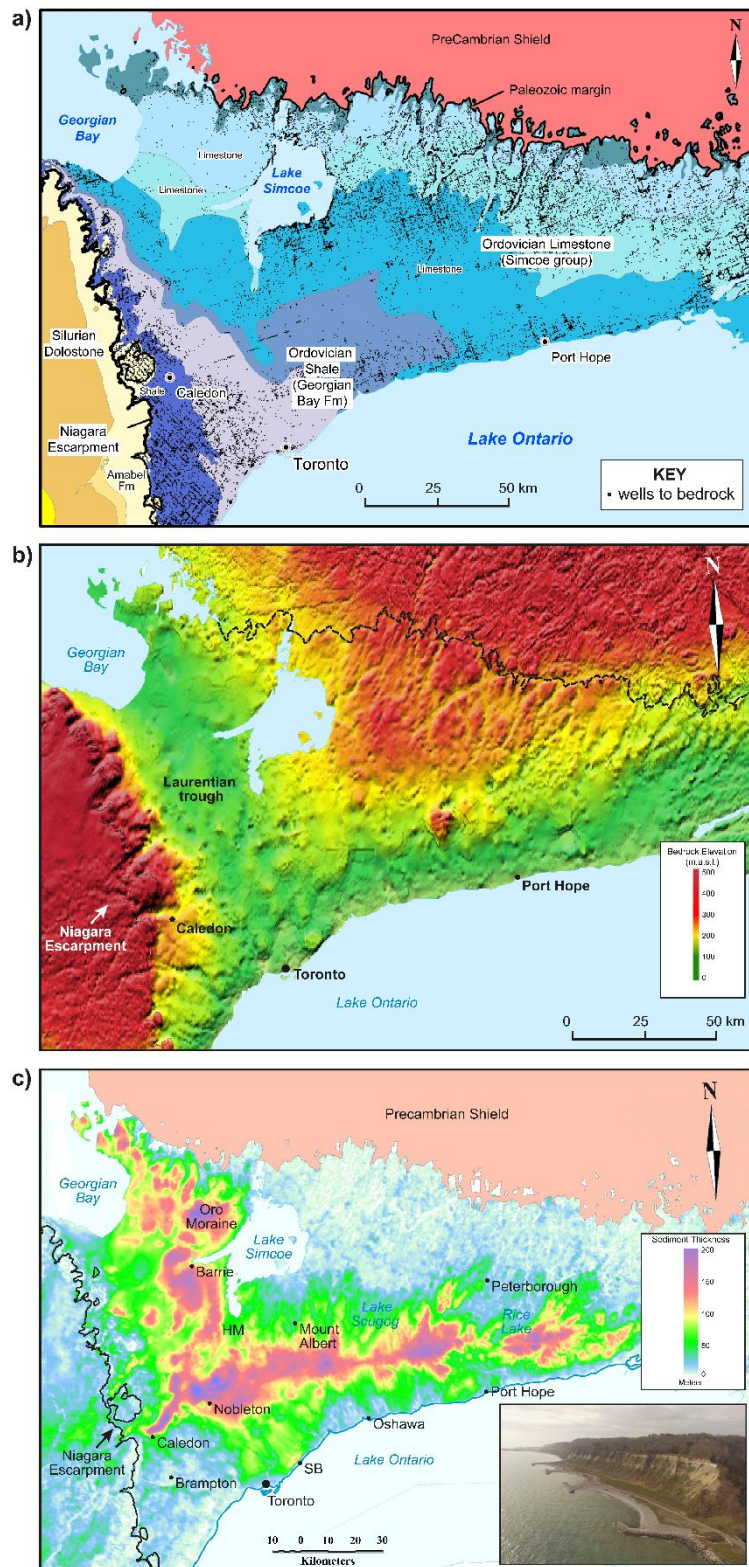


Figure 13 - Regional geological setting. a) Bedrock geology with Precambrian Shield crystalline rocks underlying Paleozoic Ordovician limestone and shale, and Silurian dolostone above the Niagara Escarpment (NE) and black circles show locations of wells drilled to bedrock. b) Bedrock topography showing a large buried valley (Laurentian Trough) from Georgian Bay to Toronto. Silurian (Amabel) dolostone caps the NE. Ordovician (Georgian Bay) shale occurs in the Laurentian Trough below the NE, and limestone sub crops east of the Trough. c) Sediment thickness is greatest in the Laurentian Trough and across the ORM highland ridge from Caledon to Rice Lake. The inset photograph shows thick sediments exposed at the Scarborough Bluffs (SB) (Data from Armstrong & Dodge, 2007; Gao et al., 2006; and Logan et al., 2020).

Geological learning progresses as each map unit (Figure 12a) contributes to developing geological concepts and two-dimensional models (Figure 12b). Digital geological and elevation mapping supports stratigraphic representations, understanding of sedimentary processes, and preliminary characterization of the hydraulic properties in surface sediments (Sharpe, 2022). Map features are then extended vertically downward using subsurface geophysical surveys and continuous sediment core drilling.

Geophysical measurements

A valuable addition to developing a stratigraphic framework was the implementation of subsurface geophysical surveys that collected high-resolution seismic reflection profiles (Pugin et al., 2018) and borehole geophysical logs (Crow et al., 2018; Sharpe, Pugin et al., 2003). ORM seismic surveys were designed to test an emerging conceptual model that predicted the presence of buried north-south channels across the area (Barnett, 1990; Brennand & Shaw, 1994). Accordingly, seismic profile lines of varying length were positioned along E–W roads to cross the inferred N–S channel orientations. Longer seismic surveys of 5–10 km were also completed across full channel widths to develop complete channel cross sections. Early seismic surveys from the 1990s used roadside ditches with individually placed geophones and shotgun/hammer energy sources to gather signals from subsurface layers. Later, more efficient powerful energy sources (Brewer et al., 2013) provided improved ground coupling along access corridors. The resultant greater frequency control and energy creation, combined with new three-component geophones (Pugin et al., 2018), expanded seismic data acquisition to include both traditional compressional wave and shear wave signals. Improved geophone reception used truck-towed land-streamer arrays several hundred meters in length, while digital processing facilitated better signal definition for improved analysis.

Over the multi-year investigation of the ORM, these seismic innovations improved both depth penetration and near-surface signal definition/resolution (Dietiker et al., 2023) as well as the speed and efficiency. Coherent signal returns from less than 250 m below surface, often to bedrock (Pugin et al., 1999), recorded reflective stratigraphic layers, truncations, erosion surfaces, and buried valley geometries with dimensions of 5 to 7 km across and up to 200 m deep. The cross-sectional dimensions of buried valleys were shown to be similar to many glacial valleys observed at ground surface, for example along the Holland Marsh (Figure 11). These new geophysical surveys significantly updated the known stratigraphic geometry at local and regional scales.

Despite the presence of numerous large, deep surface valleys across the area north of the ORM, the pre-existing conceptual model implied a layer-cake subsurface sedimentary architecture (Karrow, 1967). Seismic profiles reveal that sedimentary strata are truncated by buried valleys filled with glacial-fluvial sediments, some extending downward into bedrock (Sharpe et al., 2004). The new findings highlight the need to

incorporate erosional concepts to complement standard litho-stratigraphic approaches (Karrow, 1974).

Borehole geophysical logging proved to be an essential complement to seismic reflection profiling and to sedimentological studies that helped to identify geological strata. Most boreholes were drilled to bedrock and penetrated a complete sediment sequence in the local area, typically 100 to 200 m thick (Sharpe et al., 2025). The suite of collected geophysical data (Crow et al., 2018) could be interpreted/analyzed to estimate seismic velocity, sediment type, and physical properties.

Measured downhole geophysical parameters included natural gamma, apparent conductivity, magnetic susceptibility, P-wave velocity, relative and spectral density, and temperature. These parameters allow for sub-surface strata correlation between boreholes and within the seismic profiles (Hunter et al., 1998; Pullan et al., 2002, 2004) and can be used to estimate some hydrogeological properties (Crow et al., 2018, 2022). For example, a relatively high P-wave velocity of 2,500 m/sec correlates well with dense Newmarket Till, a laterally continuous marker horizon identified in outcrops, seismic profiles, and borehole cores (Pugin et al., 1999). This characteristic P-wave velocity is reasonable for the Newmarket Till, which is described as a dense, stoney sandy silt diamicton. In this way, surface geologic mapping, subsurface geophysical profiles, borehole geophysical logs, and core descriptions (next section) are correlated to provide enhanced geological/stratigraphic cross sections, an example of which is shown in Figure 14.

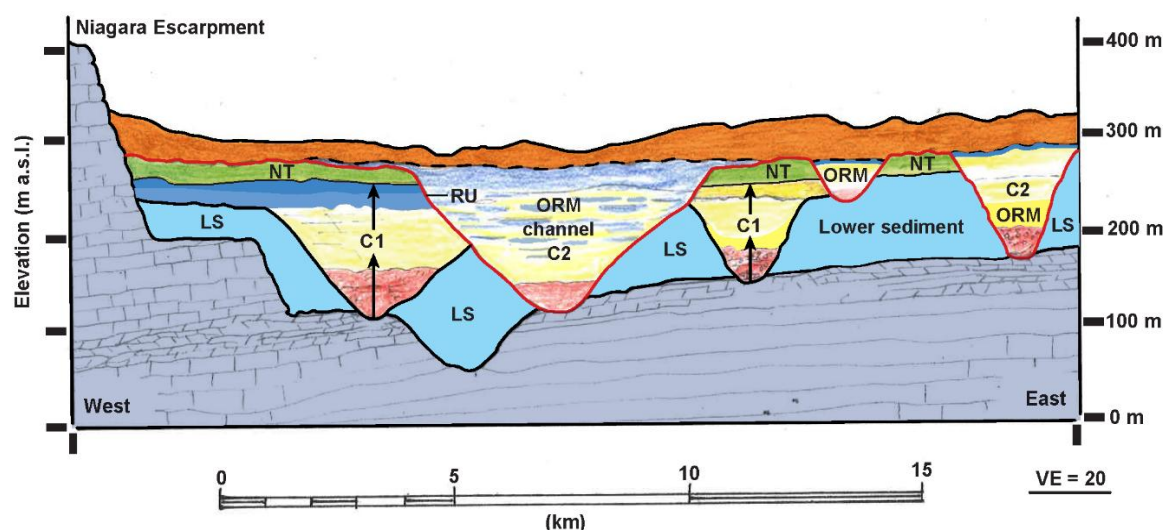


Figure 14 - Schematic east-west section of ORM multilayered geologic units across the Laurentian trough. This cross section (roughly oriented along the W-E seismic line in Figure 11) is a geological interpretation derived from several seismic profiles using the truncation, geometry, and pattern of seismic units east of the Niagara Escarpment. The cross section highlights two phases of channel erosion (C1, C2) extending downward into Lower Sediments (LS). Bedrock is grey- with a textured pattern. Lower Sediment (LS) is the blue unit. C1 is the older phase of channel development (Thornccliffe Formation) that occurred approximately 25,000 years ago. C2 is the younger phase of channel development associated with ORM materials, that occurred approximately 13,500 years ago. Newmarket Til (NT) is green. The top-surface ORM moraine deposit is orange. The buried channels have fining upward sediment sequences with sand/gravel at the bottom. Arrows in the C1 channels indicate a complete channel fill sequence that includes a fining upward of gravel-sand-mud (red, yellow, orange, or dark blue). The fining upward sequence in C2 channels consist of gravel (red), sand (yellow), and mud (light purple). Erosion of C2 channels is continuous with the top of the drumlinized NT surface to form a regional unconformity (red line). Major aquifers are represented by the colors red (gravel), yellow (coarse sand) and orange (fine sand). Aquitards are green, dark blue, and light purple. VE = vertical exaggeration. This figure is modified from Sharpe et al., 2018.

Continuous-core sediment logging

In the last 30 years, more than 100 continuously cored boreholes² have been drilled across the area. These detailed documentations of the geology and stratigraphy are often used to assist in the correlation of stratigraphic units with geophysical survey results. Most borehole cores record the full sediment sequence to bedrock—often at depths of 100 m or more. Core descriptions frequently include complete photographic records that document centimeter-by-centimeter sediment continuity, contact relationships, as well as sedimentary description and facies analysis (Russell et al., 2004), including texture, bedding thickness, structure, grain size, grading, organic content, and partial chemistry (Bajc et al., 2019; Burt, 2018; Burt & Dodge, 2011, 2016; Knight et al., 2008, 2018, 2021; Mulligan & Bajc, 2018; Sharpe, Dyke et al., 2003). Continuously cored boreholes provide the highest quality stratigraphic reference data (*golden spikes*) to develop and test stratigraphic frameworks,

² The number may be >200, if landfill investigation cored boreholes are included (e.g., Interim Waste Authority, 1994a, 1994b, 1994c, 1994d, 1994e, 1994f, 1994g, 1994h, 1994i). The estimate of >100 includes those borehole cores with published sediment logs including a sediment column figure and are available in documented public reports.

process models, and conceptual geological models (Logan et al., 2008; Sharpe, Dyke et al., 2003, Sharpe et al., 2011) that later support development of three-dimensional geologic models (Logan et al., 2006, 2024). Example cross sections from a three-dimensional geologic model are shown in Figure 10. The boreholes also provide access to install casings, allowing geophysical and groundwater measurements to be collected.

Lithological logs incorporate sediment characteristics important for determining the properties of stratigraphic layers observed on seismic profiles and for advancing ideas on sediment origin. For example, core logs obtained from N–S channels reveal a systematic change upward in grain size correlated with sediment sequences suggestive of rapid sedimentation events providing key evidence for process model development (Russell & Arnott, 2003). In addition, centimeter scale sediment logging of 100-m continuous cores distributed across the area affords geological investigation over multiple scales from individual beds to local stratigraphic and basin scale process models.

Sediment chemistry

Geochemical surveys were completed across the regional landscape (Sharpe et al., 2019) and on selected core samples along borehole transects (Knight et al., 2021). Analytical methods included full multi-element (e.g., ICP-MS) and selected element analyses (e.g., pXRF) that record chemical and associated mineralogical variations and stratigraphic markers (Knight et al., 2021). These geochemical data provide regional and stratigraphically-defined baseline sediment and rock composition. In addition, ambient groundwater chemistry was sampled on a 10x10-km grid from both surficial and bedrock aquifers (Hamilton, 2021). These geochemical results supplement sediment description, grain size, downhole geophysical data, and stratigraphic correlations (Crow et al., 2015; Pullan et al., 2002) to provide a geochemical-stratigraphic framework to address geological questions of sediment provenance and depositional processes. These data are also used to interpret host sediment and rock composition and ambient groundwater chemistry (Hamilton, 2021) across the basin. Selected geochemical tracers are discussed in later sections.

Overview of three-dimensional geological modeling

Numeric geological modeling was uncommon prior to 1990; however, one zone within the study area with extraordinary subsurface data resulted in an early three-dimensional model undertaken as part of a sedimentary basin atlas (Mossop & Shetson, 1994). Elsewhere in the study area, subsurface studies relied on widespread yet uncertain geological information provided in water well records (Russell et al., 1998). At the time, subsurface analysis relied on analogue (paper) cross sections as well as structural and isopach maps plotted by hand (Thorleifson et. al., 2019). Those cross sections commonly depicted a layer-cake subsurface geometry using single point borehole data. Work in the mid to late 1990s, such as the Oak Ridges Moraine National Geoscience Mapping Program

project focused on the development and implementation of digital modeling methods involving numerical data capture, conversion, database development (Logan et al., 2004), and data analysis using geographic information systems (GIS) (Logan et al., 2006). Work on the development of digital three-dimensional geological models (Russell et al., 2006) was advanced by deriving geological units based on stratigraphic architecture inferred from geological mapping, measured sections, and geophysical surveys in the ORM glacial basin (Sharpe et al., 2007). The geometry and architecture of units honored a framework of bounding surfaces or discontinuities (Miall, 1988). This stratigraphic method used structural elements to complement lithology-based stratigraphy (Walker, 1990) by directly extracting discontinuities from high-resolution seismic profiles and data from cored boreholes. The resulting three-dimensional modeling is built on the high- quality, resolution, reliability, and density of data captured in the database (Logan et al., 2006, 2008).

The assembled basin-analysis datasets, guided by the regional conceptual geological model (Figure 12), were combined to develop a three-dimensional stratigraphic model of the ORM area (Logan et al., 2020; Logan et al., 2024; Logan et al., 2005). A framework of high-quality stratigraphic reference records (including surface mapping, seismic profiles, continuous-core logs) and expert-based geological rules (supported by process understanding) were used to interpret a larger dataset (>50,000) of lower-quality yet widely distributed water-well records (from the Provincial Water Well Information System—WWIS) to enhance the three-dimensional stratigraphic model. Poorly constrained model areas with sparse data coverage were reliant on thematic map coverages (e.g., surficial geology; Figure 11).

The ORM three-dimensional stratigraphic model was used to delineate hydro-stratigraphic units to populate hydrogeological models (Frey et al., 2020). Additional data were needed in areas of sparse data. For example, knowledge of a regional channel network accompanied by a formative process model (Brennand et al., 2006) aided in projections of the extent of elongate sand and gravel bodies—channel aquifers. The database-development path laid out by this work regularly incorporates newly acquired geological and hydrogeological data into the three-dimensional model.

5.3 Geological Setting

5.3.1 Literature Overview of Oak Ridges Moraine Geology

Early exploration in the study area identified a sandy height of land (ORM) between Lake Ontario and Lake Simcoe extending approximately 160 km from Niagara Escarpment to beyond Rice Lake (Bigsby, 1829; Logan, 1863; Figure 11). Most of the early work was reconnaissance and identified physiographic features and landforms such as hummocky terrain and ridges of ORM (Chapman & Putnam, 1943), the Niagara Escarpment (Chapman, 1985), till plains, and drumlin fields with adjacent lowlands and wetlands representing the regional landscape (Barnett et al., 1991; Chapman & Putnam, 1984; Gwyn

& Cowan, 1978). Geological knowledge of the ORM expanded rapidly with the use of a suite of systematic field observations and detailed mapping techniques (Barnett et al., 1998) that led to an emergent conceptual geological model (Figure 12).

Significant to stratigraphic order and correlation was the identification of fossil remains in the preserved older deposits along the Scarborough Bluffs of Lake Ontario and nearby riverbank exposures (Coleman, 1932; Karrow, 1967). Organic material helped to establish a chronology of stratigraphic events (Figure 12a), including mainly glaciogenic-glaciolacustrine sedimentation from the last full glaciation, deposits with warm-climate indicators from an interglacial period, and an earlier glaciation. Strata in total originate from geologic processes active over the last approximately 135,000 years (Figure 12a), although exposed deposits older than 100,000 years old are sparse.

The main glacial episode—approximately 25 to 20 ka—was marked by deposition of a thick, regional glacial deposit—the Newmarket Till (Figure 12). As this ice sheet subsequently melted, it released large volumes of stored meltwater rapidly into eroded channels and ridges, depositing approximately 80 km³ of sorted sediment to form the ORM landform (Sharpe et al., 2007). Reworked glacio-lacustrine mud and diamicton—Halton Till—partly drape western ORM sediment (Figure 12c). Raised thin lacustrine sediments—e.g., Glacial Lake Iroquois—and valley incision record postglacial influences in the area.

Many consider the ORM to have formed between two ice lobes/streams, where ice flowing north from Lake Ontario met ice flowing south from Lake Simcoe (Chapman & Putnam, 1943; Eyles, 1997; Gwyn & Cowan, 1978; Taylor, 1913; White, 1975), as the climate warmed (Karrow, 1967). Sedimentological observations in large sand and gravel pits (Brennand & Shaw, 1994; Duckworth, 1979) complemented regional geomorphology to demonstrate the essential glaciofluvial (sand and gravel) to glaciolacustrine (capping mud; Gilbert, 1997) character of the ORM. Recent work has proposed rapid ice flow and meltwater flow models to explain the origin of ORM (Sharpe & Russell, 2020, 2023; Sookhan et al., 2018) with meltwater channels playing a central role.

5.3.2 Bedrock Geology

Rocks underlying the study area affected the regional landscape at the basin scale. Bedrock also influenced the quantity, texture, and chemistry of the eroded sediments in the basin. Precambrian metamorphic rocks (>1 billion years) of the Canadian Shield are exposed at ground surface in the northern portion of the region. Paleozoic rocks (>400 million years) of the Michigan basin (Armstrong & Dodge, 2007) overlie Shield rocks (Figure 13a). Pre-existing tectonic structures and basin strata were modified during glacial episodes: less erosion on hard silicate Shield rocks and more erosion on softer Paleozoic sedimentary rocks—shale and carbonate. This resulted in unique physiographic and geologic features. For example, the Great Lakes basins were enhanced by differential

erosion at the boundary between Shield and overlying sedimentary rocks of the Michigan basin (Brunton & Brintnell, 2020).

Differential erosion also occurred between hard (carbonate) and soft (shale) sedimentary rocks to produce regional effects, escarpments, troughs, depressions, and valleys on the Paleozoic bedrock topography (Figure 13a,b). Carbonate basin rocks, for example, form the approximately 100-m high Niagara Escarpment (NE) positioned oblique to the eroding edge of the Paleozoic–Precambrian Shield contact (Figure 13a). Scarp retreat of the escarpment’s massive Silurian dolostone cap rock (Brunton et al., 2010), due to erosion of underlying Ordovician shale and friable sandstone (Armstrong & Carter, 2010), resulted in a large bedrock trough below the escarpment (Gao, 2011; Kor & Cowell, 1998). The depth of the Laurentian trough (Figure 13b; Sharpe et al., 2018) resulted from enhanced erosion in soft shale due to multiple processes, of varying but uncertain significance. Over time, these included Tertiary fluvial (Spencer, 1907), glacial (Straw, 1968) and glaciofluvial (Kor & Cowell, 1998) agents of erosion. Northeast–southwest-trending bedrock structures in Shield rocks north of the ORM are connected to sinuous valleys in carbonate rock east of Lake Simcoe (Figure 13b) and glacial sediment, southwesterly toward the ORM (Brennand et al., 2006; Brennand & Shaw, 1994; Gilbert & Shaw, 1994; Figure 13b). Over time, this evolving bedrock physiography affected how erosional processes acted across the Great Lake basins (Hough, 1958).

Sediment distribution and composition across the area differs between Shield and sedimentary basin terrain (Figure 13). Southward ice flow across Shield rocks (Figure 13a) yielded few erosional products due to the hardness of silica-rich Shield rocks, and this resulted in sparse (<1 m) deposition of glacial sediment in the northern portion of the region (Figure 13c). In contrast, thick (>50 m) carbonate-rich sediment was deposited when ice flowed across fractured layered sedimentary rocks in the southern part of the study area (Kjarsgaard et al., 2016). The deep bedrock depression from Georgian Bay to Lake Ontario—the Laurentian trough—was infilled with glacial sediment east of the Niagara Escarpment (Figure 13c). The 100-m high Niagara Escarpment (Figure 13) also influenced sediment thickness as it ponded glacial meltwater and trapped sediments in the approximately 200-m deep Laurentian trough when ice blocked Great Lake drainage (Figure 13b; Sharpe et al., 2025).

Most of the bedrock wells intersect Simcoe Group limestone as opposed to the deeper Georgian Bay shale (Figure 13a). This pattern coincides with areas of thin sediment cover (Figure 13b) east of Lake Simcoe and close to the Shield-Paleozoic margin and the NE. Thin sediment areas exhibit near-surface carbonate dissolution and shallow karst conditions (Brunton & Dodge, 2008). Karst openings were enhanced by flow of pressurized glacial meltwater (Kunert & Coniglio, 2002) and by postglacial weathering.

Glacial loading and postglacial unloading of bedrock in the Great Lakes deformed basin geometry (Person et al., 2007) and altered water movement, chemistry, and the depth

of the fresh water–saline water interface (approximately 100 m below surface, Carter, Fortner et al., 2021). Differential glacial unloading also affected glacial lacustrine sediment as paleo shorelines are tilted to the northeast, the direction of maximum ice loading and unloading.

5.4 Glacial (Quaternary) Stratigraphic Framework

The stratigraphic framework, chronology, and glacial history of significant events in the basin were documented mainly at the spectacular, well-exposed, >10 km-long, 50 to 70-m-high bluffs along the Lake Ontario shoreline (Brookfield et al., 1982; Coleman, 1932; Eyles, 1987; Karrow, 1967). Studies at Scarborough and Bowmanville Bluffs, and nearby exposures (Karrow et al., 2000) reveal a record of two glacial episodes and an interglacial event that are described below in a segment on the stratigraphic sequence. Deposits of interglacial and an older age glaciation (Illinoisan) are sparse and scattered and occur buried inland from the lake bluffs (Mulligan & Bajc, 2018). The bluff sections display deposits of the last—Wisconsinan—glacial episode (Figure 12a); however, these sections do not record events—mainly Halton/ORM—above the late-glacial regional erosion surface—unconformity—that scoured and incised the Newmarket Till (Figure 12a,b; Sharpe et al., 2004).

The multikilometer-long sediment layers at the Scarborough Bluffs (Figure 13c inset) fostered the theory that glacial stratigraphy of the area consists of a *layer cake* sediment architecture. This theory persisted until subsurface geophysical surveys identified truncated strata and irregular structures (Pugin et al., 1999; Sharpe et al., 2004). Truncation of late-glacial strata above the regional erosion surface led to an incomplete understanding of younger events that formed the ORM and closely related Halton sediment (Figure 12a; Sharpe & Russell, 2016). Hence, the past focus on lake bluff sections, while providing significant knowledge of the area, resulted in an incomplete stratigraphic framework for the ORM region and inconsistency in updating geological and hydro-stratigraphic understanding (Meriano & Eyles, 2003). More details on up-to-date unit identification are provided in Sections 5.4.2 to 5.4.6 and in Section 5.5.

5.4.1 Developing the ORM Conceptual Geological Model

The present ORM conceptual model (Figure 12) includes important concepts regarding erosional surfaces (Shaw, 1983; Wright, 1973) that can be traced to field observations (Barnett et al., 1998). Wright (1973) and Shaw (1983) each identified a regionally significant late-glacial landform set; drumlin fields crosscut by meltwater channels that are inset with eskers. Shaw (1983) interpreted this landform set as a hierarchy of forms resulting from a sequence of large meltwater discharge events—Icelandic floods or *jökulhlaup*—that left an erosional and depositional record across the glacial landscape. The flood landform-process model became relevant in the ORM area (Barnett, 1990; Brennand & Shaw, 1994; Shaw & Gilbert, 1990; Shaw & Sharpe, 1987) with the recognition

that the drumlin-channel-esker landform set is consistent with new field observations (Barnett et al., 1998). The meltwater channel network eroded into Newmarket Till is a key feature of the conceptual model (Figure 12), representing a portion of a regional unconformity (Sharpe et al., 2004; Sharpe & Smart, 2025). We preview aspects of the stratigraphic framework by explaining the role that basin analysis methods played in developing the ORM landscape architectural model.

The role of high-resolution data collection

In areas with thick sediment, the early ORM workplan in large part focused data collection on recognition, extent, and stratigraphic implications of the proposed meltwater channel model. Building upon detailed surficial mapping that identified channels (Figure 11), the ORM stratigraphic framework was modified to incorporate the presence and character of channels using seismic profiles and continuously cored boreholes. Seismic profiles provided evidence of subsurface channel structures and the truncation of underlying layered units (e.g., till sheets; Pugin et al., 1999). This subsurface information significantly improved geological understanding (Barnett et al., 1998; Sharpe et al., 2004) as it recorded details of considerably more complex structure and geometry than the expected layer-cake concept (Karrow, 1974).

The combined seismic and borehole results reveal two ages of deep channel erosion and sediment fill (Figure 14; C1, C2). Initial work (Barnett, 1990) traced surface valleys beneath the ORM and identified a set of young channels (ORM, C2) eroded into older layered strata (e.g., Newmarket Till; Pugin et al., 1999). Further work by Pugin and others (2011) identified an older channel network (C1, upper Thorncliffe Formation; Figure 14) below Newmarket Till and deeper within Lower Sediment (Figure 12a). In places, channels of both ages were eroded to bedrock (Figure 14) as shown in an E–W schematic cross section based on multiple seismic profiles with verified cores (Sharpe et al., 2018). This cross section illustrates overlapping channel geometry in ORM area strata (Figure 14), as is common within a large bedrock depression—the Laurentian trough. Channel forms, filled with gravel-sand-mud fining-upward sediment sequences, may incise the full stratigraphic column (C1, C2; Figure 12b; Figure 14) (Gerber et al., 2018; Sharpe et al., 2011). Channel sediment (Figure 14) hosts major aquifers (red, yellow, orange) and aquitards (blue, light purple, green) in this thick sediment sequence. Delineating near-surface C2 channels progressed well where their subsurface expression could be linked to surface topography, such as the Holland Marsh channel (HM, Figure 11). C1 channels are difficult to delineate because of the lack of surface expression to guide the siting of seismic surveys and coring through the thick (>100 m) sediments. The recognition of channels and a channel network (Russell, Arnott, & Sharpe, 2003; Russell, Sharpe et al., 2003) dramatically altered the conceptual geological model and guided the type and quality of subsurface information required to understand the ORM area stratigraphy and inform the hydrogeological model (Sharpe, Hinton et al., 2002).

The collection of high-quality subsurface ORM data (Figure 15 and Figure 16) allowed for the testing of an evolving geological model to explain the origin of the ORM channel system (Brennand et al., 2006; Sharpe & Russell, 2023). The channel conceptual model also provides a basis to explain older, more deeply buried Thorncliffe channels (Gerber et al. 2018; Sharpe et al., 2011; Sharpe et al., 2025). Neither channel system was explicitly recognized in previous work due to (a) poor subsurface data coverage and quality; (b) a prevailing layer-cake stratigraphic conceptual model; (c) the lack of an appropriate process model to provide a plausible channel erosion and sedimentation scenario to focus field testing (Barnett, 2012; Sharpe et al., 2011).

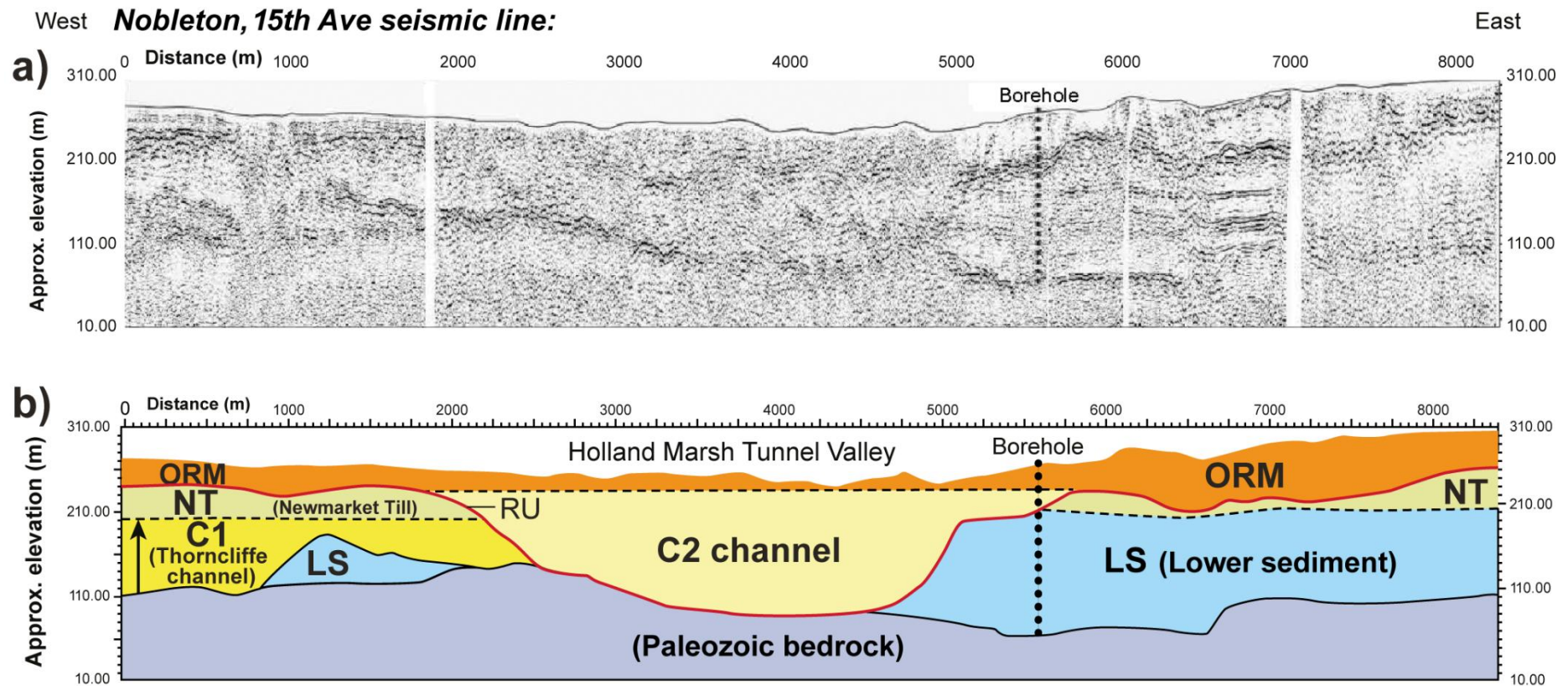


Figure 15 - An 8-km seismic section at Nobleton (Figure 11 shows the location). a) Processed seismic profile with strong reflectors (impedance contrast) defining unit boundaries to >200 m depth. b) Interpreted section shows a large ORM channel (C2) incised to bedrock through older strata, Lower Sediment (LS), and regional Newmarket Till (NT). The strong reflector on the base and walls of the channel truncate horizontal reflectors east of the channel. These horizontal reflectors (LS) are cored by a 192-m deep borehole (Figure 16a) located on the profile, east of the channel steep bank. The strong reflector traced from the C2 channel base past the borehole to the drumlinized surface of NT forms a regional unconformity (red line) with channels and drumlinized NT uplands across the area. The Thornccliffe channel (C1) is inferred on the west side of the profile. Pugin and others (1999) provide seismic profile details; Sharpe, Dyke, and others (2003) give borehole geologic information; Knight and others (2008) show sediment mineralogy; and Crow and others (2018) discuss borehole geophysical investigations (image updated from Sharpe et al., 2018).

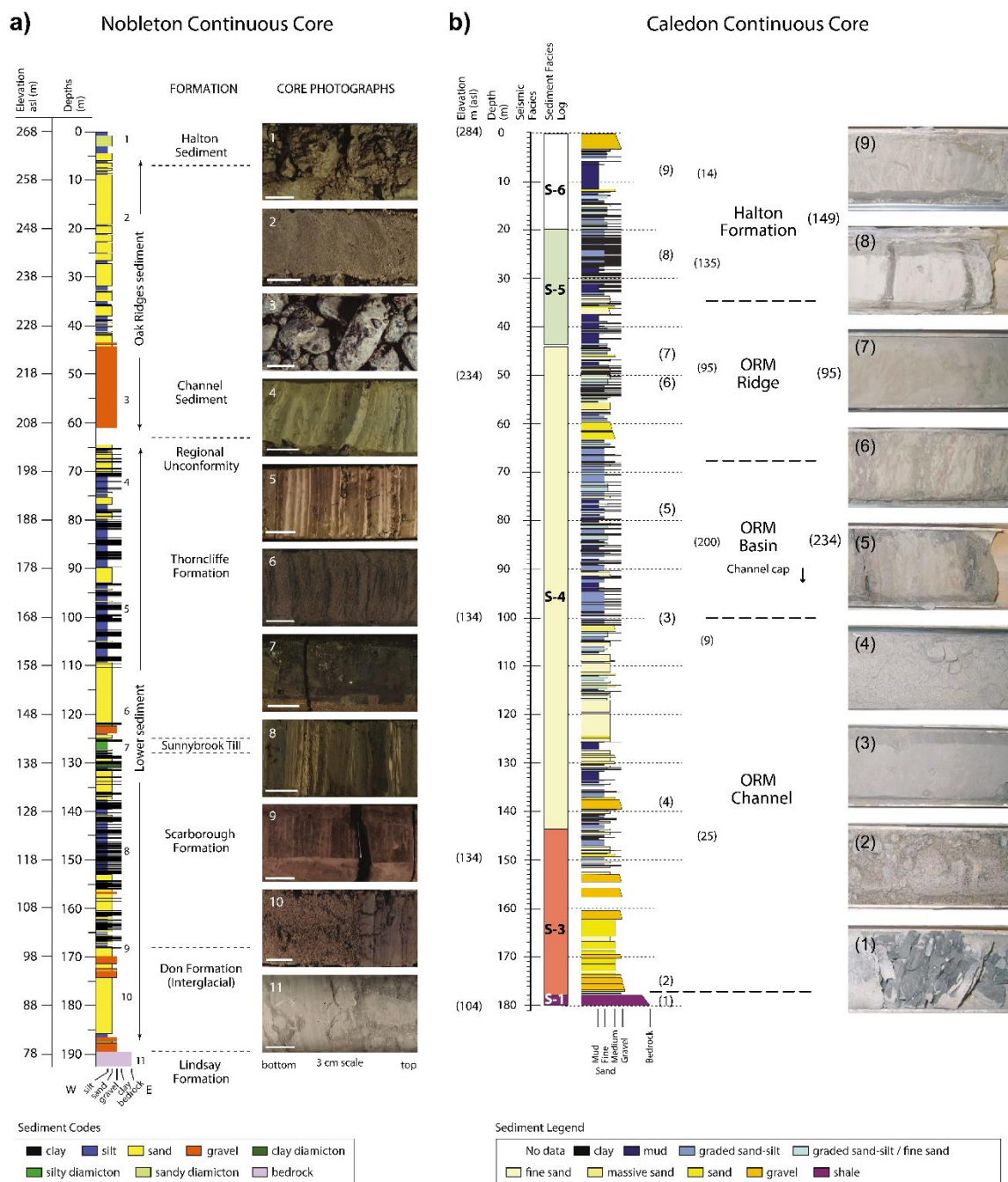


Figure 16 - a) Detailed 192-m sediment log of borehole shown on the Nobleton seismic profile (Figure 15) with sediment type and core photographs. The Nobleton continuous sediment core sampled the full local Quaternary stratigraphic sequence to bedrock. Oak Ridges Moraine (ORM) C2 channel gravel and sand (approximately 60 m) occur on the regional unconformity and represent the shallow eastern portion of a 200-m deep channel (Figure 15), which eroded Newmarket Till and approximately 130 m of Lower Sediments (Don, Scarborough, and Thorncliffe Formations; the full classification is shown in Figure 12a). **b)** The Caledon³ approximately 178-m continuous core (the borehole location is shown in Figure 11 near Caledon) intersects Halton sediment overlying a full sequence of sediments from two ORM aquifers: ORM channel (approximately 80 m) and ridge (approximately 30 m) sequences, which are separated by an approximately 35-m basin rhythmic mud interval (data from Sharpe et al., 2018).

³ Well tagged as PGMN W-165 Heart Lake Road in the ORMGP database.

Elements of the ORM conceptual geological model

The derived conceptual geological framework (Figure 12a, b) is a simplified synthesis of decades of geological analysis in the ORM area (details are in Sharpe & Russell, 2023). The full stratigraphic section (Figure 12a) is classified into four main glacial sequences that overlie bedrock (Figure 12b). These four sequences describe and characterize the key hydro-stratigraphic units in the ORM region (Figure 10). A N–S cross section (Figure 12c) shows the four sediment sequences. The ORM, with channel sediment at its base and a confining Halton Till on its southern flank, overlies the incised regional Newmarket Till and its dissected terrain architecture and thick (approximately 100 m) extensive sequences of Lower Sediment. These sequences, including ORM gravelly sand, are elevated >200 m above Lake Ontario and 100 m above Lake Simcoe. The four main elements—sediment units and subunits—that overlie bedrock (Figure 12b) are described and characterized below in order of formation from oldest to youngest.

5.4.2 Lower Sediment

Lower Sediment is an assemblage of geological units (Figure 12a) that unconformably overlies bedrock and occurs below Newmarket Till. Lower Sediment consists of multiple diamicton (e.g., York Till, from a previous glacial period, Illinoian, >135 ka), interglacial stream sediments (Don Formation, approximately 115 to 80 ka), glaciofluvial (Pottery Road Formation), deltaic (Scarborough Formation), and glaciofluvial-glaciolacustrine sediment (e.g., Thorncliffe Formation, including muddy diamictons, and Sunnybrook drift), all considered to represent deposits older than the last glacial episode, more than 25,000 years before present (Karrow et al., 2000). This formal stratigraphy (Figure 10; Figure 12b, c) has been mapped over the past 100 years along well-exposed riverine sections, aggregate pits, and Lake Ontario shorelines (e.g., Scarborough Bluffs). Exposures are typically <75-m high bluffs of bedded mud, sand sheets, diamicton, and rare channels (Figure 17 inset; Coleman, 1932; Eyles, 1987; Karrow, 1967).

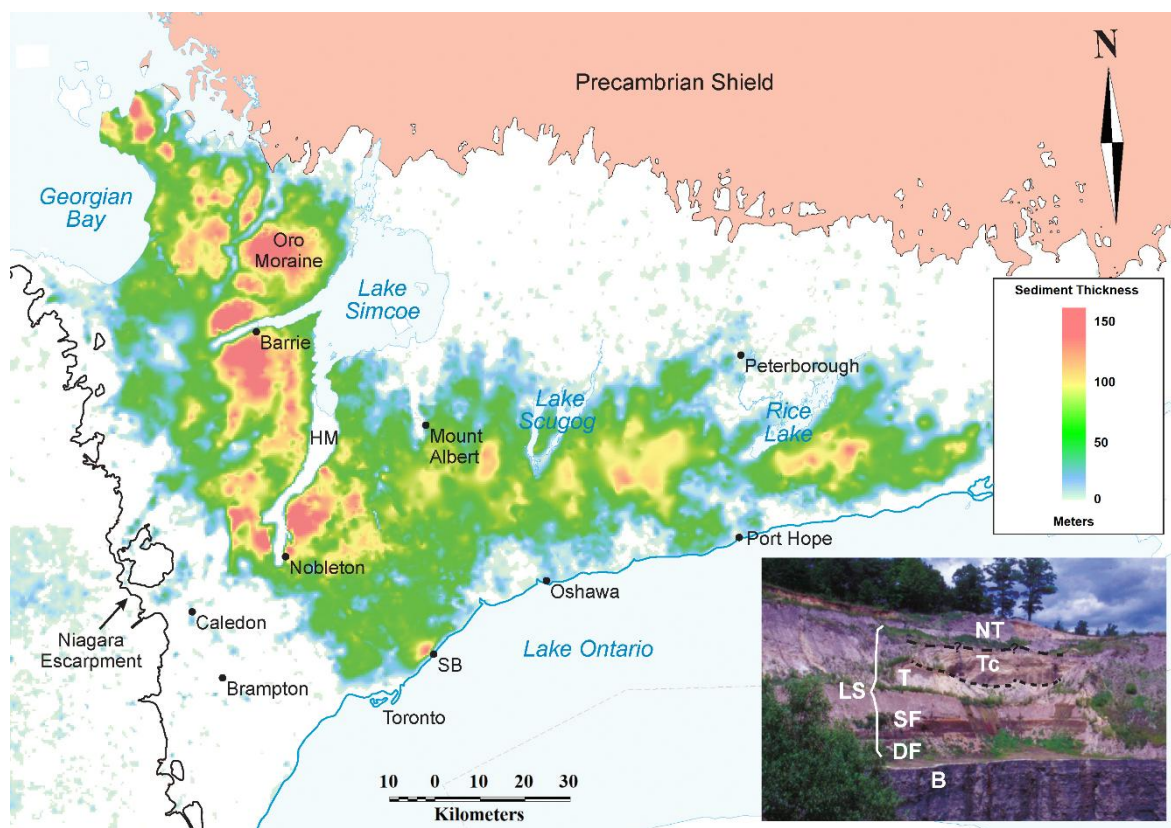


Figure 17 - Lower Sediment (LS) thickness: thickest areas are approximately 150 m. The northern boundary is irregular and trends ESE south of the Canadian Shield. Inset: photograph from the Don Valley Brick Works (approximately 5 km west of SB) shows LS overlying bedrock (B) and below Newmarket Till (NT). Units within LS (Figure 12a; also Karrow, 1967); from base up, Don Formation (DF) interglacial sediments, Scarborough Formation (SF) deltaic deposits and Thornclyffe Formation (TF) lower mud truncated by channel (C1), fan sand and gravel (Map data from Logan et al., 2020).

Lower Sediment units rarely outcrop north of the Lake Ontario shoreline, except for limited exposure in river valley bluffs (Karrow et al., 2001), and more commonly in borehole intersects (Sharpe et al., 2005b). It has been mapped northward through geophysical surveys and continuous core data (Mulligan & Bajc, 2018). The Lower Sediment assemblage forms an approximately 100-m thick sediment sequence that extends from the base of the Niagara Escarpment near Georgian Bay southeast beyond Rice Lake (Figure 17). It represents an extensive, approximately 900 km³, multi-unit sequence of aquifers and aquitards (Sharpe et al., 2025; Sharpe et al., 2018).

Seismic profiles and outcrops within the lower part of the Lower Sediment sequence reveal a widespread tabular, sub-horizontal architecture (Figure 14, Figure 17). These strata are truncated by a younger, channelized erosion surface that originates from within the Upper Thornclyffe (Figure 12a, Figure 17) and may extend to bedrock (C1, Figure 14). Channels range in scale from large, approximately 2 km wide and 100 m deep, to <0.5 km wide and <50 m deep (Figure 17, inset). Buried channels within LS have no topographic expression across the area (Pugin et al., 2011), so it is problematic to plan geophysical surveys to detect their presence. Channel aquifers, once identified, can be delineated using hydraulic data related to municipal groundwater pumping (Gerber et al., 2018). In such a

scenario, hydrogeological data inform the geological model regarding channel orientation and dimensions. Younger (ORM) channels (approximately 5 km wide and 100 m deep, C2; Figure 14) truncate the northern margins of LS (Figure 17), leaving Lower Sediment thin or even absent below large surface valleys such as Holland Marsh or other lowlands leading south and west from Lake Simcoe (Sharpe et al., 2025).

Continuous core at Nobleton documents the full Lower Sediment sequence (Figure 16a) revealing an approximately 132-m thick sequence that intersects, from the base up, Don Formation interglacial fluvial sediment, Scarborough Formation mud and sand, Sunnybrook drift and Thorncliffe Formation mud and sand, truncated by a younger (ORM) channel (Knight et al., 2008). These bedded sediments record the lithology of horizontal reflector patterns that are truncated on the Nobleton seismic profile (Figure 15a). The Nobleton core and seismic profile provide an informal yet detailed type-site for Lower Sediment (Logan et al., 2008), mainly comprising glacial lake deposits, mud with interbedded sand and mud diamicton.

Thorncliffe and Scarborough Formation aquifers

The Nobleton borehole core (Figure 16a) intersects horizontal seismic reflectors, revealing a mainly mud-dominated Lower Sediment sequence with two prominent sand units (aquifers) found within the Scarborough and Thorncliffe Formations (Figure 12a). Scarborough Formation deltaic sediments comprise a lower 30-m clay member and a 20-m thick upper sand member (Kelly & Martini, 1986). Scarborough Formation is considered to occur within the footprint of the Laurentian bedrock trough (Figure 13, Figure 14, Figure 17) with the noted presence of organic material. It rises northward from approximately 120 masl at the Scarborough Bluff reference section to approximately 170 masl 50 km inland (Mulligan & Bajc, 2018; Turner 1977). The elevation rise relates to differential postglacial land rebound, assuming that the sand beds are equivalent.

Thorncliffe Formation forms an extensive approximately 75 to 100-m-thick glacial lake sequence that comprises approximately 75 percent of Lower Sediment (Figure 12) and covers the area shown in Figure 17 (Sharpe et al., 2025; Sharpe et al., 2026) with a volume of approximately 400 km³. Thorncliffe Formation includes thick mud and interbedded sand beds dissected by upper formation channels (Sharpe et al., 2018). Sub-channel Thorncliffe sediment (Figure 17) consists of laminated silt-clay, sorted sands, and muddy diamictons (Karrow, 1967; Mulligan & Bajc, 2018). The muddy diamicton units recorded at Scarborough Bluffs as till—a direct glacial deposit—Sunnybrook, Seminary, Meadowcliffe (Karrow, 1967)—cannot be traced inland with certainty. Mud diamictons are more likely debris flows that occur at variable positions within Thorncliffe Formation glacial lake sediments. Rhythmites (sand-silt-clay cycles) within the lake sediment document seasonal sedimentation of approximately 1,000 to 2,500 years. Deposition into the Thorncliffe glacial lake basin marked a transition from organic-rich to organic-poor banded sediment,

representing rising water levels as westward advancing glaciers blocked eastward drainage of the Great Lakes via the St. Lawrence River. Reworked detrital organic matter in Thorncliffe Formation sand (Karrow, 1967) yielded age estimates >28.1 ka (Mulligan & Bajc, 2018), documenting time before the last major ice advance into the area.

The top surface of Thorncliffe Formation glacial lake sediment is mostly undeformed and occurs over a large region where it is in contact with Newmarket Till. The top surface elevation of Thorncliffe Formation beds at Lake Ontario is approximately 130 masl, 200 masl at Nobleton, and 320 masl northwest of Lake Simcoe (Sharpe et al., 2025). The sloping surface of the Thorncliffe Formation rises to the north due to high sedimentation patterns—sediment influx from the north—and basin tilt following postglacial rebound from former thicker glacial ice loads to the north (Sharpe et al., 2025; Sharpe et al., 2018).

Thorncliffe channel system

Thorncliffe channels comprise a network that yields prominent aquifers (Sharpe et al., 2025). Channel geometry and sediment is well recorded by seismic profiles, cores, and large pits (Figure 14, Figure 15, Figure 17; Sharpe et al., 2018). Most channel sequences fine upward from gravel to sand to muddy rhythmites (Figure 14; Figure 16). For example, the 80-m thick Aurora channel sequence grades from gravel and sand into approximately 10 m of silt-clay rhythmites (refer to Gerber et al., 2018's Figure 7). This sequence is part of an approximately 20-km-long N–S trending, 20–80-m-thick channel fill (approximately 0.5 to 2 km wide) running south from Queensville to Aurora (Figure 11; Gerber et al., 2018). Large (5 to 8 m) south-trending sandy gravel cross beds occur near the base of this sequence (Sharpe et al., 2013). South of Aurora the channel expands to become a broad fan with lithologic change from gravel to sand (Sharpe et al., 2011). Hydraulic monitoring had earlier identified this linear aquifer geometry as a valley/channel feature (International Water Consultants Ltd., 1991).

Prior to the 2000s (Sharpe et al., 2011), Thorncliffe channels were not explicitly recognized in previous work. This omission was due to poor subsurface data coverage and quality and the inference that the recorded linear hydraulic connection occurred in a bedrock valley or possible channel (Gerber et al., 2018; International Water Consultants Ltd., 1991). Using deep borehole logs and active groundwater monitoring, Sibul and others (1977) defined an approximately 10 to 15-km-long linear hydraulic pattern, termed the Markham aquifer. Sibul's work (and that of International Water Consultants Ltd., 1991) was groundbreaking in that it identified a buried Thorncliffe channel aquifer with sparse geological data combined with hydraulic monitoring data. Where quality geological data are sparse, systematic hydraulic monitoring can enhance the interpretational range of geological data. In the Markham aquifer case, the critical information on the extent and paleo flow direction of the Thorncliffe channel is clearly defined as a northeast–southwest trend based on hydraulic drawdown patterns (Husain et al., 2007). Similarly, the Yonge

Street channel aquifer had approximately N–S paleo flow estimates derived from hydraulic monitoring of the municipal water supply wells (International Water Consultants Ltd., 1991), a stressed system later identified as a Thorncliffe channel aquifer (Gerber et al., 2018; Sharpe et al., 2011). Thus, hydraulic monitoring of these two aquifers has improved knowledge of the continuity, length, and coarse-grained nature of Thorncliffe Formation channels (Gerber et al., 2018).

An Icelandic-type glacial flood model (Russell et al., 2007) represents one origin of Thorncliffe Formation channels. This inference is mainly due to the thickness of gravel-sand deposition (approximately 80 m), and the rapid transition upward in the sequence and downflow into sand and distal silt-clay rhythmities. Younger ORM channels are also consistent with a flood origin, and both Thorncliffe Formation and ORM channel systems are best explained within a subaqueous setting and channel-fan process model (Russell & Arnott, 2003). The drill core logs from Sibul and others (1977), which identify a silt-clay drape over the Markham channel sand and gravel, are consistent with the fining-upward sequence from subaqueous fan sedimentation. Of note, previous interpretations of Thorncliffe Formation include deltaic to lake-level (base level) controlled sandy sedimentation (Eyles & Clark, 1986; Karrow, 1967; Mulligan & Bajc, 2018). The high, top sediment surfaces of Thorncliffe Formation, however, are approximately 100 m above elevations that would be consistent with a subaerial depositional system for the Thorncliffe Formation (Sharpe et al., 2025).

The presence of Newmarket Till overlying Thorncliffe Formation channel sediment was a key to the recognition of C1 (Thorncliffe) channels (Figure 14). Newmarket Till marker beds indicate that C1 channels are older than near surface ORM, C2 channels (Figure 12a,b). The silt-clay channel drape forms a conformable contact with overlying Newmarket Till (Knight et al., 2018), combining to create a significantly thicker aquitard that caps the Thorncliffe channel aquifers.

5.4.3 Newmarket Till

Newmarket Till is a widespread, <50-m thick, compact to very dense, stony (5 to 8 percent), massive, silty sand diamicton that primarily overlies Thorncliffe Formation sediment and bedrock (Figure 11, Figure 18). It has well-documented regional characteristics based on thousands of field site observations and more than 30 measured sections, 400 grain-size analyses (Sharpe & Russell, 2016), 100 borehole sediment and geophysical logs including distinct downhole p-wave characteristics (Pullan et al., 2002), and mineralogy (Kjarsgaard et al., 2016). These physical properties make it a reliable marker bed across the region (Sharpe et al., 2005a).

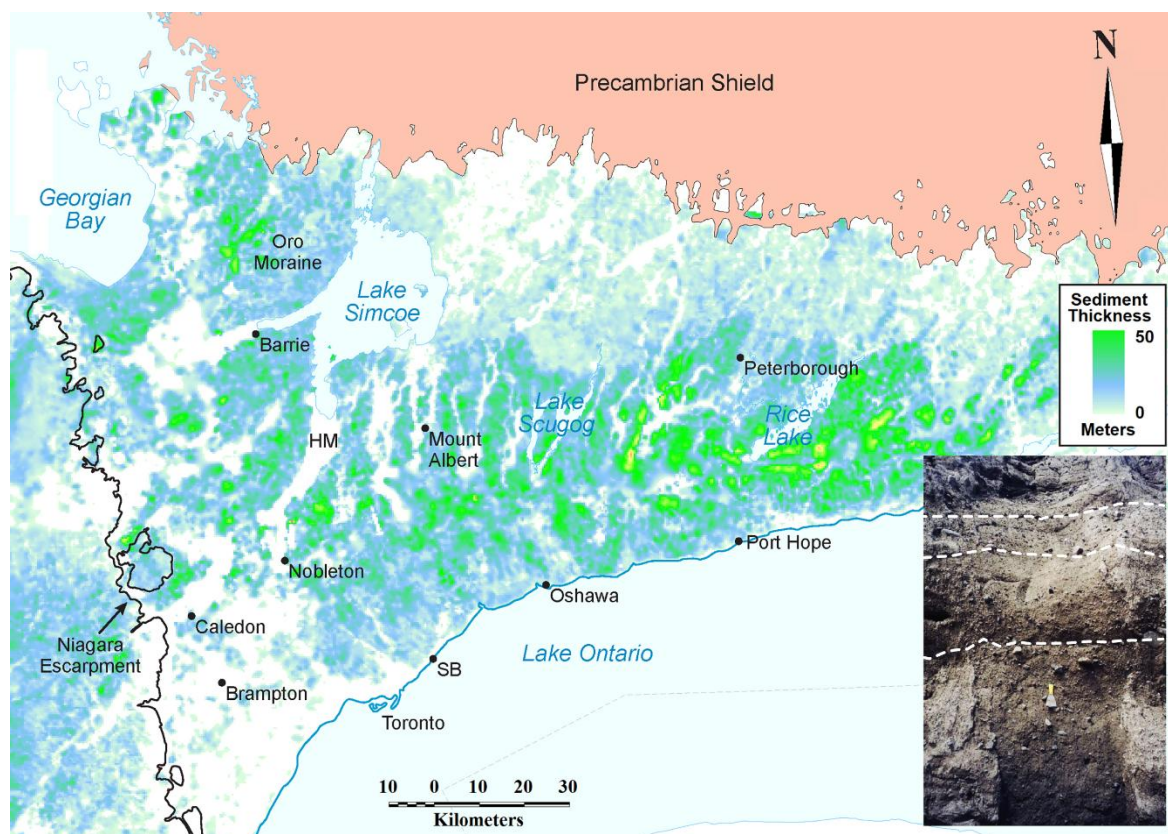


Figure 18 - Newmarket Till thickness: The Newmarket Till extends across the region as a massive unit ≤ 50 m thick from Georgian Bay to east of Rice Lake, mainly derived from Paleozoic carbonate rocks south of the Canadian Shield. The Newmarket Till was eroded and incised by NE–SW-oriented channels (Figure 11). Dissection of the Newmarket Till is best observed south of Lake Simcoe to Nobleton, where erosion breaks the continuity of the till across the region, in places through Lower Sediment into bedrock. The inset photograph shows the distinct lithology of the till marker bed: dense, stony, sandy diamicton with vague bedding (dashed white lines) indicative of amalgamated bed elements (approximately 2-m view). The trowel is approximately 15 cm long. These consistent sediment properties across the ORM area make it a prominent bed for stratigraphic positioning (map data from Logan et al., 2020).

Newmarket Till is mapped continuously from the Lake Ontario shoreline northward beneath ORM to drumlinized uplands, channel interfluvies, and Lake Simcoe lowlands (Boyce & Eyles, 2000⁴; Mulligan, 2016; Mulligan et al., 2018; Sharpe & Barnett, 1997; Sharpe et al., 2006; Sharpe, Russell, & Logan, 2002; Stepner et al., 2020; Todd & Lewis, 2007; Figure 11). High seismic velocity, approximately 2,500 m/sec (Pullan et al., 2002), recorded on seismic profiles and on borehole p-wave logs improve subsurface unit

⁴ Newmarket Till (Gwyn & DiLabio, 1973) has been called Northern Till (Gerber & Howard, 2000; Meriano & Eyles, 2009). The long term, common use of Newmarket Till as a formal unit, as in this book, means that Northern Till is pre-empted. Northern Till focused on properties representative of a northern source area (Knight et al., 2021). The northern provenance confirmed that Halton Till (with inferred lake-based source areas) does not occur in areas close to or at Scarborough Bluffs (Sharpe & Barnett, 1997) or on most of the till plain south of ORM (Figure 11; Sharpe & Russell 2016). It also means that sand beds, beyond presumed Halton Till, are Newmarket Till interbeds and not Mackinaw Interstadial sediments (discussed in Section 5.4.3).

correlation based on high sediment density, although variations in density are known locally.

Newmarket Till thickness varies regionally from a typical approximately 10 to 20 m up to 50 m thick (Figure 18) to an observed few meters thick in uplands north of the ORM (Sharpe et al., 2025). It has a usual elevation range of approximately 250 to 300 masl in uplands, although it is reported in valley bottoms at approximately 130 masl (Mulligan & Bajc, 2018). The base of Newmarket Till can be remarkably planar on seismic profile (please refer to Sharpe et al., 2004's figure 4e,f) and in river bluff sections and uplands where it conformably overlies Thorncliffe Formation (Figure 14). The planar contact shows local deformation, boulder scour and fill, load structures, and interbedding with Thorncliffe sediment (Sharpe et al., 2025; Sharpe, Russell, & Logan, 2002). Till interbeds (gravel, sand, and silt horizons) that separate diamicton layers or elements (Boyce et al., 1995; Stepner et al., 2020) commonly occur as <1-m beds that can be traced for tens to perhaps 100 m as measured in river and lake sections or as sparse thick beds up to 10 m. Where interbeds are missing, diamicton elements combined to form thicker (<10 m), amalgamated beds (Figure 18, inset; Sharpe, Hinton et al., 2002).

In some areas (uplands south of Lake Simcoe, northeast of the Scarborough Bluffs; Figure 11), thick sand beds support a subdivision of upper and lower massive Newmarket Till⁵. However, a review of approximately 150 cored boreholes and measured sections shows no consistency in where interbeds occur, and some Newmarket Till intervals of >25 m have <1 percent total interbed thickness. In outcrop, <3 m of near-surface Newmarket Till may show looser, fissile, less-dense consistency and oxidation staining (Knight et al., 2021). This weathering effect and documented discontinuous sandy interbeds within massive diamicton alter local sediment properties and enhance horizontal and vertical hydraulic conductivity as observed in hydraulic response data (Gerber & Howard, 2000; Gerber et al., 2001).

Newmarket Till is interpreted to be a regional subglacial till (Boyce & Eyles, 1991; Gwyn & DiLabio, 1973) with a northern provenance (Knight et al., 2021). High seismic velocity, approximately 2,500 m/sec, and high sediment density are likely due to optimum grain packing and Ca-silicate matrix cement (Kjarsgaard et al., 2016) in addition to ice loading beyond the Thorncliffe lake basin—no buoyancy effect where ice was grounded. Interbeds of sand and silt observed close to the Thorncliffe Formation contact indicate

⁵ Some reports (e.g., Earthfx Inc., 2006) use the terms *upper and lower Newmarket Till* where sparse thick sand beds occur. The thick beds are called *inter-Newmarket sediments* (INS) in such reports. This section does not use those terms, as thick beds are rare in Newmarket Till and interbedding has variable thickness. Sand and diamicton interbed occurrence at the Newmarket Till–Thorncliffe Formation boundary makes it difficult to define the exact contact (Sharpe et al., 2025). The terms *upper* and *lower* are used in Section 6 to provide continuity with their use in the hydrogeological literature. Some Newmarket Till interbeds have been interpreted as Mackinaw interstadial beds (Meriano & Eyles, 2009; Section 5.4.3).

gradational sedimentation from Thorncliffe sediment into Newmarket Till (Sharpe et al., 2025).

Traditional analysis of sand beds in till sequences interprets the sand bed to be a proglacial deposit due to ice retreat and readvance (Karrow, 1974). The term *Mackinaw interstadial* has been used to interpret sand beds within till sequences—including Newmarket Till—south of ORM, close to Lake Ontario (Meriano & Eyles, 2009), as being due to ice retreat and readvance under climate forcing, even though no climate indicators are reported within such sand beds. Interbeds and thick sand beds more likely represent periodic subglacial drainage events leading to fluvial (Boyce & Eyles, 2000) and lacustrine deposition as the glacier periodically lifted from and reattached to its bed (Sharpe & Russell, 2023; Stepner et al., 2020). The buoyancy effect of trapped and stored subglacial water aided these occasional drainage episodes (Roberts, 2005). Such features are likely related to small cavities and conduits at the glacier sole that captured sediment influx. The glacier lift process model explains the limited lateral extent of Newmarket Till interbeds (<100 m) and locally thick beds (<10 m), as opposed to km-scale extents if the ice had repeatedly retreated and readvanced across a wide pro-glacial till plain. Locations with more abundant and thicker interbeds appear to occur where subglacial water flowed during uplift to transport and trap more interbed sediment (Lesemann et al., 2010). Geological variability increases where Newmarket Till interbeds occur and results in variability in the hydrogeological properties of Newmarket Till.

At a regional scale, Newmarket Till was dissected and breached by a set of meltwater channels approximately 1 to 5 km wide of variable depth, even eroding to bedrock in places (Figure 14, Figure 15b; Sharpe et al., 2004). South of the ORM, channels scoured Newmarket Till to shallow depths (approximately 10 to 25 m) (Sharpe & Barnett, 1997) as part of regional erosion, which removed approximately 25 percent of the Newmarket Till (Logan et al., 2024; Sharpe, Russell, & Logan, 2002). This created a drumlinized till landscape consisting of uplands approximately 5 to 10 km across and 10 to 20 km long—drumlins up to 30 m high—adjacent to valleys and wetlands kilometers wide and with approximately 50 to 75 m of relief. These erosion events radically altered the geometry and hydrogeological behavior of the regional Newmarket Till sheet (Figure 18).

5.4.4 Oak Ridges Moraine

This section develops a model of how ORM stratified sediment originated to improve understanding of aquifer distribution and properties. Documented immense volumes of sand and gravel (Sharpe and Russell, 2023) were deposited rapidly as glacial meltwater floods, analogous to the floods observed in Iceland today (*jökulhlaup*, or glacier bursts; Roberts, 2005). Others have argued that ice streams played a role in the deposition of ORM stratified sediments (Sookhan et al. 2018), yet ice streams are predicted to have deposited large amounts of till (Eyles et al., 2011). The viability of these process models, and how they may contribute to understanding the ORM landscape, is critiqued in the

literature (Russell, 2019; Sharpe & Russell, 2020), including a detailed regional assessment (Sharpe & Smart, 2025). Oak Ridges Moraine (ORM) consists of two distinct high-energy sequences (Barnett et al., 1998), separated by a low-energy sequence that rests on a regional unconformity (Figure 19 inset cross section). A stage 1 erosional event led to formation and deposition within a network of approximately N–S channels. High-energy channel sedimentation waned rapidly to low-energy rhythmites (Figure 19, Figure 20a). Stage 2 channel erosion led to deposition of an east–west ridge (Figure 19). Thus, ORM sediment consists of two main sediment architectures: (a) approximately NE–SW-oriented channels (ORM channels) and (b) prominent E–W surface ridges (four main sediment wedges, Figure 11, Figure 19; Sharpe & Russell, 2023). Channel sediments can be up to approximately 150 m thick, whereas ridge sediments are up to approximately 50 m thick. Combined, these can comprise 25 to 100 percent of total sediment thickness in some areas (Figure 19 inset). A persistent, approximately 10-m thick, mud unit caps channel sediments, separating channels from overlying ridge sediments (Figure 14, Figure 16b, Figure 21). Thus, ORM formation comprises channel, rhythmite, and ridge sediment (Figure 21).

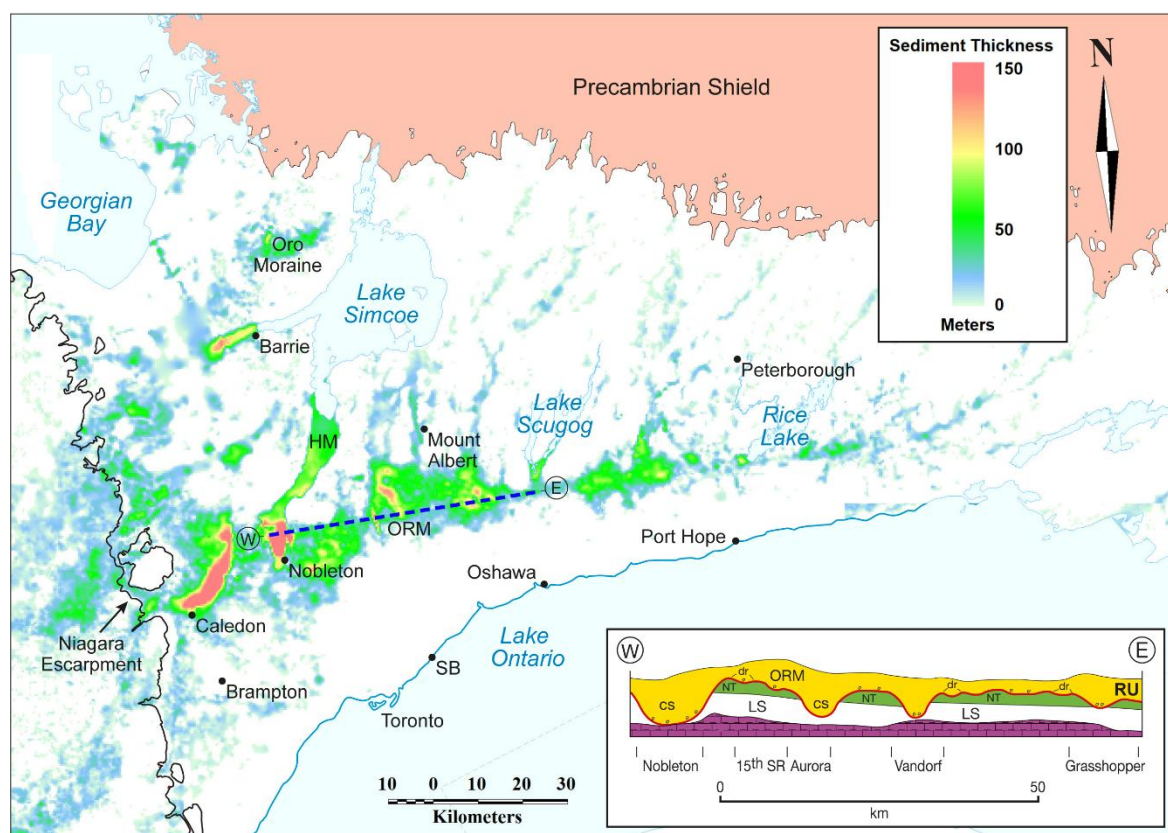


Figure 19 - Thickness of ORM (and related) stratified sediment (<150 m) is variable in a series of east to west wedges. ORM sediment occurs on an erosional base (inset W–E) or regional unconformity (RU, red line). Mapped channel sediment occurs in partially filled valleys north of ORM ridge and as very sparse deposits south of ORM and shallow channel scours (not shown). Channels with eskers (Figure 11) contributed sediment from the north, whereas little sediment was supplied from Lake Ontario to ORM. Westward flow of ORM sediment overtopped Niagara Escarpment (>400 masl). This confined westward flow meant that former grounded glacial ice north of Lake Ontario blocked thick ORM glaciofluvial sediment at >300 masl from being swept into the Lake Ontario (75 masl) basin.

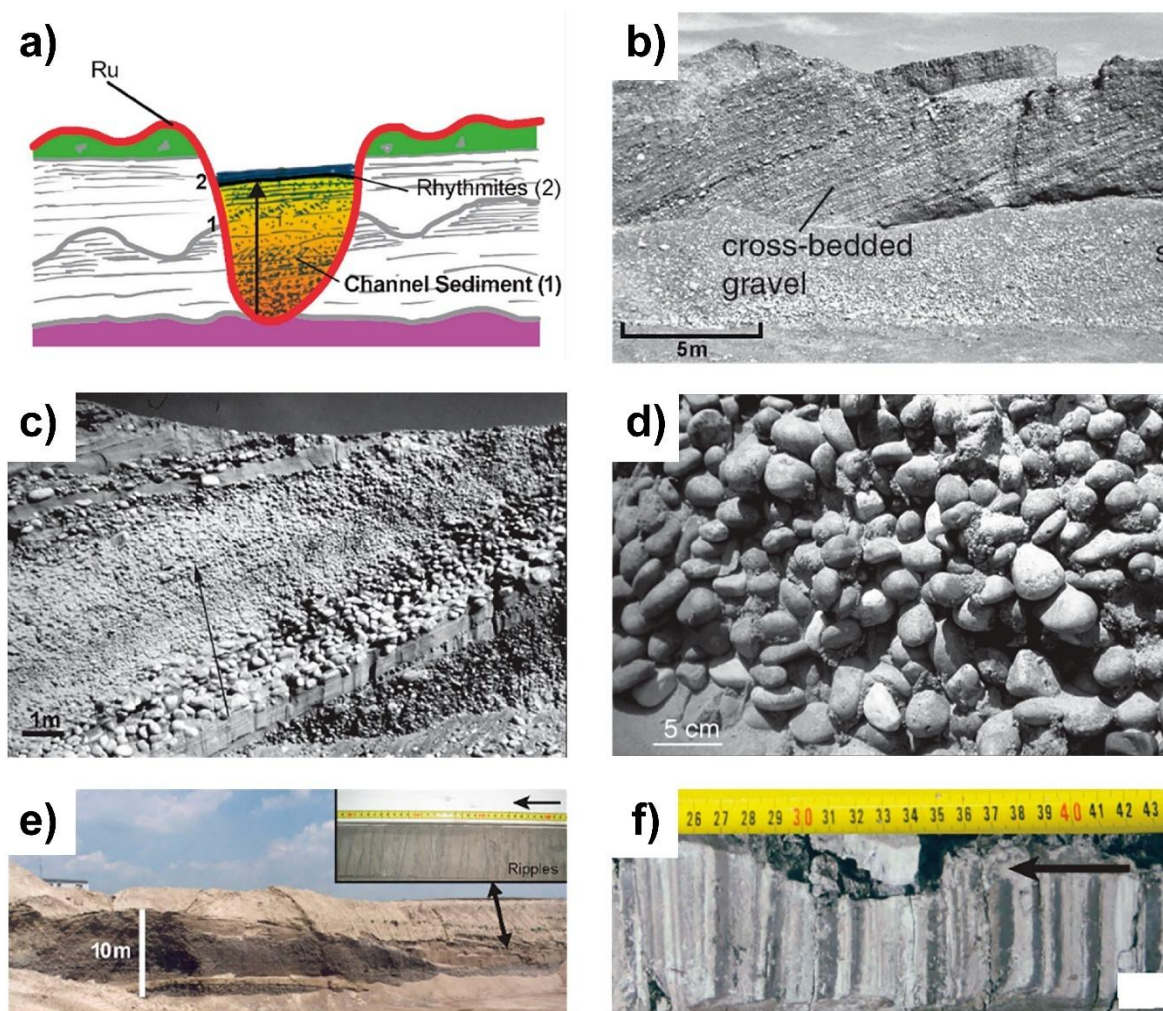


Figure 20 - ORM channel sediment characteristics: a) sediment occurs on eroded surface (red line) as fining upward sequences of gravel-sand-mud (black arrow, orange, yellow, blue; and shown Figure 14). b) and c) Channel sediment sequences are cross bedded, photographs with graded (black arrow) and d) bimodal cobble-sand sets that show typical variability in channel sediment texture and porosity from openwork gravel to laminated sand. e) Photograph showing approximately 15 m-high gravel bar with overlying rippled sand (inset) within the Mount Albert meltwater channel (Figure 11). f) Rhythmites (silt-clay couplets) that cap the gravel-sand channel fill, (a). Map data from Logan and others (2020).

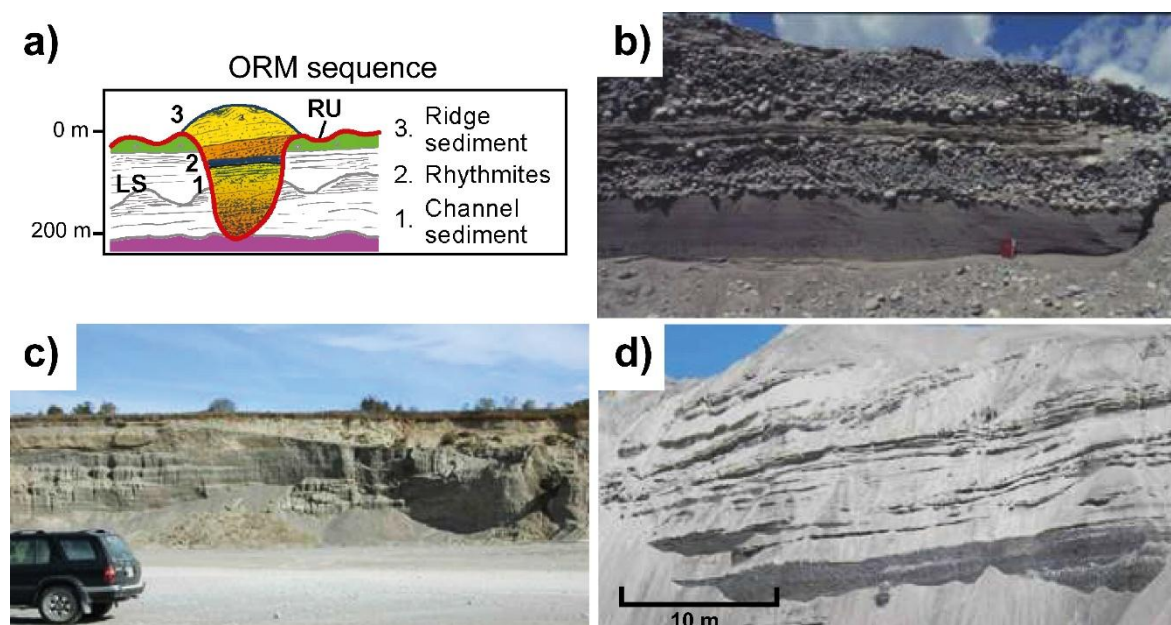


Figure 21 - ORM ridge sediments: a) ridge sediments lie conformably on channel rhythmites to create the ORM topographic landform; b) and c) >10 m high, >100 m long, E–W-oriented gravel forms are overlain by laminated to rippled sand; d) massive- to graded- gravel and diffusely-graded sand indicate variable hydraulic conductivity.

Channel geometry

A series of large valleys that truncate Newmarket Till—deeper north of ORM—are observed, mapped, and recorded on seismic profiles across the regional landscape (Figure 11, Russell et al., 2000) and beneath the ORM (Figure 14, Figure 15; Figure 19 inset). Seismic profiles show large trough structures with steep walls defined by a prominent inclined seismic reflector that truncates lower horizontal reflectors (Figure 15a, Nobleton). This main reflector cuts across and incises Newmarket Till and Lower Sediment, extending into shale bedrock (Figure 15b; Pugin et al., 1999). This erosion surface forms large ORM-age channels (C2, Figure 14) that are approximately 3 to 4 km wide and 150 m deep as observed on the Nobleton seismic profile (Figure 15). The channel can be traced northward to Holland Marsh (Figure 11), a partially filled, approximately 5-km-wide surface valley. The Holland Marsh channel branches southwest past Schomberg to form a >75-km-long meltwater channel that extends to Caledon (Figure 19) and further west, rising to form a re-entrant valley in the Niagara Escarpment (Sharpe et al., 2018). Other E–W profiles collected across north–south valleys (Sharpe et al., 2004) reveal truncation of horizontal substrata by variable size channels. C2 channels are approximately 1 to 5 km wide south of Lake Simcoe (C2, Figure 11) and eroded to depths >100 m (Figure 14, Figure 15b; Sharpe et al., 2004). South of the ORM, C2 channels are shallow—approximately 10 to 25 m deep—yet they are eroded into Newmarket Till (Sharpe & Barnett, 1997). The channels are part of a regional unconformity (Sharpe et al., 2004; Figure 19 inset) that scoured and dissected Newmarket Till with a network of channels (Brennand et al., 2006). The channel network extends beneath the ORM and eastward beyond Rice Lake (Pugin et al., 1999; Russell,

Pullan et al., 2004; Russell et al., 2000) creating an anastomosing pattern of uplands and valleys with approximately 50 m of relief.

The size and dimensions of the Nobleton and other channels, and the truncation of all older sediment that eroded into bedrock, required a significant erosional event. The scale of channel erosion, evidence of rising pressurized flow over Niagara Escarpment, and evidence of a network of buried channels (C2 Figure 14) all point to regional meltwater erosion (Brennand et al., 2006). This event radically altered the landscape and sediment architecture across the study area (Sharpe et al., 2004) and led to revision of the conceptual geological model as predicted in the meltwater process model of Brennand and Shaw (1994).

Channel sediment

Continuously cored boreholes were drilled to characterize channel sediment observed on seismic profiles and in shallow pits (Figure 15, Figure 16; Sharpe & Russell, 2023; Sharpe et al., 2007). Cored boreholes were originally collected to test the hypothesis that surface channels identified north of ORM extended south beneath the ORM (Figure 14; Barnett 2012). Results show abrupt-based sediment successions, 60 to 150 m thick, with seismic facies that occur with weaker signals upward in the profile (Pugin et al., 1999). This pattern correlates to fining-upward gravel, sand, and mud sequences in core (Figure 16). For example, the continuously cored borehole along the Nobleton seismic profile intercepted a 60-m thick channel gravel and sand sequence (Figure 16a) associated with the irregular, high-impedance seismic facies signals observed by Pugin and others (1999). This coarse-grained channel sediment occurs on the eastern flank of a 3-km-wide channel that truncated Newmarket Till (Figure 15b). The related Holland Marsh to Caledon channel contains up to 80 m of sand and gravel (Russell, Pullan et al., 2004) that fines upwards to silt and clay (Figure 16b). Overall, channel sediment comprises four main facies that transition upward 1) gravel bed forms that are approximately 10 to 15 m high, 50 m wide, and 100 m long (Figure 20e) and sheets about 30 m thick; 2) graded and cross-bedded sand up to 40 m thick (Figure 20e inset); 3) cross-stratified sand, fining upward to laminated fine sand up to 40 m thick; and 4) fine sand to silt-clay rhythmites in sequences approximately 15 m thick (Figure 16b; Figure 20f; Russell, Arnott, & Sharpe, 2003; Russell, Sharpe et al., 2003; Sharpe & Russell, 2023).

To support informed predictions on sediment characteristics and trends across the basin, we review the formative process of the mapped channels and their sediment fill. The network of large sand and gravel filled valleys that truncates Newmarket Till formed as

subglacial meltwater channels⁶ (Barnett et al., 1998; Pugin et al., 1999). Their origin was similar to channels recently formed during meltwater floods in Iceland (Russell et al., 2007). Channel geometry, steep walls, and >100-m deep truncation, with erosion into bedrock (Figure 15) and with no base level control, indicate rapid erosion by pressurized, high-velocity meltwater floods (Brennand et al., 2006; Brennand & Shaw, 1994; Burke et al., 2008). Erosion was followed by rapid glacial-fluvial to glacial-lacustrine sedimentation into standing water (Russell, Arnott, & Sharpe, 2003; Figure 22). The marked vertical transition from thick (tens of meters) coarse gravel on channel floors to thick (tens of meters) sand sequences, then to clay rhythmites (Figure 16, Figure 19, Figure 20, Figure 21) indicates a short-lived, Icelandic-style glacial flood (Burke et al., 2008; Carling et al., 2009). Seasonal/diurnal meltwater flux and rhythmic clay sedimentation followed for approximately 100 to 200 years (Sharpe & Russell, 2023). The fining upward channel sediment architecture common in ORM (C2) channels indicates sedimentation into a deep (approximately 100-m) lake (Gilbert, 1997). Valleys with incomplete sediment fills north of ORM (Figure 11) contain mapped eskers (Barnett et al., 1998), features that also support a subglacial channel origin. Rapid sedimentation on the regional unconformity implies that sand and gravel may be present at depositional traps (mainly channels <200 masl) along the erosion surface and thus a prospecting strategy for potential aquifers.

⁶ Channel origin by ice erosion and drumlin formation (Mulligan et al., 2018) does not account for the lack of till in channel fills compared to the observed 80 m of gravel and sand deposited over 10 km or more in channel reaches (Russell, Pullan et al., 2004). Groundwater piping erosion (Mulligan et al., 2018) would not have eroded a 200-m deep ORM channel into bedrock as observed at Nobleton (Figure 15) nor would it be associated with thick gravel sequences. Gravel-sand channel sequences up to 80 m thick are exceptional because till deposits eroded by meltwater events contain <10 percent gravel. Thus, to erode and concentrate thick gravel sequences kilometers in length required remarkable meltwater discharge such as jökulhlaup floods, as recorded in Iceland in recent years (Bjornson, 2009).

Depositional model: Subaqueous fan

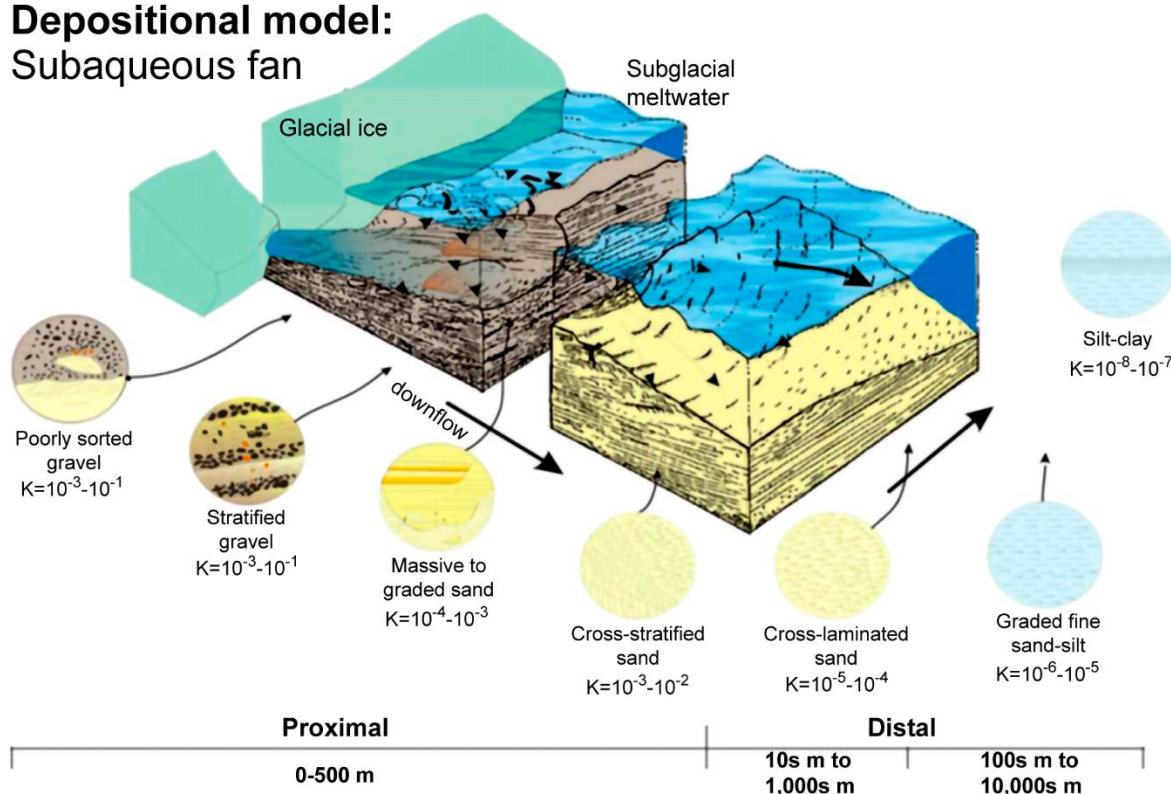


Figure 22 - Subaqueous fan depositional setting—e.g., applies to Thorncliffe Formation and ORM channel and ORM ridge sediments. A jet of channelized subglacial meltwater disperses sediment in an organized array at a glacier grounding line conduit into a deep glacial lake (or into a subglacial opening). A sequence of gravel, sand, and mud occurs downflow and vertically from such meltwater jets (Hoyal et al., 2003). The dispersed sediment changes from disorganized to better-organized beds downflow from proximal fan (approximately 500 m) to distal fan (>3 km). Hence, this depositional model provides a framework to predict sediment characteristics and to estimate related hydrogeological properties—estimated K values, in m/sec, linked to sediment facies. This sediment architecture occurs in ORM at several scales, from hundreds of meters in length to kilometers and potentially close to the scale of ORM sediment wedges in Figure 11 (Modified from Russell & Arnott, 2003).

Ridge sediment

ORM ridge sediments occur as four E-W-oriented wedges (Figure 11) along its approximately 160-km extent from Rice Lake to the Niagara Escarpment (Barnett et al., 1998). Wedge sediment thickness is commonly approximately 50 m thick but can vary considerably on the undulating erosional topography (Russell, Pullan et al., 2004) where ridge wedges have local relief of approximately 25 to 50 m. Where channels extend to bedrock (Nobleton, Figure 12, Figure 15), the combined ridge and channel ORM sediment thickness can be approximately 200 m (Figure 16c; Figure 19). Ridge sediment fines westward from gravel, sand to mud rhythmites (Sharpe & Russell, 2023) and becomes finer grained along the depositional flow path from east to west, arranged as fan-shaped sediment bodies (Figure 22). There is a prominent sand/gravel sediment pattern (couplets) on a scale of approximately 5 to 15 m in thickness found in coarse sequences (Figure 21b,c). Gravel is often well-sorted, massive with cross-bedded sand, forming 2 to 5-m-thick beds (Figure 21c). Gravel beds also occur in approximately 15 to 25-m-high, 50 to 100-m-wide, and 100-m-long E-W directional forms (Sharpe & Russell, 2023). Massive to graded sand

occurs in sets up to 10 m thick (Figure 21d) or in scours eroded into laminated sand. Western ORM ridge sediments consist of fine sand to silt-clay rhythmites in sets approximately 5 to 30 m thick (Figure 16b). This finer grain size is due to overall sediment fining from east to west (Sharpe & Russell, 2023) in a ponded setting distal from the eastern source of sediment input. On the geological map (Figure 11), ORM is narrow with sand and gravel in the east, becoming wider and covered with Halton mud in the west, the possible geometry of one large esker-fan feature.

Sand and gravel deposits that occur between till units on the southern exposures of ORM and the adjacent till plain (Figure 11) have been called *Mackinaw Interstadial sediments* (Boyce & Eyles, 2000). These deposits are shown to be ORM sediments that occur between overlying (surficial) Halton Till and underlying Newmarket Till (Sharpe & Russell, 2016; Figure 13). These sandy ORM sediments have no climatic indicators, and they are most likely splay deposits from high-energy, east-to-west ORM sedimentation—for example, near Maple (Figure 11; Sharpe & Russell, 2023). Therefore, the term *Mackinaw Interstadial*—also referred to as the Maple Formation in Karrow, 2005—is inconsistent with the geological model (Figure 12), has no climatic significance and is discontinued for geological consistency in this book.

A strong ice seal on the southern ORM flank resulted in rare ‘elevated’ deposition as sediment lobes or splays south of the main E–W ridge, east of Nobleton (Figure 19). Meltwater flowed from east to west as high-energy discharge with rapid sediment transition from a confined esker conduit to a fan and basin setting (Figure 22; Russell, Arnott, & Sharpe, 2004). Deposition of ridge sediment wedges formed along an ice-supported, E–W axis of deposition (Barnett et al., 1998), elevated approximately 200 m above Lake Ontario (approximately 75 masl; Figure 11, Figure 19, Figure 20, Figure 21). Confined meltwater flow produced large (>100 m) elongate gravel bodies—mainly in the Rice Lake region—from high concentration discharge (Russell & Arnott, 2003) within confined meltwater flow. Flow beyond the ice margin led to rapid basin deposition of thick sand and mud rhythmites in fan-shaped bodies (mainly west of Nobleton, Figure 11). Ridge sediment was also sourced from NE–SW esker flow north of the ORM (Figure 19). Rapid meltwater flow produced stranded ice blocks in deposited sediment, as occurs in Icelandic glacial floods (Russell et al., 2007); the resultant melted ice blocks form present-day kettle depressions and lakes in the ORM upland area (Figure 23b, vi).

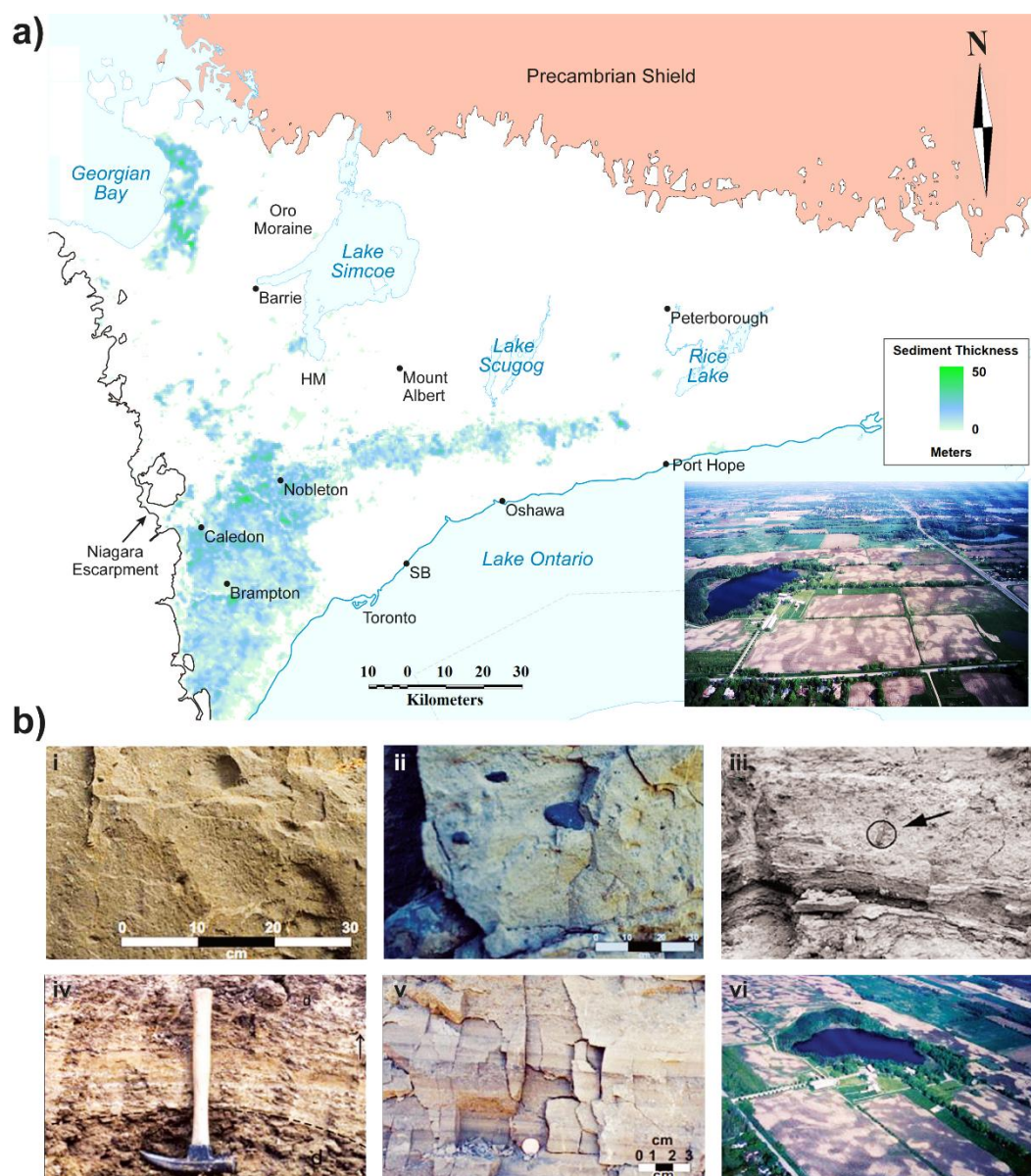


Figure 23 - a) Halton Till and interbedded glacial lake mud and sand form a combined unit, where sediment thickness is concentrated along a narrow eastern-crest, southern flank of ORM and a broad western area below the Niagara Escarpment. b) Photographs show bedded Halton sediment comprising massive diamicton beds (i, ii), interbedded diamicton, mud, and sand (iii, iv, v), and a kettle lake (vi) in Halton Till (From Sharpe & Russell, 2016) (Map data from Logan et al., 2020).

The channel-fan process model (Figure 22) provides a predictive framework for flow-parallel and flow-normal depositional features and for estimating directional sediment heterogeneity. The commonplace depositional succession of restricted gravelly (esker) settings transitioned to deposition within less-restricted sandy fan settings, succeeded distally and stratigraphically (upward) by waning-flow deposited silt clay—approximately 10 to 20 m thick—is a unifying distinction of subaqueous deposits. The subaqueous fan sediment model can predict sediment distribution (Figure 22), analogous to superior tested delta models (Miall, 2000). Thus, the distribution of sediment grain size

and aquifer properties can be readily extrapolated in areas with sparse data and used as a norm for testing new data.

5.4.5 Halton Sediment

Halton sediment forms a thin, muddy unit across the west central ORM extent, where it onlaps the ORM's southern flank at elevations >300 masl (Figure 11, Figure 12c). Sediment cores indicate <20 m of Halton draped on sandy ORM hummocks (Russell, Arnott, & Sharpe, 2004), found along with numerous dry and water-filled (kettle) depressions/lakes (Figure 23, vi; Sharpe & Barnett, 1997).

West of the Humber River Valley, Halton sediment extends from ORM south to Lake Ontario (Figure 11), where it is up to 50 m thick, filling lows between ORM sediment wedges. Halton sediment is a muddy diamicton with low clast content (Figure 23b); it is commonly gradational from, or interbedded with, underlying sandy ORM sediment (Sharpe & Russell, 2016). Halton diamicton is stratigraphically interbedded with laminated to massive mud, sand, and minor gravel (Figure 23b, iii, iv, v).

The description, extent, and of use of the term "Halton Till" needs clarification (Sharpe & Russell, 2016) to be consistent with the geological model (Figure 12). Clayey-silt Halton Till near Hamilton (Karrow, 1963) was inaccurately mapped eastward as sandy silt diamicton (Leaside Till, Karrow, 1974) near Toronto. This reclassification of Halton Till as a dense, stony, sandy silt till south of the ORM (Barnett et al., 1991; Boyce et al., 1995; Sharpe, 1988) is shown to be Newmarket Till based on detailed mapping of Sharpe and Barnett (1997; Figure 11).

Correlation of Halton Till around the Scarborough Bluffs (Karrow, 1974; Sharpe & Barnett, 1985) resulted in an unsupported conceptual landform model for the drumlinized till plain north of the lake bluffs (Gwyn, 1976; Sharpe et al., 1994; Sharpe et al., 2004). For example, Karrow (1967, 1974) used a depositional drumlin/fluting landform model for Halton Till to infer ice movement and deposition by flow from the southeast out of the Lake Ontario basin (please refer to Sharpe & Russell, 2016's Figure 1b, c). Several workers (Boyce & Eyles, 1991; Sookhan et al., 2018) also inferred that lake-bordering drumlins were formed of Halton Till and that the drumlins were directly related to the ORM, an unsupported interpretation (Barnett et al., 1998; Russell, 2019; Sharpe & Russell, 2020). The drumlinized till north of Lake Ontario is documented as Newmarket Till (Sharpe & Barnett, 1997; Sharpe & Russell, 2016), as it has a northern provenance (Knight et al., 2021). Younger, subtle shallow west-northwest-oriented fluting was identified where mud-rich Halton is the surface till west of the Humber River, near the Trafalgar Moraine (Karrow, 2005; Eyles et al., 2011). These clarified map extents, properties, and landform associations are incorporated in an updated model of Halton Till formation (Sharpe & Russell, 2016; Figure 12).

Halton Till formed following rapid ORM deposition that deposited mud west of the Humber River valley (Figure 11). Thin, grounded ice oscillated within glacial lake ponding against the Niagara Escarpment approximately 13,000 years ago (Sharpe & Russell, 2016). Proglacial and subglacial sediment accumulated as subaqueous debris flow, suspension settling, and minor ice-rafting for approximately 150 years based on counting rhythmites which are interpreted as varves (Sharpe & Russell, 2023). Ice grounding and melting ice blocks led to slightly consolidated or deformed Halton diamicton/till. Thin till (<5 m) near kettle depressions indicates that ice-block hollows are floored and formed in underlying ORM sediment. These hummocky depressions provide potential hydraulic windows from the land surface through Halton mud to underlying sandy ORM sediment. Where mud, marl, and organic material has accumulated within depressions, kettle lakes have formed (Figure 23b, vi). Ice blocks are common in glacial meltwater floods recorded in Iceland (Russell et al., 2007). The presence of kettle lakes (melted ice blocks) within ORM sediments (Russell & Arnott, 2003) is indicative of rapid sedimentation and transition to mud-rich Halton sediment. Rapid sedimentation implies that glacial hydro-dynamic processes—stored and released meltwater reservoirs—were more prominent than direct climate forcing in constructing the ORM glacial landscape (Sharpe & Russell, 2023).

5.4.6 Glaciolacustrine Sediment

Postglacial glaciolacustrine sediment occurs as sand and mud rhythmites from lakes Schomberg and Peel on the Halton Till surface west of the Humber River (Figure 11). The rhythmites are <10 m thick in uplands (Bajc et al., 2012; Sharpe et al., 2007), and >20 m thick in large valleys such as the Holland Marsh and Cookstown valley (Bajc et al., 2012; Figure 11). Such valley sequences may also contain approximately 50 m of muddy channel rhythmites that transition upward from ORM channel sand and gravel. On the Halton Till surface, glaciolacustrine sediment may be interbedded and difficult to distinguish from Halton sediments (Figure 23b). The combined muddy rhythmites indicate *deep-water* glaciolacustrine sedimentation (Gilbert, 1997) in a channel-proglacial lake sequence. These sequences provide a >50-m mud unit/aquitard above ORM channel sand and gravel sediment north of ORM. The upper rhythmite counts indicate that postglacial lake sedimentation—e.g., Lake Schomberg—lasted approximately 150 years (Sharpe & Russell, 2023).

Postglacial Lake Iroquois eroded a 5 to 15-m-high lake bluff 50 m—rising to the northeast—above present-day Lake Ontario. Erosion resulted in a scoured zone with a coarse boulder lag, and nearby downflow deposition of a discontinuous sand and gravel shoreline deposit, across the southern portion of the area close to Lake Ontario (Figure 11). These deposits are 2 to 10 m thick in elongate bodies, hundreds of meters long and <25 m wide.

5.4.7 Sediment Geochemistry

Accurate, high-precision geochemical data provide significant information to the ORM stratigraphic sequence (Knight et al., 2018). Geochemical fingerprinting, added to geophysical, core and outcrop observations, improves regional correlation and characterization of sediments. Primary variation in Newmarket Till matrix geochemistry, for example, is clearly linked to glacial erosion-deposition of Paleozoic rocks as ice flowed south from the Canadian Shield (Stepner et al., 2020; Figure 13). Downflow geochemical variation indicates rapid erosion and transport mixing of Paleozoic carbonate bedrock and thick deposition, approximately 25 m, within short distances, <100 km, of glacial passage (Kjarsgaard et al., 2020). Carbonate content overwhelmed Shield mineral and chemical influence and contributed to slightly higher metal content (Sharpe et al., 2019). Higher metal content shows up in sandy sediments—magnetic susceptibility—due to the concentrating effect of rapidly flowing water.

Geochemical and mineralogical analysis work also helps to refine stratigraphic and process interpretations (Knight et al., 2018; Knight et al., 2021). Geochemical transitions from Thorncliffe Formation sediment to Newmarket Till provide information on glacial processes. Most geochemical transitions from Thorncliffe Formation to overlying Newmarket Till are abrupt and show little if any evidence of incorporation of underlying sand and silt that would indicate there was geochemical mixing. Data from a core at Pickering (Knight et al., 2021) highlights a sharp Thorncliffe Formation–Newmarket Till sediment contact that is jointly expressed in sediment grain size, geophysics, and geochemistry (Knight et al., 2021).

5.5 Building the ORM three-dimensional Geological Model

The above geological observations, results, and interpretations are integrated at multiple scales to derive a three-dimensional ORM geological model (Logan et al., 2020; Logan et al., 2024). Model development produced a representation of the data-supported and tested conceptual stratigraphic model (Figure 12b; and the animated video⁷). Starting with the detailed surficial geology (Figure 11) that includes thousands of field site observations, and measured sections—e.g., Lake Ontario bluff sections—the three-dimensional ORM geological model used a strategic set of subsurface seismic profiles (Figure 14, Figure 15) and cored borehole results (Figure 16) to establish an initial high-quality geological configuration (Logan et al., 2006). To build a study-area-wide three-dimensional stratigraphic model, abundant, widespread lower-quality data—i.e.,

⁷ Model development begins with conceptual pictures of the geological setting and its likely means of formation. A video animation of the simplified formation of the Oak Ridges Moraine (ORM) may help to make the abstract geological notions in this chapter become more tangible (<https://youtu.be/uaZYKXktyOg>). The video focuses on the origin of the ORM aquifer sediment, 80 km³ of sand and gravel.

water-well records—were then integrated within this reference configuration (Figure 17, Figure 18, Figure 19, Figure 20, Figure 21) to further improve the process models (Figure 22).

Domestic water-well records provide widespread subsurface areal coverage—approximately 85 percent—for a regional three-dimensional model. However, drilling typically stops when household aquifers—approximately 3 gals/min, or 13.6 L/min—are encountered, often well above deeper sequences needed to improve the three-dimensional geological model. These well logs—approximately 34 percent—were not deep enough to encounter bedrock (Figure 13). Less than 5 percent of well logs occur in areas of total sediment thickness >50 m—where municipal wells occur—and the average borehole depth is only approximately 30 m (Logan et al., 2020). Given the depth limitations of water-well records, the acquisition of high-quality geophysical and deep continuously cored borehole data, as described above, is critical for robust geological model development and ongoing testing.

Water-well records have been the primary source of information for groundwater-resource assessment in the ORM region and across Ontario for approximately 80 years. They can yield accurate information on shallow subsurface sediments and groundwater resources but contribute little insight to the development of a conceptual geological model (Figure 12; Logan et al., 2020). Water-well records were of insufficient quality to recognize the presence of buried channels in the ORM area, such as those mapped near Nobleton using seismic profiles and cored boreholes (Figure 15, Figure 16). Water-well records do not lead to advanced conceptual process models (Figure 22) or to the understanding that could anticipate a buried channel network and the accompanying stratigraphic truncation of regional unconformities (Figure 12a; Sharpe et al., 2004). However, once a conceptual geologic model has been developed, water-well records—within a training framework—can contribute to the model by significantly extending its spatial and volumetric coverage. For example, there are several high-yield water wells that intercepted thick sands and/or gravels on the flank of the buried channel near Nobleton (Figure 15, Figure 16a). These wells helped to improve the understanding of the channel sediment orientation and continuity at sites away from, yet related to, high-quality seismic and borehole information. Also, deep water wells are often the only wells available that help to identify deeper bedrock valleys. For example, the Laurentian trough has largely been framed on the basis of deep water well records.

The resultant digital three-dimensional geological model for the ORM region was extracted from a more regional model (Logan et al., 2024), which includes a synthesis of four published local three-dimensional models (refer to Figure 1 in Logan et al., 2024). The model is the result of defining, developing, and testing the conceptual geological model (Figure 12a, b; Logan et al., 2024).

5.5.1 The Completed ORM Three-Dimensional Model

The completed ORM three-dimensional stratigraphic model (Logan et al., 2020) signals significant progress in establishing a geological framework for the large, complex ORM region—approximately 15,000 km². In a similar manner to the ORMGP three-dimensional model that follows, it integrates all the significant elements in the basin analysis database, including a wealth of high-quality surface and subsurface data. Data integration occurred at multiple scales, including (a) site-scale cored boreholes and field mapping sites; (b) sediment architecture from seismic profiles and from landform mapping; and (c) basin-wide topographic and geological structure. The model serves as a benchmark for ongoing enhancement of the geological conceptual and stratigraphic models as new data is collected. Credible testing requires high-resolution subsurface data.

The three-dimensional model also helped delineate hydrostratigraphic units for use within hydrogeological models (Frey et al., 2020). As geological models cover larger areas, defensible geological knowledge becomes more valuable to offset deficiencies in data coverage and quality and to continue to test evolving geological understanding. For example, knowledge of a regional channel network and formative process model (Brennand et al., 2006) aided not only in the design of subsequent field work (location and orientation of seismic surveys and drilling) but also the prediction of the extent of dissection of the regional Newmarket Till sheet (aquitard) and the extent of elongate sand and gravel bodies (channel aquifers) based on modern process analogues (Russell et al., 2007; Iceland glacial and hydrodynamic regime).

Beginning in 2018, the ORMGP website (www.oakridgeswater.ca/[↗]) has made available an up-to-date working version of a similar three-dimensional geological model to that presented above. Since this time, various consultants routinely make use of the ORMGP three-dimensional model, in many ways, in their everyday work to assist their clients in making sound decisions. The three-dimensional model is available for public access, use, and commentary⁸. Following the basin analysis workflow (Section 5.2.2), the

⁸ Since 2001, the ORMGP analysis system has incorporated geological and hydrogeological data from new wells to an updated geological model (Earthfx, 2014; GeoProcess & Papadopoulos, 2021). Provincial updates from the Source Water Protection (SWP) program were also added to improve the understanding of the subsurface geology and hydrogeology. Since 2018, the ORMGP website (www.oakridgewater.ca/[↗]) makes this geological model available to practitioners—consultants, provincial, municipal and conservation authority staff—and all are invited to contribute to updating data and interpretations. Different geological models have and are being constructed by various groups within the study area—e.g., Geological Survey of Canada, Ontario Geological Survey, ORMGP. While all models follow a similar regional stratigraphic framework, differences exist, mainly due to how units are coded—ideally by a knowledgeable and experienced field geologist. Differences are discussed, analyzed, and refined as part of ongoing scientific dialogue and vetting. At times, model differences are portrayed as alternate scenarios (Logan et al. 2024), although high-quality data act as

ORMGP study team regularly incorporates newly acquired geological and hydrogeological data into the model. At the oakridgeswater.ca website, all well site data can be readily accessed, filtered, and queried along with geological cross sections created from the three-dimensional model. Attributes may include depth, sediment type, stratigraphic unit and hydrogeological parameters such as pumping rates and specific capacity estimates.

5.5.2 Model Updates and Geological Correlation and Refinement

Geological map units and names provide shorthand to describe often complex, variable landscape characteristics. They present a qualitative probability of expected sediment properties where data support is lacking. Characterization of a regional glacial landscape at multiple map scales calls for terminology consistent with the most up-to-date datasets and concepts as presented in the above discussion. This involves a continuing process of testing and updating the conceptual model (Figure 2; Sharpe, Hinton et al., 2002). We have expanded current geological descriptions to explain unit revisions and refinements to the conceptual geological model (Figure 12) within the Geological Framework section. Use of these changes is recommended in future reporting to present consistent correlation, reporting across the area, and links to available high-quality datasets. Nonetheless, some terms (upper and lower Newmarket Till, Inter-Newmarket Sediments) are used in the next section to maintain continuity with the hydrogeological literature. Most importantly, these revisions link geological variability to hydrogeologic heterogeneity also observed in hydraulic response data (Gerber & Howard, 2002).

To illustrate the link between geological names and hydrogeology (groundwater flow), we briefly review the geology of the till plain south of ORM and north of Lake Ontario (Figure 11). Here, sand beds occur between till units in three different yet nearby geological settings. Various names have been used to describe the south slope till plain; however, a detailed map based on more than 2,000 field sites (Sharpe & Barnett, 1997; Figure 11) is the reference standard for unit characterization, supplemented with coded core logs (Sibul et al., 1977).

On the south slope till plain, three sand bed scenarios may occur within approximately 25 m depth of land surface (Sharpe & Russell, 2016; Figure 13): (a) Halton Till overlies ORM sand and Newmarket Till on the south flank of ORM; (b) Newmarket Till, found south of the ORM covering most of the south slope till plain, has interbedded sand and till with approximately 1 to 3-m-thick sand units; and, (c) where Newmarket Till is eroded and thin (<10 m), Thorncliffe Formation sand occurs below Newmarket Till, close to land surface (<25 m; Sharpe & Russell, 2016; Figure 13). Thus, within approximately

decisive reference points (Sharpe et al., 2011). The geologic literature related to the study area contains differences in described unit identification and extent as briefly outlined in sections 5.4.3, 5.4.5, and 5.5.2. The hydrogeologic conceptual model of the flow system presented in subsequent sections of this book accounts for these differences by focusing on incorporating unit coverage and sediment properties.

25 m of land surface, three prominent sand bed units—ORM, Newmarket Till sand beds, Thorncliffe Formation—within three different geological units and ages can best be described as a common aquifer unit or local groundwater flow system. In the next section, we present the idea of combining the units to create a single hydrogeological element where data support is lacking to identify the three different geological units.

In short, referenced geological units aid correlation and prediction of sediment properties and their variance, where data support can overcome local complexity. Unit names with expected characteristics carry more weight when extrapolating from site to regional scales, where in situ observations and measurements become sparse.

5.6 Summary

A geological framework for the ORM glaciated region was developed based on basin analysis methodology. Detailed mapping efforts discussed above have focused on the integration of historical and new observations, including targeted high-resolution geophysical, geological (borehole), geochemical and improved physiographic (DEM) mapping techniques (Sharpe & Smart, 2025). These datasets enabled the building of innovative conceptual and related process models that best explain the entire assembled data. Dataset collection focused on a basin analysis workflow that characterized the geological character, origin, and history of the (ORM) glaciated terrain. Basin understanding proceeded progressively using a multi-scaled and multidisciplinary approach that fostered iterative data testing and analysis. The classical notion of a layer-cake, lithologic stratigraphy has been updated significantly using high-resolution geophysical surveys that mapped regional unit truncation and deep incision of networks of previously undocumented glaciofluvial channels. Detailed geological mapping inspired new conceptual thinking that anchored the three-dimensional model by contributing densely supported, site-specific data to the existing regional scale two-dimensional model.

Four main stratigraphic volumes, structures and compositions comprise the geological framework.

1. Lower Sediment is approximately 100 m thick over a large portion of the region—approximately 11,000 km²—and is overlain by a regional till aquitard unit. Thorncliffe Formation is most prominent, comprising about 70 percent of Lower Sediment within an approximately 400-km³ mud basin with channelized gravel and sandy fans. Lower Sediment rests on sedimentary bedrock and includes several glaciogenic units that followed the last interglacial, an interval with a basin drainage system likely similar to modern day. As glaciers returned, drainage became disrupted, and ice eventually blocked the St. Lawrence valley drainage of the Great Lakes. This blockage resulted in the widespread deposition of fine-grained sediment with intercalated sand beds such as Scarborough (delta) and Thorncliffe (channel-fan) Formations in a ponded

environment with thicker sediment accumulating within the large bedrock trough east of the Niagara Escarpment.

2. Newmarket Till is a regional approximately 5 to 50-m-thick, dense diamicton (Figure 11) that separates Lower Sediment mud and sand from overlying ORM sand and gravel. The regional continuity of the Newmarket Till sheet was dissected by a network of large meltwater channels of varying depths, including erosion into bedrock. Dissection through approximately 25 percent of Newmarket Till created an irregular till sheet with landscape elements approximately 5 to 10 km by 10 to 20 km long with adjacent valleys and wetlands of <75 m combined relief. Newmarket Till has uniform and consistent regional characteristics with few interbeds, and it has locally variable characteristics consisting of thin sandy interbeds (<1 m) and rare thick (~10-m) beds. This range in scales of variability in Newmarket Till occurrence and properties results in significant hydrogeological heterogeneity.
3. Oak Ridges Moraine comprises two distinct architectures: (a) channel sediment (fines upward) deposited within NE–SW-oriented sequences and (b) ridge sediment deposited within four main east–west-oriented, esker-fan sediment wedges (Barnett et al., 1998; Figure 11, Figure 19, Figure 20, Figure 21; Sharpe & Russell, 2023). Channel sediments are up to approximately 150 m thick, fining upward gravel-sand-mud successions. These sediments occur in ascending facies transitions (Russell, Arnott, & Sharpe, 2003): (a) gravel bed forms and sheets; (b) graded to cross-bedded sand; (c) laminated fine sand; and (d) fine sand to silt-clay rhythmities (Figure 16b; Sharpe & Russell, 2023; Figure 20f). Ridge sediments fine regionally from east to west, are up to approximately 50 m thick (Figure 19, Figure 20, Figure 21), and each ridge wedge consists of a westward fining gravel-sand-mud sequence, away from the sediment source. Of note, gravel occurs as large, approximately 100-m-long E–W directional forms in eastern wedges, whereas the western ridge consists of thick sets of fine sand to silt-clay rhythmities (Figure 16b; Sharpe & Russell, 2023). ORM ridge fining-west deposition occurs as subaqueous fans (Figure 22) fed by channels and/or eskers. The fan sediment architecture occurs in ORM at several scales, from hundreds of meters in length (many in wedges) to kilometers (within wedges) to potentially the scale of the full ORM ridge landform (Figure 11). In Figure 11, ORM sand and gravel is narrow in the east and wider in the west where it is covered with Halton mud, thus constituting one large esker-fan setting.
4. Halton sediment, a muddy diamicton <20 to 50 m thick, onlaps west central and southern ORM flanks (Figure 11c, Figure 19) with an interbedded to transitional deposition from sandy ORM sediment. The presence of numerous depressions—dry depressions or with kettle lakes—on the Halton Till surface

indicates melted former ice blocks within ORM sediments (Russell & Arnott, 2003). Such ice blocks are indicative of Icelandic flood sedimentation (Roberts, 2005). The common presence of dry depressions within hummocky terrain likely provides improved hydraulic connection to ORM sand and gravel (Sharpe & Russell, 2016). In brief, detailed mapping and analysis of ORM regional glacial landform-sediment design and composition led to the formulation of a sound, testable geological model, a key component of the study area flow system conceptual model. Widespread drumlinized till plains, dissected by meltwater channels and inset with channel sediment and eskers, represent a high proportion and character of the ORM landscape. This clear depiction of the regional geological architecture provides support for the meltwater flood erosion-deposition model that is put forward as the possible origin of most of the major aquifers in the ORM region (e.g., Yonge Street Aquifer; Gerber et al., 2018; Sharpe et al., 2025). This process model is consistent with, and supports, the conceptual geological model, as depicted in Figure 12 and Figure 14, and allows for the construction of a defensible three-dimensional geological framework for the ORM region.

6 Hydrogeology

A robust three-dimensional geologic framework is vital to understand how a groundwater flow system functions. Section 5 describes the work undertaken and the methods used to understand the depositional setting and develop the current geologic framework. This includes the identification of key geological components or elements that might influence groundwater flow. This section describes the current understanding of how water flows within the study area. Central to this understanding is that both surface water and groundwater are connected to form the flow system. As in the previous geology discussion, this hydrogeology section starts with a description of the various datasets and analysis tools that have been used to understand the groundwater flow system.

6.1 Data and Analysis System

Common data needs exist for many applications related to any hydrogeological analysis. For example, hydraulic head data from monitoring wells are essential to estimate groundwater flow directions and hydraulic gradients. Similarly, groundwater chemistry can be used to examine spatial and temporal trends in water quality, to delineate natural groundwater evolution and processes, and to investigate how land use might be affecting groundwater resources.

Acquiring these subsurface data is costly. In a limited funding world, it is prudent to share information that is generated by many different government and private-sector undertakings. In this way, all organizations using a common data source can readily identify data gaps and explore opportunities in their ongoing roles to infill them, thus building upon current groundwater flow system understanding. The ORMGP manages and interprets data and information from many different agencies. The premise is that robust, coordinated consolidated groundwater knowledge and technical understanding will be shared among many different agencies, and will lead to more timely and effective water-resource-management decisions.

The pyramid diagram (Figure 2) summarizes much of what is unique about the approach to water management taken at the ORMGP. Firstly, the structure of the pyramid conveys the idea that each plank or layer of the pyramid is built upon the one below. The importance of data at the base of the pyramid is emphasized, including: (a) accessibility; (b) the value of both new and archival data; (c) reliability, including the need for proper maintenance, management, and appropriate QA/QC procedures; and (d) regular database updates. Building upon the data foundation are the planks of geology (presented in Section 5), and hydrogeology (presented here in Section 6). With those elements carefully constructed, numerical modeling can be used as an effective tool to investigate the groundwater system and its inherent links to climate and streamflow. Where forward-looking land use decision-making procedures are put in place, all the information

gleaned from the lower part of the pyramid can be applied to enhance effective decision-making.

The second unique aspect of the pyramid (Figure 2) is that of the recursive nature of the ORMGP analysis system as underscored by the arrows. The need to regularly circle back from past predictions and/or decisions, and the monitoring data collected from these decisions, to learn from the past—e.g., how well predictions held up—is critical. Adjustments are regularly necessary at each plank of the pyramid as new data is collected and analyzed, forcing reconsideration of previous assumptions. All of this makes for a robust system that should be used over the long term to drive many types of land use and water-management decisions. Key ORMGP elements include

- a focus on data management;
- mapping, including various GIS products—for example, ground surface digital elevation model (DEM) and lake bathymetry;
- three-dimensional geologic and hydrogeologic interpretations;
- access to a library of relevant technical consultant, government, and research reports and papers;
- statistical and graphical data analysis tools; and
- numerical models of the flow system.

The understanding obtained from all these elements is combined into a hydrogeological conceptual model of the flow system, subject to continual testing and refinement as new information becomes available.

6.1.1 Data Sources

The geologically related data and information collection methods described in Section 5 are also useful for hydrogeological analysis. These data include geologic maps, surface and borehole geophysical surveys, borehole logs, particularly continuous coring of rock and sediment, along with associated testing—geotechnical, mineralogic, and chemical analyses. These data are combined and interpreted to construct a three-dimensional geological model, but to extend the geological interpretation into a full hydrogeological conceptual model, more data and analyses are necessary. Key additional data requirements include measurements of groundwater levels, groundwater chemistry, and estimates of porous media hydraulic properties, including hydraulic response to various imposed stresses on the flow system induced both naturally and anthropogenically—e.g., climate, pumping tests.

Wells installed for water supply, investigation, and/or monitoring are required by Ontario law to have a qualified driller/technician complete the work and to have a well record prepared by a qualified installer or well driller/technician. This well record is submitted to the Province of Ontario and is added to a provincial database. Prior to 2003, this was only required for water well records, and other wells or boreholes were exempt.

However, it has been noticed that wells recorded within consulting reports can sometimes be absent from the provincial database. Wells or piezometers installed under the direction of a consultant may also have a more detailed borehole/well log prepared by a qualified consultant, engineer, geologist, or technician and may be included in a consulting project report. Water-well records submitted to the province are publicly available, whereas consultant reports commonly have limited distribution. It is noteworthy that, in addition to regularly importing and updating the provincial wells, that the ORMGP regularly digitizes and adds important, previously undocumented wells, either from older consulting or government reports, or newer wells that are absent from the provincial database, into the ORMGP database. This has resulted in the ORMGP database being the most robust, comprehensive hydrogeological database across the study area. An example of a water-well record that is submitted to the province is included in Figure 24. While the actual format of the form used has evolved over time, water-well records have been collected by the province since the 1950s, with some records dating back to 1899 (<https://www.ontario.ca/page/well-records>⁷).

Ontario Ministry of the Environment and Climate Change

Well Tag No. (Place Sticker and/or Print Below) **A172641**

Well Record
Regulation 903 Ontario Water Resources Act
Page 1 of 2

Measurements recorded in: ☒ Metric ☐ Imperial

Well Owner's Information

First Name: _____ Last Name / Organization: **The Regional Municipality of York** E-mail Address: _____
☐ Well Constructed by Well Owner

Mailing Address (Street Number/Name): **17250 Yonge Street** Municipality: **Newmarket** Province: **ON** Postal Code: **L3Y6Z1** Telephone No. (inc. area code): _____

Well Location

Address of Well Location (Street Number/Name): **256 Old Yonge Street** Township: _____ Lot: **25** Concession: **2**
 County/District/Municipality: **York** City/Town/Village: **Aurora** Province: **Ontario** Postal Code: _____

UTM Coordinates Zone: **18** Easting: **762262** Northing: **4875024** Municipal Plan and Sublot Number: _____

Overburden and Bedrock Materials/Abandonment Sealing Record (see instructions on the back of this form)

General Colour	Most Common Material	Other Materials	General Description	Depth (m/ft)
From	To			From To
	Topsoil			0 0.61
Brown	Clay			0.61 6.40
Grey	Clay	Soft		6.40 19.82
Grey	Gravel	Sand		19.82 33.54
Grey	Clay	Gravel		33.54 49.09
Grey	Clay	Dense		49.09 67.38
Grey	Silt			67.38 73.17
Grey	Fine-Med Sand			73.17 87.80
Grey	Gravel	Sand		87.80 99.70

Annular Space

Depth Set at (m/ft)	Type of Sealant Used (Material and Type)	Volume Placed (m³/ft³)
From	To	
47.3	46.0 Bentonite	0.173
46.0	0 Cement Grout	6.12

Method of Construction

☐ Cable Tool ☐ Diamond ☐ Public ☐ Commercial ☐ Not used
☒ Rotary (Conventional) ☐ Jetting ☐ Domestic ☒ Municipal ☐ Dewatering
☐ Rotary (Reverse) ☐ Driving ☐ Livestock ☐ Test Hole ☐ Monitoring
☐ Boring ☐ Digging ☐ Irrigation ☐ Cooling & Air Conditioning
☐ Air percussion ☐ Industrial ☐ Other, specify _____

Well Use

☐ Water Supply ☐ Replacement Well ☐ Test Hole ☐ Recharge Well ☐ Dewatering Well ☐ Observation and/or Monitoring Hole ☐ Alteration (Construction) ☐ Abandoned, Insufficient Supply ☐ Abandoned, Poor Water Quality ☐ Abandoned, other, specify _____
☒ Other, specify _____

Construction Record - Casing

Inside Diameter (cm/in)	Open Hole OR Material (Galvanized, Fibreglass, Concrete, Plastic, Steel)	Wall Thickness (cm/in)	Depth (m/ft)	Status of Well
			From To	
30.5	Steel	0.95	1.0 89.6	☒ Water Supply ☐ Replacement Well ☐ Test Hole ☐ Recharge Well ☐ Dewatering Well ☐ Observation and/or Monitoring Hole ☐ Alteration (Construction) ☐ Abandoned, Insufficient Supply ☐ Abandoned, Poor Water Quality ☐ Abandoned, other, specify _____ ☐ Other, specify _____

Construction Record - Screen

Outside Diameter (cm/in)	Material (Plastic, Galvanized, Steel)	Slot No.	Depth (m/ft)
			From To
26.7	Steel	80	89.6 92.7
26.7	Steel	60	92.7 97.5

Water Details

Water found at Depth (m/ft)	Kind of Water: ☐ Fresh ☒ Untested	Depth (m/ft)	Hole Diameter (cm/in)
		From To	
32.9 - 107	☐ Gas ☐ Other, specify _____	0 47.3	51.0
	☐ Fresh ☐ Untested	47.3 97.5	32.4
	☐ Gas ☐ Other, specify _____	97.5 102.7	15.24

Well Contractor and Well Technician Information

Business Name of Well Contractor: **Gerrets Drilling 2014 Inc.** Well Contractor's Licence No.: **75164**
 Business Address (Street Number/Name): **215154 10th Line** Municipality: **Aurora**
 Province: **ON** Postal Code: **L9W0G8** Business E-mail Address: _____
 Bus. Telephone No. (inc. area code): _____ Name of Well Technician (Last Name, First Name): **Devon Best**
 Well Technician's Licence No.: **34443** Signature of Technician and/or Contractor: **Devon Best** Date Submitted: **2016/09/15**

Results of Well Yield Testing

After test of well yield, water was: ☒ Clear and sand free ☐ Other, specify _____

If pumping discontinued, give reason: _____

Pump intake set at (m/ft): **56.11**

Pumping rate (l/min / GPM): **3300**

Duration of pumping: **72 hrs + 0 min**

Final water level end of pumping (m/ft): **18.61**

If flowing give rate (l/min / GPM): _____

Static Level	Draw Down	Recovery	
Time (min)	Water Level (m/ft)	Time (min)	Water Level (m/ft)
13.61			
1	14.41	1	17.35
2	14.44	2	17.33
3	14.47	3	17.28
4	14.48	4	17.24
5	14.50	5	17.23
10	14.54	10	17.12
15	14.57	15	17.04
20	14.61	20	16.99
25	14.62	25	16.94
30	14.64	30	16.90
40	14.68	40	16.84
50	14.72	50	16.77
60	14.74	60	16.72

Map of Well Location

Please provide a map below following instructions on the back.

Comments: **Pumping & Chlorination completed Aurora by Lotawater**

Well owner's information package delivered: **2016/09/15** Date Work Completed: **2016/09/15**

Ministry Use Only
 Audit No.: **2228675**
 Date Submitted: **APR 11 2017**

0506E (2014/11) Ministry's Copy © Queen's Printer for Ontario, 2014

Figure 24 - Example of a water-well record that must be submitted to the Province of Ontario for well installation, maintenance, or decommissioning of any well or piezometer (monitoring well). Requirements and recommendations for water-supply wells in Ontario are available at the Ontario Ministry of the Environment (2015) (<https://www.ontario.ca/document/water-supply-wells-requirements-and-best-practices>). Source-water well record may be obtained at Ontario Ministry of Environment, Conservation and Parks; ontario.ca/page/map-well-records.

In Ontario, water-supply wells drilled for domestic use generally have only a short-term (1 to 2 hours) pumping test undertaken upon well completion, and water sampling/analysis is not typically done. However, many consultants' well installations are also subject to various hydraulic tests, including slug tests and pumping tests. Further, long-term monitoring and groundwater sampling are often undertaken at some of these wells. When available, all these data are linked to the correct screened interval and stored in the ORMGP database, thus adding a level of sophistication and practicality that is missing from the provincial and other databases. The various subsurface observations and data generated by any well installation are considered as reliable as the objectives and training of those conducting the work. For example, geologic observations and hydrogeological measurements collected by staff from the Ontario Geological Survey, Geological Survey of Canada, consulting firms, or researchers at a university, often have a higher reliability than information generated during installation of a private well. In the latter case, the drilling team may not have specific geologic training but are skilled in drilling and installing a properly functioning well for a water supply.

6.1.2 Long-Term Monitoring – Groundwater and Surface Water

Groundwater level (quantity) and quality data, along with stream flow (quantity) and quality data, are vital to any hydrogeological analysis. Monitoring data are necessary not only for purposes such as compliance with permitting conditions but also for testing and refinement of conceptual models of the flow system, and determination of trends including seasonal and longer-term (e.g., changing climate). These data are also needed to calibrate and test numerical flow system models. Climate data are also vital to any hydrogeologic analysis. The climate for the study area is discussed in Section 3. In general, most of the climate data—e.g., precipitation, temperature, wind speed, humidity—within the study area are collected and disseminated by the Canadian federal government through Environment and Climate Change Canada. These data are regularly imported into the ORMGP database, and are readily available on the ORMGP website in various formats—i.e., graphs, tables, etc. On a more limited basis, some of the climate data that are also collected by other agencies, such as the provincial government, municipalities, and conservation authorities, can also be found within the ORMGP database.

Monitoring of groundwater and streams is currently conducted by various agencies including federal, provincial, conservation authority, municipal, consulting, and research groups. Some monitoring programs are focused on natural, or background, groundwater level fluctuations and chemistry—e.g., ORMGP, PGMN—while others, such as consultants and municipalities, often monitor in the vicinity of spills or other contaminant sources or in areas where municipal groundwater-supply pumping occurs. These latter wells therefore may be subject to anthropogenic impacts to both groundwater quality and levels. Long-term groundwater monitoring locations managed by the ORMGP are focused on characterization of different hydrogeologic settings that constitute the conceptual model

(e.g., bedrock valley, channel, or till plain). A summary of some of the monitoring networks that currently exist within the study area is listed in Table 2. Data from all of programs listed in Table 2 are included in the ORMGP database.

Table 2 - Summary of groundwater and surface water monitoring within the study area. *Quality* refers to analyses of groundwater chemistry. *Regular* observations refer to monthly or hourly measurements. *Periodic* refers to snapshot measurement or sampling events.

Medium	Program	Agency	Quantity	Quality	Inception
Groundwater					
1	Provincial Groundwater Monitoring Network (PGMN)	Provincial government and conservation authorities	Regular	Regular	2001
2	Municipal	Municipal	Regular	Regular	1970s
3	Oak Ridges Moraine Groundwater Program (ORMGP)	ORMGP	Regular	Periodic	2001
Surface water (streams)					
1	HYDAT	Environment Canada	Regular	None	1960s
2	Provincial Water Quality Monitoring Network (PWQMN)	Provincial government	None	Regular	1960s
3	Watershed monitoring programs	Conservation authorities (CA)	Regular	Regular	1980s
4	Low-flow streamflow surveys	Conservation authorities (CA)	Periodic	Periodic	1990s

^aThe above monitoring information is included in the ORMGP database and available at www.oakridgeswater.ca/.

The number and locations of monitoring stations by each program do not necessarily remain constant and that they, historically, have changed, largely depending on agency technical needs and funding availability. Monitoring locations are also evolving to become more integrated with data users belonging to various organizations. For example, monitoring locations that have been discontinued by one program have been continued by another program—e.g., some discontinued PWQMN locations have been continued by the local conservation authority and included in their watershed-monitoring programs. Regardless of which agency collects information, the ORMGP incorporates data from all the monitoring programs listed in Table 2, allowing for integrative analyses to be undertaken. Further exploration of these data can be found at www.oakridgeswater.ca/. Figure 25, Figure 26, and Figure 27 provide illustrations of maps that can be generated on the ORM website displaying monitoring-location density for both groundwater and surface water (rivers and streams) within the study area.

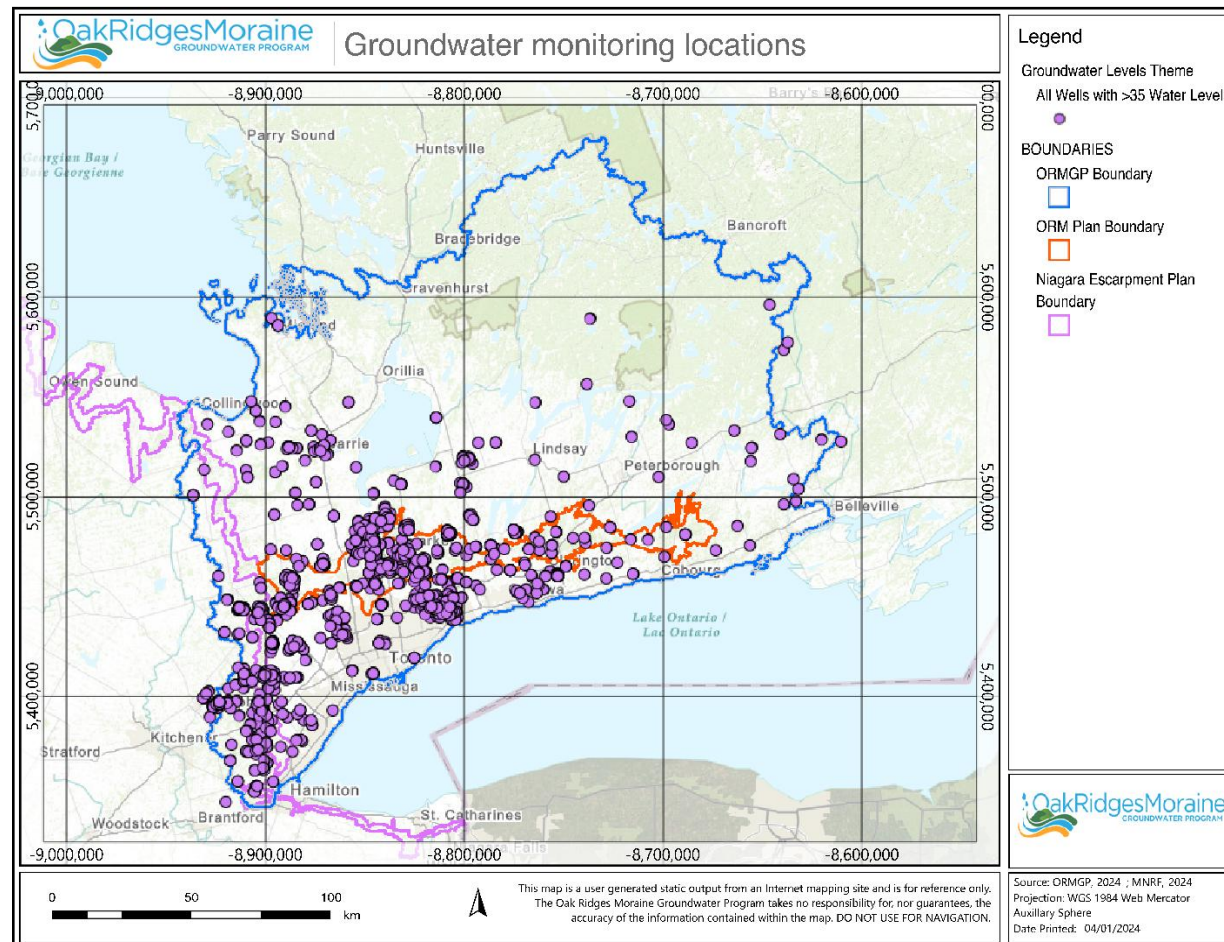


Figure 25 - Long-term groundwater monitoring locations in the study area. Locations of wells that have more than 35 groundwater-level readings are shown. These monitoring locations are distinguished from Ontario MECP water well records, which will have fewer than 35 groundwater level readings collected during testing of newly constructed water supply wells. In the ORMGP database, there are more than 1,100 wells that have had dataloggers installed. Approximately 700 monitoring wells in the database are currently active based on groundwater level readings within the last two years. Groundwater monitoring locations and groundwater level data can be further explored at [ORMGP-Maps-groundwater levels theme](#) and [ORMGP-Data Snapshot-groundwater level variability](#).

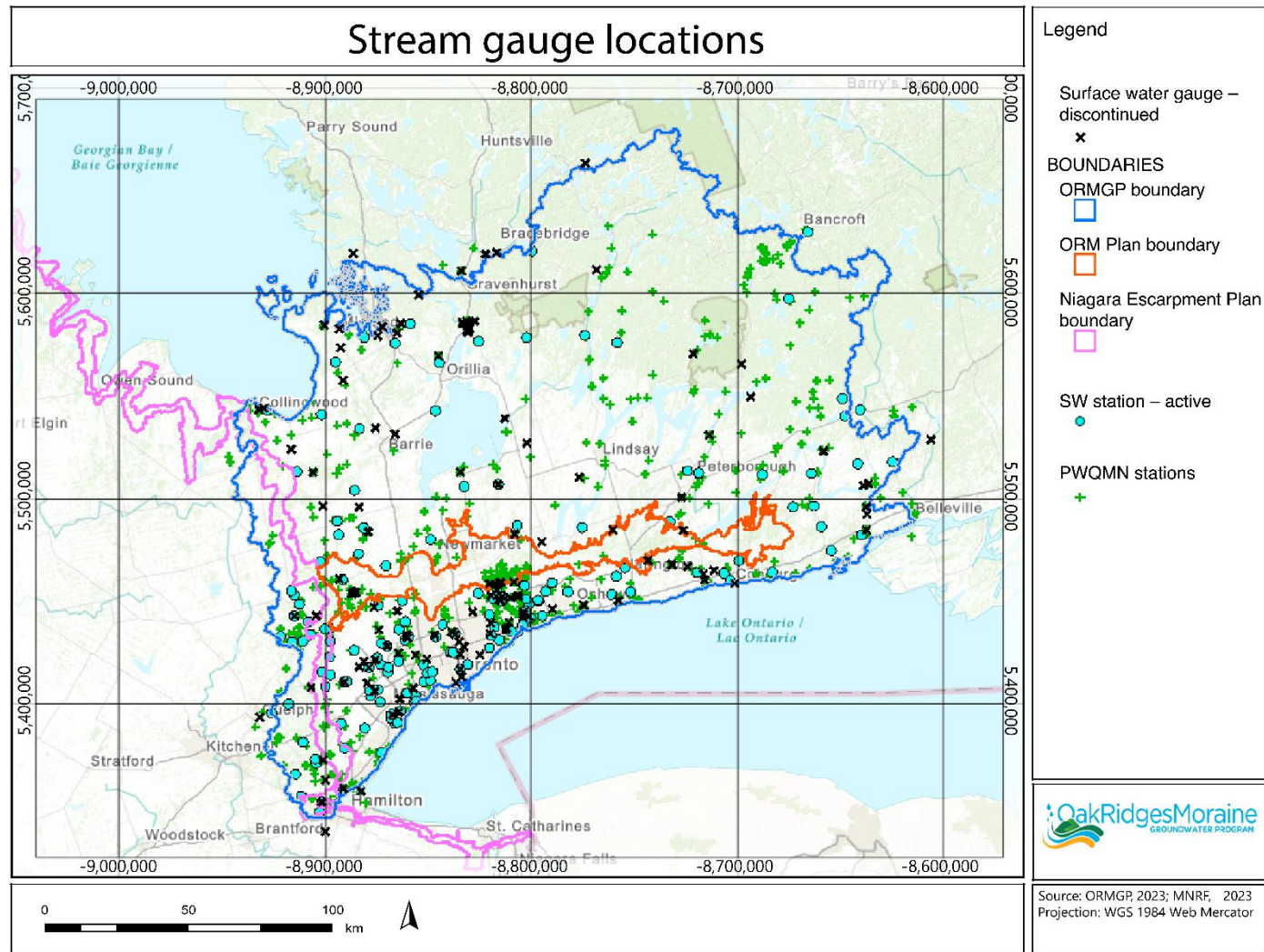


Figure 26 – Gauged surface water monitoring locations in the study area. PWQMN stations measure surface-water quality. Surface water monitoring locations can be further explored at [ORMGP-Maps-locations theme](#). Flow data including various statistical analyses can be explored at [ORMGP-Hydrograph explorer](#).

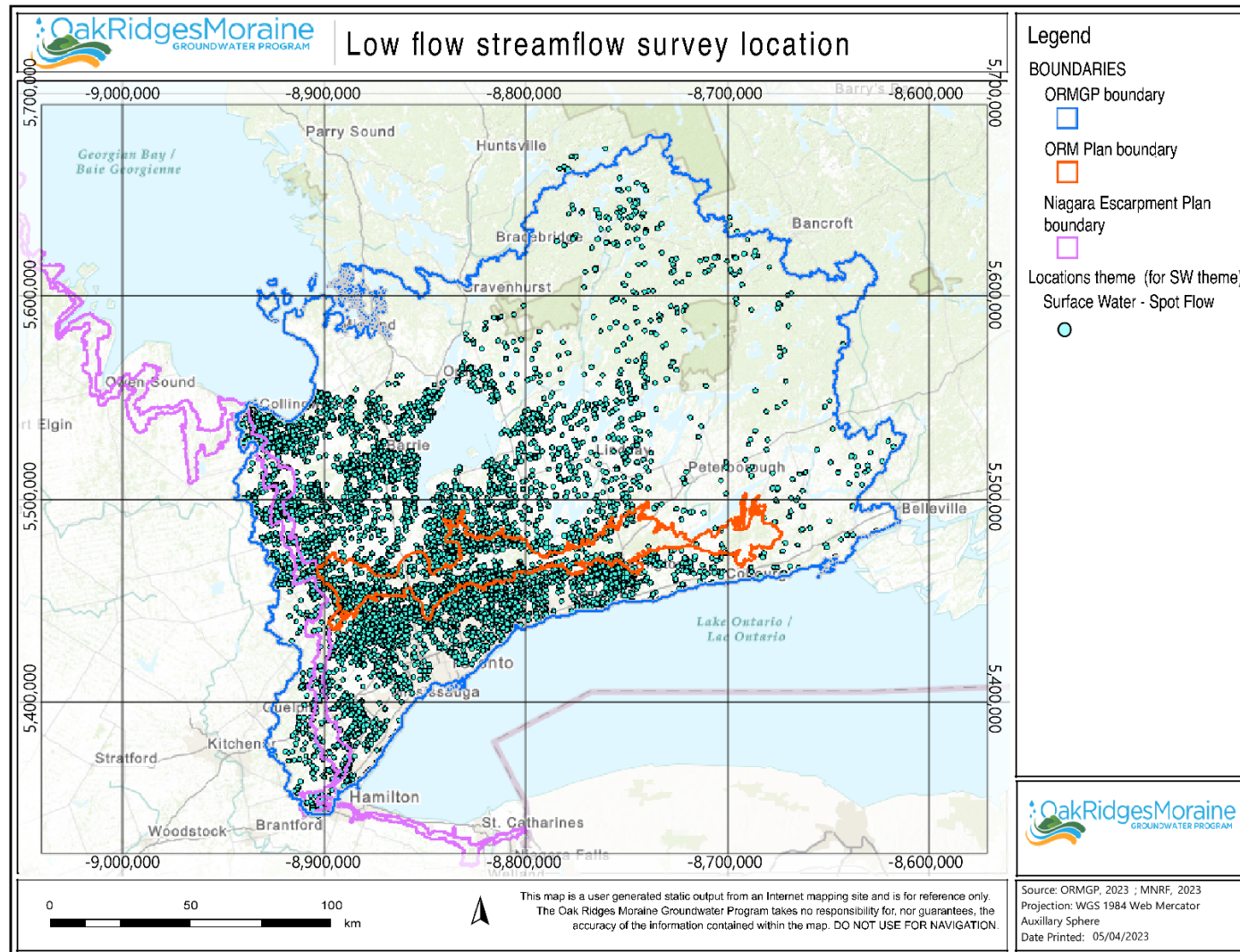


Figure 27 - Low-flow streamflow survey locations. The locations and data can be further explored at [ORMGP-Maps-locations theme](#) and [ORMGP-Tool-spot flow \(baseflow\)](#).

6.1.3 Numerical Model Archive

Within the ORMGP area, numerical groundwater flow models have been used in a wide variety of applications, including the testing of conceptual models of flow system behavior, delineating planning areas such as wellhead protection areas, which may have certain land use restrictions applied, pumping well vulnerability analyses, preparation of watershed-based water budgets related to drinking-water source protection, and prediction or scenario analysis where changes in stressors—e.g., pumping scenarios, climate change—are applied to the flow system. Anderson and Woessner (1992) suggest that “most modeling efforts are aimed at predicting the consequences of a proposed action.” Often water-management issues and analyses are complex and require the consideration of many factors and details related to flow system configurations and properties. Numerical models allow for the incorporation of increasing complexity to analyze various problems and scenarios.

It is worth noting that the output from models is only as reliable as the information input into the model and that model results or simulations do not provide the answer; rather, they provide approximations that when used with expert knowledge and experience can help to formulate a better understanding of the flow system, ultimately helping to address water-resource issues. Models allow for the consideration of the best readily available information. In the study area, the input data and a conceptual model or interpretation of the flow system are maintained by the ORMGP and are thought of as *numerical model building blocks* (Figure 28). An important aspect shown in Figure 28 is the iterative nature of the analysis, emphasizing ongoing regular refinement. Interesting discussions on the use and evolution of numerical models are included in Andersen and others (2018); Berg and Sudicky (2019); Bredehoeft (2010); Bredehoeft and Konikow (2012); and Konikow (1986, 2011).

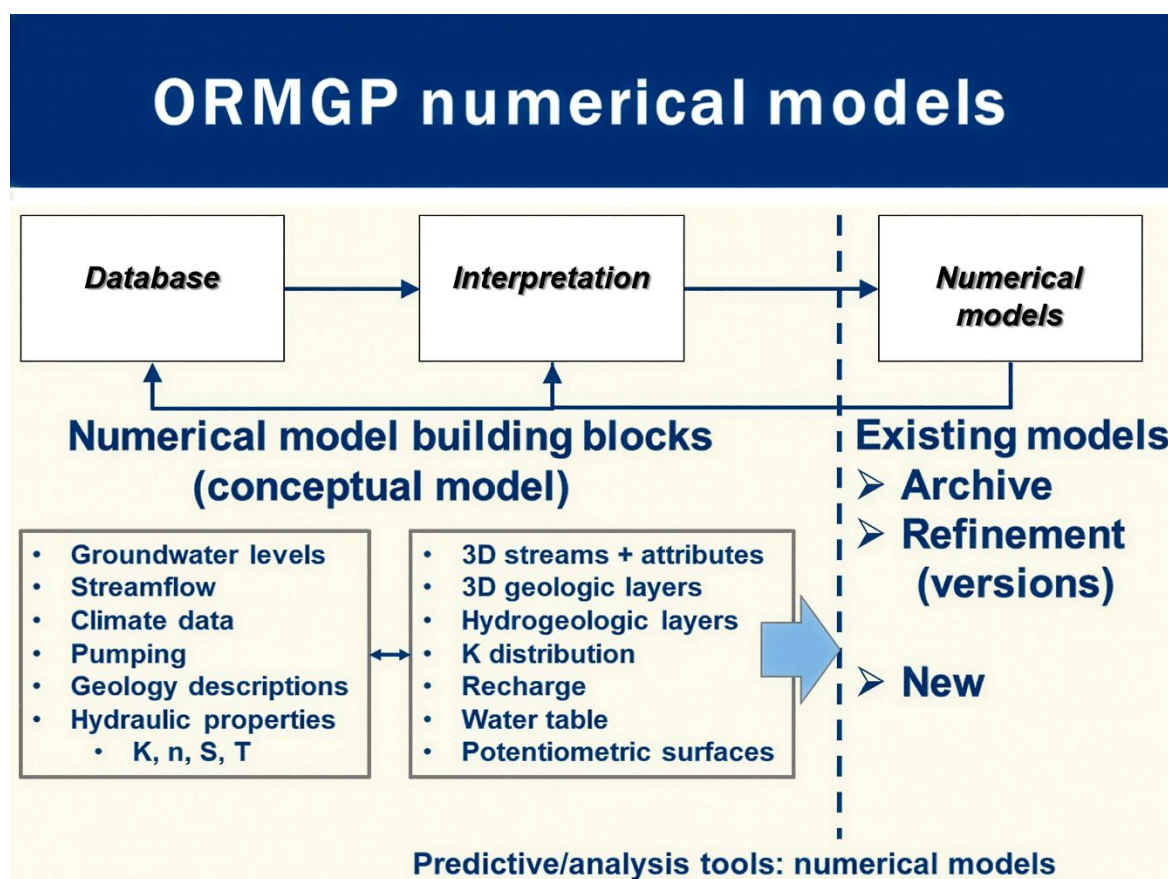


Figure 28 - Numerical model building blocks and numerical model archive. Numerical model building blocks—data and interpretations—are the first two levels forming the base of the information and analysis system outlined in the pyramid diagram in Figure 2. Numerical model construction needs a strong foundation of data and sound interpretations.

Within the study area, the numerous groundwater and integrated surface water/groundwater numerical flow models have been assembled into the Numerical Model Custodianship Program, where model files and reports are archived and made available for future use. When models are requested for reuse, model-sharing agreements are put in place and a versioning system is developed, which also includes documentation of model changes between versions. Currently there are over 90 models available in the ORMGP archive. On the ORMGP website, users can access an overview of the model and obtain model-related reports to see whether specific models might prove beneficial to their ongoing analyses (Figure 29). The models exist at scales ranging from sub-watershed to regional, depending on the objectives. Objectives of the model management component of the ORMGP are to continue analyzing and refining the conceptual model (Figure 10) of the groundwater flow system and to continue leveraging previous efforts and analyses in an iterative learning process (Andersen et al., 2018). Considerations for future model use can be found in a York Peel Durham Toronto–Conservation Authorities Moraine Coalition report (2009). The philosophy and outline of the ORMGP model custodianship program are discussed in Marchildon and others (2017) which is available at www.oakridgeswater.ca/reports.

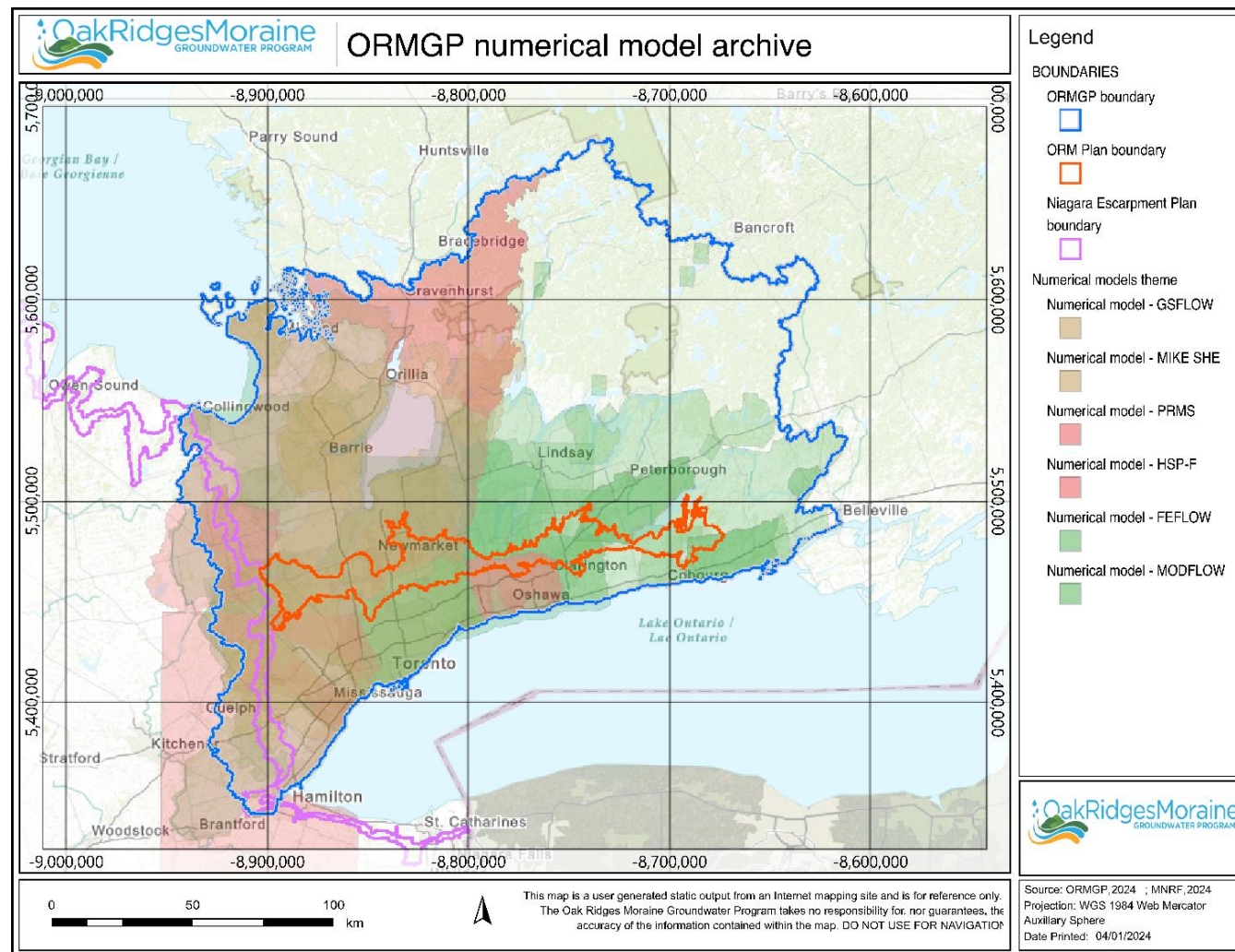
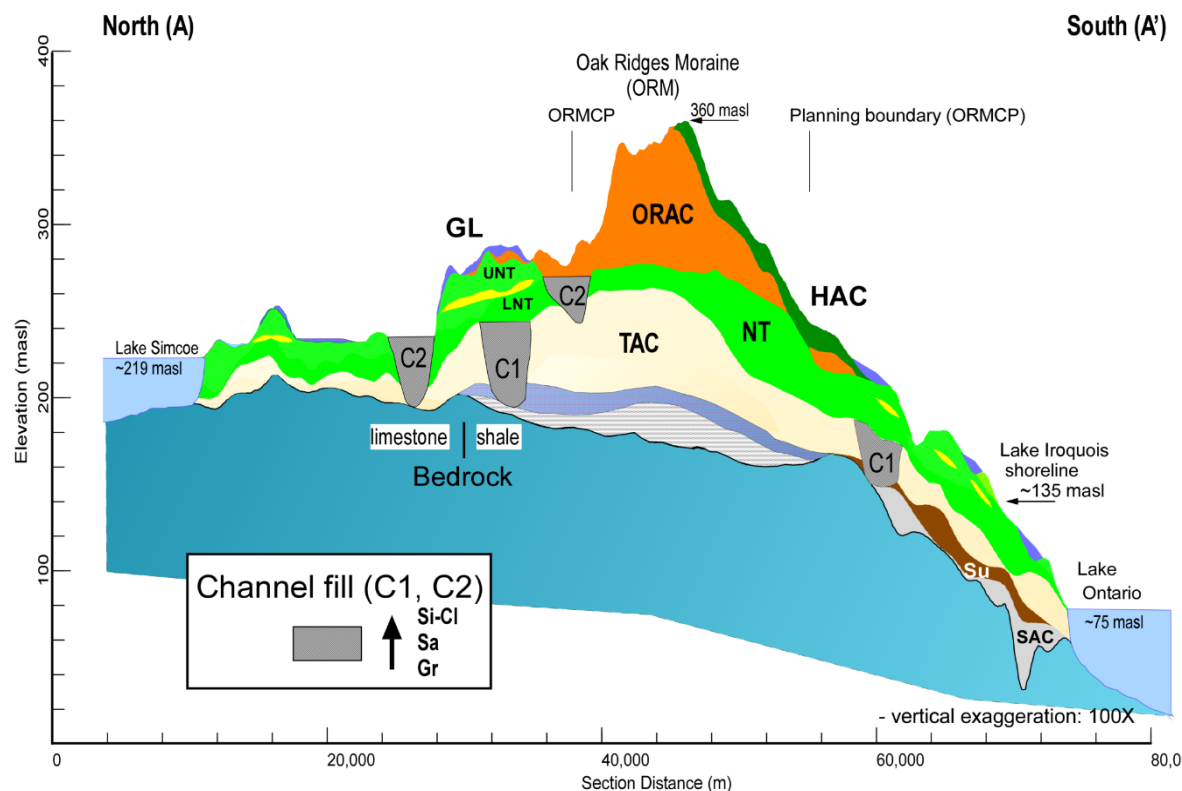


Figure 29 - Extent of more than 90 numerical models that are currently archived in the ORMGP model custodianship program. Locations of groundwater models along with the associated supporting technical reports can be found at [ORMGP-Maps-numerical models theme](#). A further summary of the numerical model custodianship program can be found at [ORMGP-Data Snapshot-numerical models](#).

6.2 Hydrostratigraphy

Typically, either geologic layers or formations are classified into hydrostratigraphic units for analysis during hydrogeologic investigations. A hydrostratigraphic unit is a geologic formation, part of a formation, a group of formations, or a group of zones of a group of formations with similar hydrologic characteristics or properties—e.g., hydraulic conductivity or permeability. Hydrostratigraphic units are classified into aquifer or aquitard units (Domenico & Schwartz, 1998; Fetter, 2001; Freeze & Cherry, 1979; Seaber, 1988). Fluids flow more readily through aquifer units—e.g., sand and gravel—compared to aquitard units—e.g., clay and till. The five main geologic units discussed in Section 5 that occur within the study area have been subdivided and classified into hydrostratigraphic units (Figure 30), with the hydrostratigraphic complexity largely being addressed through hydraulic conductivity variation. This interpretation, as with many aspects of the ORMGP program, is subject to refinement as new subsurface information becomes available. Also, the geologic literature for the study area contains differences in interpretation, particularly regarding provenance and depositional environments. The hydrostratigraphic framework discussed in this section is seen as containing enough lithologic information to accommodate differences of geologic interpretation. Nomenclature from the geologic literature is used in this hydrostratigraphic framework, thus allowing for the use of documented material descriptions and, by extension, relative hydrogeologic properties—e.g., hydraulic conductivity. The units can be placed in order based on superposition or stratigraphic position.



Geologic unit ^a	Hydrostratigraphic unit ^a	Type	
5) Halton Sediment (H)	Recent ^b /Glaciolacustrine (GL)	Aquifer or aquitard	Upper/shallower
	① Halton Aquitard Complex (HAC)	Aquitard	
	- Halton Sediment deposits (or equivalent; till, Cl, Si)		
4) Oak Ridges Moraine (ORM)	② Oak Ridges Aquifer Complex (ORAC)		Upper/shallower
unconformity ^c	③ ORM Channel (C2)	Aquitard/aquifer	
3) Newmarket Till (NT)	④ Upper Newmarket Till (UNT)	Aquitard	
	⑤ Inter-Newmarket Sediments (INS)	Aquifer	
	⑥ Lower Newmarket Till (LNT)	Aquitard	
unconformity ^c	⑦ Thorncliffe Channel (C1)	Aquitard/aquifer	Lower/deeper
2) Lower Sediments (LS)	⑧ Thorncliffe Aquifer Complex (TAC)		
	- Thorncliffe Fm. (TF) deposits (or equivalent) - Facies changes according to proximal/distal relationship to sediment source		
	Silt, clay	Aquitard	
	Sand	Aquifer	
	⑨ Sunnybrook Drift (Su) ^d	Aquitard	
	⑩ Scarborough Aquifer Complex (SAC)		
	- Scarborough Fm. (SF) deposits (or equivalent) ^d		
1) Bedrock	⑪ Bedrock	Aquifer or aquitard	

Notes:

^a Not all geologic or hydrostratigraphic units are present everywhere throughout study area.

^b Recent deposits are largely glaciolacustrine but also include glaciofluvial and alluvium. Utilized to estimate recharge and incorporated into surficial diamict (till) unit.

^c Erosion/Infill events interpreted to variable depths, deepest to bedrock, termed ORM Channel (C2; ~<14 ka), or Thorncliffe Channel (C1; ~>20 ka). Infill - fining-upward sequences (Si-Cl/Sa/Gr; aquitard/aquifer).

^d Su/SF/Don Fm./York Till mapped along Lake Ontario shore area. Northern extent uncertain. SF also mapped northwards within bedrock valleys (full extent uncertain). Don Fm. and York Till not mapped regionally.

Figure 30 - Hydrostratigraphic units. Quaternary sediments within the study area represent an alternating glacial-interglacial assemblage with major glaciations occurring approximately 190 to 135 ka (Illinoian) and 30 to 10 ka (Late Wisconsinan; Barnett, 1992). The five major geologic units are discussed in Section 5. Use of the term *complex* denotes variable facies and by extension variable hydrogeologic properties within a hydrostratigraphic unit. Use of the term *or equivalent* refers to similar materials and hydraulic properties leading to the possibility of being hydrostratigraphically equivalent. Cross section location is shown in Figure 7.

As discussed in Section 5, the glacial stratigraphy in the study area is complex with frequent facies changes leading to hydraulic conductivity values that transition from high to low over short distances, typical of glacial environments (Anderson, 1989; Ritzi et al., 2000; Ritzi et al., 1994). Thus, assigning hydrostratigraphic units is difficult in this glacial terrain. To address the stratigraphic complexity, the term *aquifer complex* has been used by the ORMGP in the study area to signify a unit with mostly moderate- to high-permeability sediments—e.g., sand and gravel—that may or may not be laterally continuous but are likely derived from similar depositional processes. For example, the term *Thorncliffe Aquifer Complex* (TAC) is used to describe the widespread sequence of interpreted Thorncliffe Formation interbedded sandy layers—sandy silt/silty sand—and silt-clay layers. The sandier layers are frequently the target of domestic and farm wells. However, the TAC also includes the lacustrine silt and clay muds as well as the interpreted channels (C1) that dominate parts of the Thorncliffe Formation. In general, within the study area, the Thorncliffe Formation thickens and contains more finer-grained facies—silt, clay—in the southwest with coarsening north over the Laurentian trough area, and thins and contains more sand-rich sediments to the east. These facies changes reflect varying proximal/distal relationships to sediment supply, which is assumed to be over the Canadian Shield to the north and east. In the hydrogeological discussion that follows, the terms *Oak Ridges*, *Thorncliffe*, and *Scarborough* are used with the term *complex* added or implied.

The term *or equivalent* is used in cases where units are in a similar vertical position in the stratigraphic package, but there is some uncertainty as to whether they were formed by the same depositional process or whether they are contemporaneous. For example, the term extends the position of the geologic stratigraphic nomenclature established in studies near and along the Lake Ontario shoreline, northward (Brookfield et al., 1982; Eyles, 1987; Karrow, 1967). Away from the Lake Ontario shore, the term *Sunnybrook drift or equivalent* is used to incorporate aquitard material (silt) that separates deposits of the TAC from the underlying Scarborough Aquifer Complex (SAC). Because there is less information available on the deeper units as one moves north from Lake Ontario, it is not known for certain whether the various units that occur within the Lower Sediments of the study area are the same as those described along the Lake Ontario shore. Similarly, along the eastern bluffs—e.g., Bowmanville Bluffs—aquifers and aquitards were named differently such that the geological nomenclature for similar units changes along the Lake Ontario shore. This unification of stratigraphic and hydrostratigraphic nomenclature using ‘or equivalent’ across the region recognizes the regional extent and the similar hydrogeological character of these units. The extension of the nomenclature used at the Don Valley Brick Works and Scarborough Bluff type sections provides a common reference framework into which aquifers and aquitards can be placed and referenced. For some hydrostratigraphic units, the exact northern extent away from the Lake Ontario shore area remains uncertain (Figure 30). For example, the silt and clay within the TAC appears similar, material-wise—

silt-rich—to the Sunnybrook drift seen in outcrop near Lake Ontario and may therefore be hydrostratigraphically equivalent, as may the sand unit—sand to silty sand—denoted beneath the TAC, which is similar to the Scarborough Formation and may also be hydrostratigraphically equivalent. The Scarborough Formation is mapped and inferred to occur as deltaic sediments near the Lake Ontario shore but also to extend inland to the north within the Laurentian trough bedrock valley.

In the following discussion, groundwater flow and hydrogeological conditions are frequently presented in terms of a shallow (or upper) flow system and a deeper (or lower) flow system. Although it is breached by channels in places, the Newmarket Till aquitard serves as a significant low-permeability unit separating these two distinct parts of the groundwater flow system. For the purposes of this discussion, references to the deep flow system will signify all the hydrostratigraphic units beneath the Newmarket Till, referred to as the Lower Sediment geologic unit. Conversely, references to the shallow groundwater flow system will generally signify the Oak Ridges Moraine Aquifer Complex, largely including all sedimentary units above the Newmarket Till. Where noted, the Inter-Newmarket Sediments are also included in the shallow system. *Inter-Newmarket Sediments* is used to denote sand- and silt-rich deposits between two different parts of the Newmarket Till: the Upper Newmarket Till, which has higher hydraulic conductivity, more weathering, and less consolidation/cementation; and the Lower Newmarket Till that is denser and has lower hydraulic conductivity.

Currently, efforts are underway to explore the subdivision of the Oak Ridges Moraine ridge sediments into multiple hydrostratigraphic units based on the subaqueous fan depositional model, which includes overlapping or stacked fans. The Don Formation and underlying York Till have not been mapped throughout the study area because of the paucity of deep higher-quality borehole information to more fully delineate these deposits. It is possible that remnants of these deeper deposits may be found restricted to small geographic areas where they were not eroded away. Local occurrences of a basal till at depth have been observed beneath the Oak Ridges Moraine at Uxbridge and west of Lake Simcoe. These may be the York Till (Bajc et al., 2019), but the hydrogeologic significance of this unit would be largely restricted to groundwater movement near the contact zone between the Quaternary sediment and the bedrock.

Appreciable thicknesses (>200 m) of unconsolidated Quaternary-age sediment occur within the study area (Figure 13c) that contain a sequence of mostly glacial-glaciolacustrine with some minor occurrences of deeper interglacial sediment. In general, three aquifer complexes occur within this thick sequence, with aquifer units mainly associated with glaciolacustrine and glaciofluvial deposits. The shallowest aquifer occurs within ORM sediments and Inter-Newmarket Sediments north and south of the ORM. Two deeper aquifer complexes—Thornccliffe Aquifer Complex and Scarborough Aquifer Complex—occur within the Thornccliffe and Scarborough Formations (Figure 30) beneath

the Newmarket Till (Gerber & Howard, 1996). These deeper aquifers are thickest in the Laurentian trough and pinch out along higher elevation bedrock areas in the north and east (Paleozoic bedrock), and west (the Niagara Escarpment). Bedrock aquifers and bedrock contact aquifers are important locally and are utilized in areas where thin Quaternary sediments overlie carbonate rock—limestone, dolomite—largely associated with the Niagara Escarpment to the west and Paleozoic rocks onlapping the Canadian Shield to the north. Shale bedrock within the study area might yield sufficient water for domestic purposes, especially where fracturing is induced—i.e. hydrofracturing—however, it does not form an aquifer due to low yield and often poor water quality.

Separating the aquifer complexes is a series of aquitards that tend to restrict both the horizontal and vertical flow of groundwater. The Halton aquitard is found at ground surface and reflects the uppermost confining unit on the groundwater flow system. It is generally found south of the ORM and is thicker to the west in Peel and Halton Regions. North of the ORM, the use of *or equivalent* is used to incorporate thin low permeability geologic units such as the Kettleby Till, Lake Schomberg silt sediment and other similar miscellaneous low permeability units. Underlying the ORM aquifer complex is the Newmarket Till aquitard, including both the Upper and Lower parts, interlayered with the Inter-Newmarket Sediments. Finally, beneath the TAC is the Sunnybrook drift or equivalent, a lower permeability unit that separates the Thorncliffe from the Scarborough aquifer complex.

The term *tunnel channels* refers to large-scale ORM related (C2) features—subglacial meltwater channels—that are eroded to various depths through the Quaternary sediments, including down to bedrock in places (Figure 31), followed by deposition of fining-upward sequences of infill sediments (gravel to sand to silt-clay rhythmics; Sharpe et al., 2018). Gravel deposits, and by extension the most permeable sediment materials, are associated with valleys or channels (Gerber et al., 2018; Mulligan et al., 2018; Sharpe et al., 2018; Slomka & Eyles, 2013). Within the study area, two different ages of channel formation are interpreted: upper Thorncliffe Formation (C1), termed *Thorncliffe-channels* (Gerber et al., 2018), and those formed during deposition of the Oak Ridges Moraine (C2), termed *ORM-channels* (Gerber et al., 2018; Russell et al., 2000). The mechanisms of channel erosion and fill are discussed in Section 5.

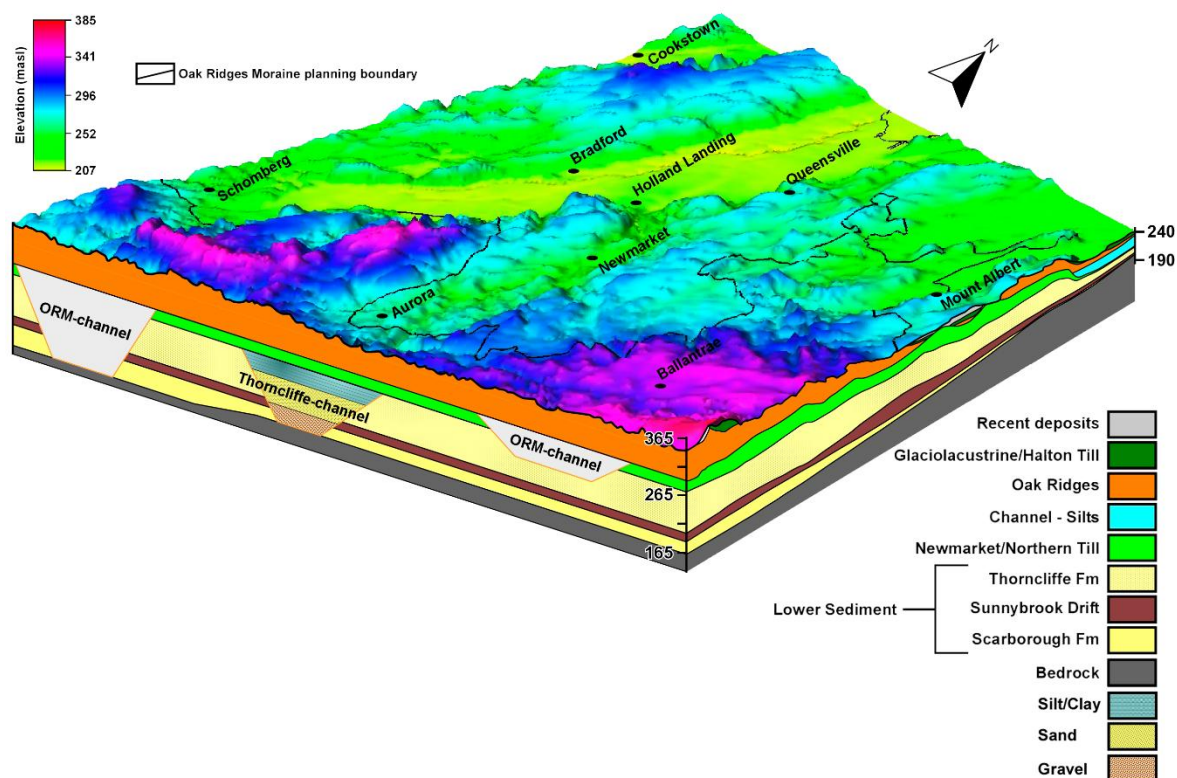


Figure 31 - Three-dimensional view of geology and topography along and north of the Oak Ridges Moraine illustrating two interpreted ages of channelization, looking northwest. ORM channels are visible on the ground surface as large valleys. Thorncliffe channels are older and overlain by Newmarket Till. Geologic layers across the front panel of block diagram are simplified to illustrate general architecture and to illustrate channel positioning. Key to distinguishing the age of channelization is the presence or absence of Newmarket Till, deposited during a regional glacial maximum approximately 20 ka.

The channels are also significant in terms of deeper groundwater flow, since the ORM channels often have eroded through the Newmarket Till, some ultimately to bedrock. Such deep incision may provide hydraulic connection between the shallow and deeper parts of the flow system. The nature and thickness of the infill sediments (facies) and the magnitude and direction of vertical hydraulic gradients control the amount of leakage between the shallow and deep parts of the flow system. Similarly, Thorncliffe channels found beneath the Newmarket Till have also eroded to depth—locally to bedrock—thereby creating hydraulic connection between aquifer complexes that occur within the Lower Sediments. Both channelization events were followed by deposition of fining-upward sequences of infill sediments transitioning from gravel to sand to silt-clay rhythmities. The infill for one tunnel channel system, located near King City and Nobleton, is described in detail by Russell, Arnott, and Sharpe (2003), and others are shown at Nobleton and Caledon (Figure 16). A conceptual rendering of groundwater flow through tunnel channel sediments both beneath the ORM—with downward vertical hydraulic gradients—and north of the ORM—with upward vertical hydraulic gradients—is shown in Figure 32. Mapping of tunnel channels within the study area is described in Russell, Sharpe and others (2003) and was extended by Sharpe and Russell (2023).

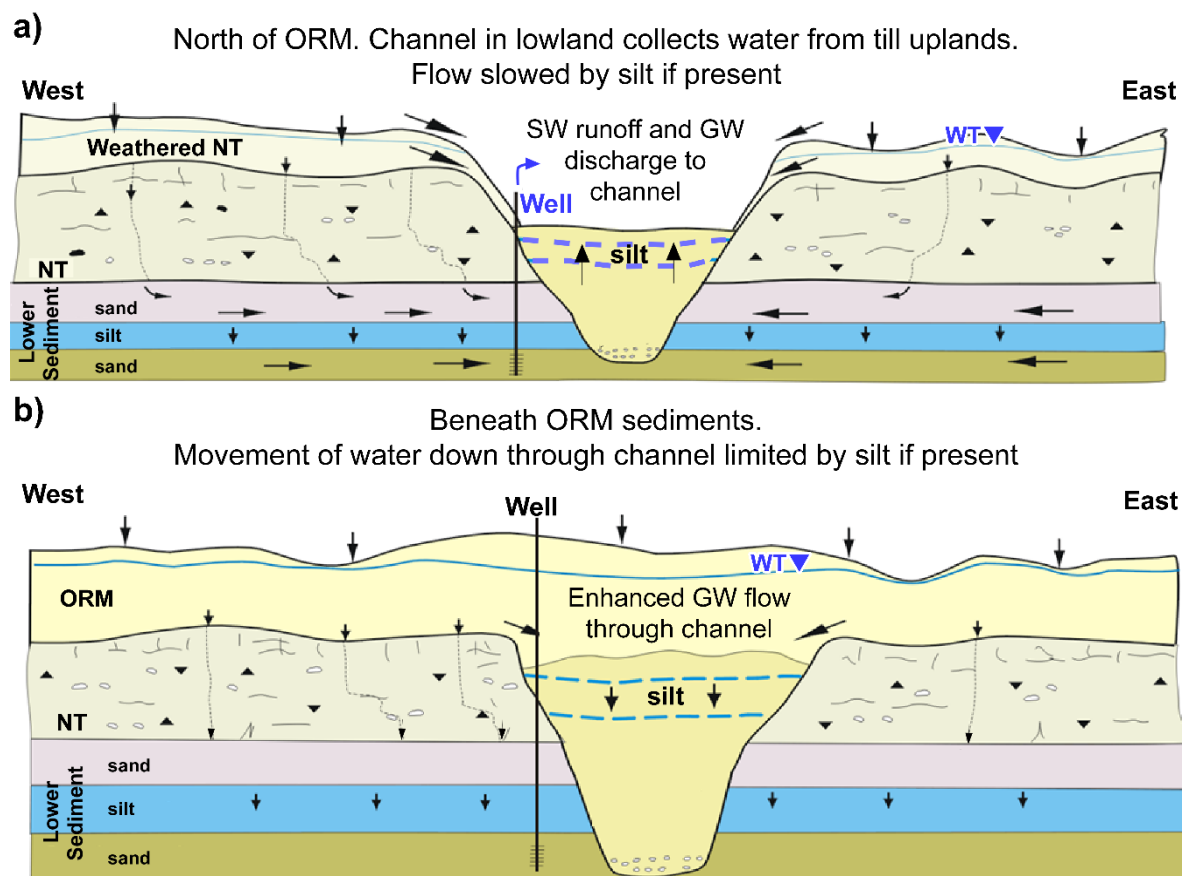


Figure 32 - Generalized hydrogeologic function of tunnel channel (ORM, C2 channel) sediments. Channel infill is a fining-upward sequence transitioning from gravel at base to sand capped by silt and clay rhythmites. a) ORM channels north of the Oak Ridges Moraine (ORM) often breach the Newmarket Till (NT), leading to formation of lowlands containing streams and wetlands surrounded by till uplands. Recharge into Newmarket Till over uplands is low but locally enhanced by fractures or heterogeneities. Upward groundwater flow within the channel may be reduced across silt and clay layers (dashed line) within channel fill sediment. Local flow systems develop where recharge over till uplands discharges to stream valley lowlands containing ORM-channel sediments and in places results in the presence of flowing wells. b) ORM channels beneath the ORM—upslope from channels north of ORM—often breach the Newmarket Till, leading to enhanced vertical groundwater flow to aquifers in Lower Sediment units—Thorncliffe and Scarborough Formations. Regional groundwater flow within the ORM sediments and Lower Sediment is perpendicular to the cross section. (modified from Earthfx, 2006; originally from Sharpe, Hinton et al., 2002). WT = water table.

In addition to the two types of channels discussed above, there is a third set of deeper channels that have been eroded into the bedrock. Although some of the bedrock channels might be linked to the C1/C2 channels, it is likely that some of the channels that are cut into the bedrock are independent and older than the Oak Ridges (C2) or Thorncliffe (C1) related channels. These features are generally poorly defined, only being intersected by isolated wells along their thalwegs. However, they are, or were in the past, important aquifers supplying municipal quantities of drinking water for many of the smaller communities—e.g. Georgetown, Huttonville, Milton, Bolton, etc.—especially in the west parts of the study area, where the Quaternary sediments are thinner, and aquifer materials are scarcer. In the hydrostratigraphic model, they are typically incorporated as high permeability linear features within either the TAC or SAC, whichever unit is found near to the bedrock.

Similar to geologic units, not all hydrostratigraphic units are present throughout the study area. For example, the Thorncliffe Formation deposits comprise much of the Lower Sediment package up to approximately 330 masl, with the Scarborough Formation deposits possibly extending northward as infill within the broad Laurentian bedrock valley system trending from Georgian Bay southward to Toronto. All geologic units situated beneath the Newmarket Till are referred to as *Lower Sediments* (Sharpe et al., 2005b). As shown on the isopach map in Figure 17, the Lower Sediments are thickest in the Laurentian trough and pinch out as the bedrock surface rises in the west—toward the Niagara Escarpment—and north—toward the Paleozoic bedrock. In the locations where the units are pinching out upon the rising bedrock surface, they become increasingly confined to tributary bedrock valleys.

The shallow Oak Ridges Aquifer Complex (ORAC) is thickest coincident with the ORM landform (Figure 33). Localized sand bodies occurring within the till plains to the north and south of the Oak Ridges Moraine have been mapped as Inter-Newmarket Sediments.⁹ These coarse-grained sediments are largely localized within lower elevations on the surface of the Lower Newmarket Till. Hydraulic connection with the main ORAC diminishes in these shallow sand bodies with distance away from the moraine. Along the south flank of the ORM, Halton sediment overlies the ORAC, leading to confined and often flowing conditions ([Exercise 5](#) ) ([Exercise 6](#) ).

⁹ To the south of the moraine across the south slope till plain, sand and gravel deposits occurring between till units have also been mapped in the literature as Mackinaw Interstadial sediments between surficial overlying Halton Till and underlying Northern till—now Lower Newmarket Till. The Northern till—also known as the Lower Newmarket Till—contains thinner discontinuous sand and cobble boulder horizons—termed *interbeds*—generally <0.3 m thick that separate diamict layers that have been termed *diamict elements* (Boyce et al., 1995; Gerber & Howard, 1996; Gerber & Howard, 2002). Discussion regarding the nomenclature and depositional setting of these shallow coarser grained sediments south of the ORM is ongoing (Barnett et al., 1998; Sharpe & Russell, 2016; Sharpe & Russell, 2020; Sookhan et al., 2018). The nomenclature currently used in this book is summarized in Figure 30.

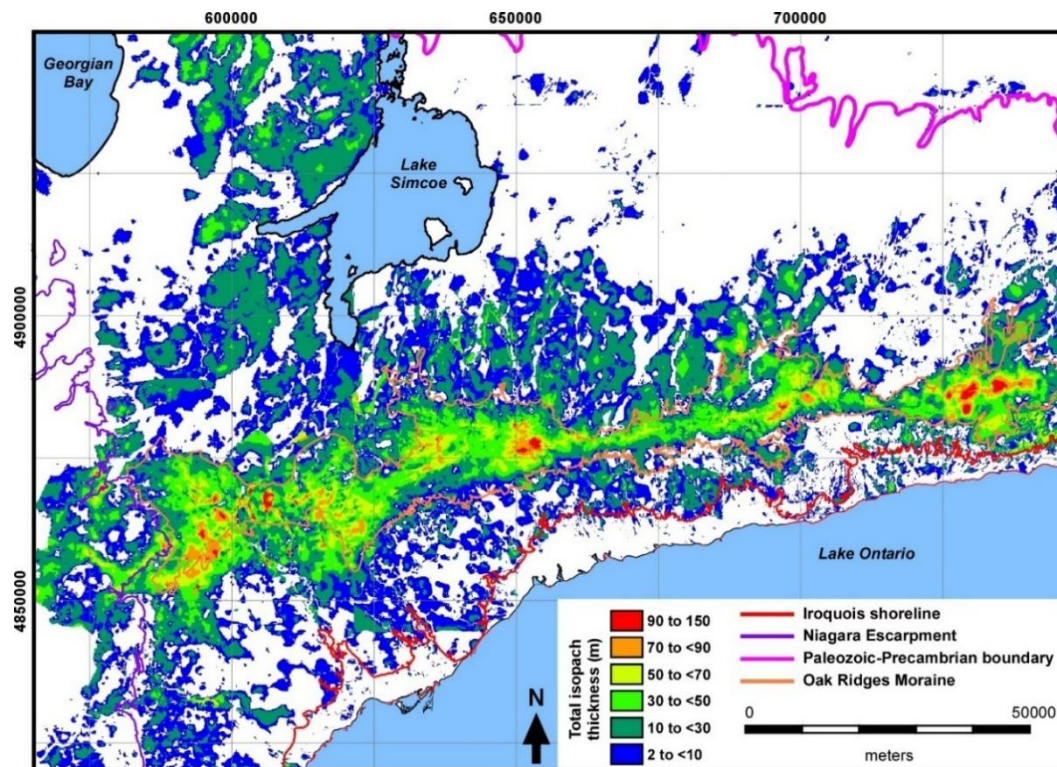


Figure 33 - Interpreted thickness (m) of the uppermost aquifer (ORAC) including both the ORM sediments along the moraine ridge and Inter-Newmarket Sediments (silt, sand, and gravel) between the Upper and Lower Newmarket Till to the south and north of the moraine ridge. Significant thicknesses of sand and gravel occur between the moraine and the glacial Lake Iroquois shoreline. Mapping from the ORMGP is available at [ORMGP-Maps-geology theme](#). It is useful to compare this with Figure 19 which restrict ORM sediment to the moraine ridge and areas north. Projection UTM NAD83 Zone 17.

6.3 Hydraulic Properties

Groundwater flow through porous media depends on six basic physical properties. For water, they are density (ρ), dynamic viscosity (μ), and compressibility (β), and for the media they are porosity (n , or void ratio e), permeability (k), and compressibility (α). For porous media, porosity can be further subdivided into total porosity and effective porosity, the latter term referring to the degree of interconnectedness of the pore spaces through which fluid flows. Commonly used porous media parameters, including hydraulic conductivity (K), specific storage (S_s), storativity (S), and transmissivity (T), are derived from the above six basic properties (Domenico & Schwartz, 1998; Freeze & Cherry, 1979).

The ORMGP continues to compile hydrogeologic parameter estimates—e.g., porosity, specific capacity, storativity, transmissivity, hydraulic conductivity—into the program's database. A focus has been directed to collating hydraulic conductivity estimates, and this section discusses hydraulic conductivity estimates for the various geologic deposits present within the study area ([Exercise 7](#)).

6.3.1 Hydraulic Conductivity (K)

Hydraulic conductivity (K) is a quantitative parameter that describes the capacity of a soil or rock unit to transmit water and is dependent on the properties of both the fluid

(groundwater) and the solid matrix (Bear, 1979; Domenico & Schwartz, 1998; Freeze & Cherry, 1979). K is defined in Equation (1) .

$$K = \frac{(k p g)}{\mu} \quad (1)$$

where:

K = hydraulic conductivity (LT^{-1})

k = intrinsic permeability, a property of the matrix (L^2)

p = mass density of the fluid (ML^{-3})

g = acceleration due to gravity (LT^{-2})

μ = dynamic viscosity of the fluid ($ML^{-1}T^{-1}$)

Hydraulic conductivity of rocks and sediments varies over many orders of magnitude (Figure 34). This is true for the geologic deposits found within the study area that can be characterized as having large facies changes, and therefore a large variability in hydraulic conductivity, often over very short distances. The glacial sediments overlying bedrock within the study area are mainly till and glacio-fluvial/lacustrine sediments ranging from gravel and cobbles to clay.

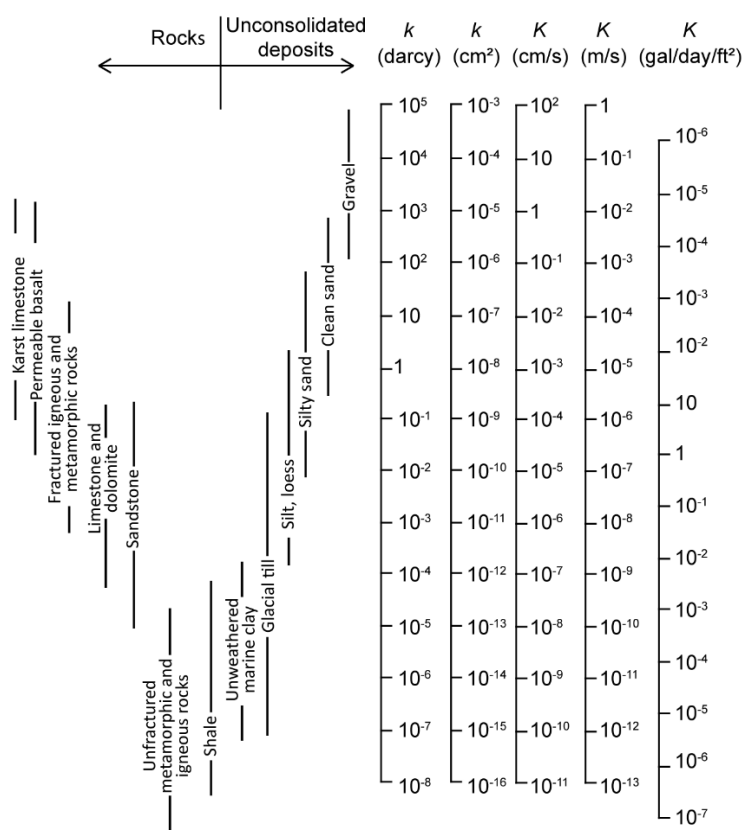


Figure 34 - Approximate values of hydraulic conductivity (K) and permeability (k) for geologic materials (from Freeze & Cherry, 1979). Materials in glacial depositional systems exhibit a particularly large range.

Hydraulic conductivity estimates can be obtained in two broad ways: through testing of sediment and rock samples in the laboratory and by measurements in the field—e.g., slug testing, pumping tests. Estimates can then also be evaluated at various scales through numerical modeling. Care must be taken when estimating based on physical samples if secondary permeability features such as fractures, sand bodies, or matrix cement are present. Secondary permeability features are commonly found in till deposits within the study area. Field measurements tend to reflect—to varying degrees, depending upon the type and length of testing—the hydraulic conductivity of the geological formation in the vicinity of the well screen (i.e., slug testing) or between well screens (i.e., pumping tests). Estimates of hydraulic conductivity obtained by calibrating regional numerical models typically reflect a *bulk* hydraulic conductivity because practitioners assign a value of hydraulic conductivity to a hydrostratigraphic unit that includes a range of materials. As an example of the variability in hydraulic properties, a summary of the estimated field hydraulic conductivity values within the Duffins and the Petticoat Creek watersheds, in the south-central part of the study area, is provided in Table 3.

Table 3 - Summary of field-measured hydraulic conductivity estimates (in meters per second) within the Duffins and Petticoat Creek watersheds of the Oak Ridges Moraine (ORM) (modified from Gerber & Howard, 2000).

	Minimum	Maximum	Average	no.	σ	Geometric mean
ORM spec-cap K_h	2×10^{-6}	7×10^{-3}		1287		5×10^{-5}
Upper Newmarket Till (termed Halton Till in Gerber and Howard, 2000)						
slug K_h	2×10^{-9}	2×10^{-5}	3×10^{-6}	54	4×10^{-6}	4×10^{-7}
pump K_h			6×10^{-6}	1		
pump K_v	1×10^{-8}	1×10^{-7}		1		
Inter-Newmarket Sediment (termed Mackinaw Interstadial in Gerber and Howard, 2000)						
slug K_h	3×10^{-8}	5×10^{-4}	5×10^{-5}	16	1×10^{-4}	6×10^{-6}
Lower Newmarket Till (termed Northern Till in Gerber and Howard, 2000)						
lab K_v	1×10^{-11}	7×10^{-10}	5×10^{-11}	40	1×10^{-10}	3×10^{-11}
slug K_h	3×10^{-12}	3×10^{-6}	3×10^{-7}	39	7×10^{-7}	8×10^{-10}
pump K_h			6×10^{-6}	1		
pump K_v	3×10^{-11}	3×10^{-7}		4		
Thornccliffe Aquifer Complex (termed Middle Aquifer in Gerber and Howard, 2000)						
slug K_h	1×10^{-8}	3×10^{-4}	2×10^{-5}	42	6×10^{-5}	2×10^{-6}
pump K_h	1×10^{-7}	9×10^{-5}	3×10^{-5}	4	4×10^{-5}	5×10^{-6}
spec-cap K_h	1×10^{-6}	2×10^{-3}		286		4×10^{-5}
Sunnybrook Drift						
Slug K_h (1)	3×10^{-7}	4×10^{-7}		2		
Scarborough Aquifer Complex (termed Lower Aquifer in Gerber and Howard, 2000)						
slug K_h	2×10^{-8}	2×10^{-4}	5×10^{-5}	5	8×10^{-5}	2×10^{-6}
spec-cap K_h	6×10^{-7}	7×10^{-4}		311		2×10^{-5}

K_h = horizontal hydraulic conductivity K_v = vertical hydraulic conductivity

σ = standard deviation

Data from M. M. Dillon Limited, 1990; Interim Waste Authority Limited, 1994a-e; Gerber, 1999.

Spec-cap = Specific Capacity estimates from water well records.

Specific capacity estimated according to Bradbury and Rothschild (1985) from Boyce, 1998.

(1) piezometers in sand layers in aquitard unit.

Hydraulic conductivity estimates within the ORMGP database emanate from several different methodologies and include the following.

1. Laboratory analysis—e.g., triaxial permeability—on soil and rock cores.
2. Slug tests conducted on piezometers. Slug testing has been conducted by partner agency staff on piezometers and wells associated with the various groundwater monitoring programs listed in Table 2. Also, the ORMGP has an extensive library of hydrogeological reports. Efforts have begun to compile hydraulic conductivity estimates from within these reports for incorporation into the database.
3. Pumping tests (short-term) with duration generally less than four hours. These single-well tests are conducted by well drillers immediately following well installation. Specific capacity (pumping rate/maximum drawdown) estimates are generated from these data, which are then used to estimate T and K according to the methodology of Bradbury and Rothschild (1985). These estimates are further discussed below.
4. Pumping tests (longer-term) with duration generally greater than 24 hours. These pumping tests are conducted by partners and consultants related to water-supply and infrastructure projects (e.g., sewer projects). These are multi-well tests where observations are collected on the pumping well and adjacent monitoring wells. Full analyses generate S, T, and K estimates.
5. Numerical modeling. Numerical models are used to test the hydraulic property estimates generated by any of the four above testing methods and also to analyze bulk values of hydraulic conductivity for unit sizes defined by the modeler.

A summary of hydraulic property estimates currently in the ORMTP database can be found at www.oakridgeswater.ca (at Data Snapshots/Hydraulic Properties).

Farvolden and Cherry (1988) refer to an unusual feature of two major aquifers—Waterloo Moraine and Oak Ridges Moraine—situated in the St. Lawrence Lowlands hydrogeologic region. They state that high-capacity aquifers are seemingly surrounded by low hydraulic conductivity material, yet numerical modeling and other lines of evidence indicate the presence of extensive aquifers. The authors suggest that perhaps the aquifer units have low average hydraulic conductivity over a thick section with higher permeability gravel and coarse sand units restricted to local areas. This is consistent with the study area where localized higher-permeability channels (C1, C2) exist (Gerber et al., 2018), along with thick ORM ridge sediment as described in Section 5 (Figure 19). The range of hydraulic conductivity estimates for the Oak Ridges Aquifer Complex, Thorncliffe, Scarborough—are consistent with this suggestion, as the data reflect a wide range of estimates depending on facies adjacent to the well screen. Aquifer units within the study area are deposited in glaciolacustrine and glaciofluvial environments with the wide range of hydraulic conductivity estimates reflecting deposition in either proximal (coarser-grained) or distal (finer-grained) locations from the sediment supply.

6.3.2 Aquitard Hydraulic Conductivity

Determining the hydraulic conductivity of aquitard units is more difficult than for aquifers owing to the longer timeframes needed to induce and measure a hydraulic response and because secondary permeability structures such as fractures may become important (Bradbury et al., 2006; Cherry et al., 2006; Fredericia, 1990; Keller et al., 1986; Konikow & Neuzil, 2007; Neuzil, 1994; Simpkins & Bradbury, 1992; van der Kamp, 2001). This is particularly true for the three major aquitards present within the study area—Halton Till/Upper Newmarket Till, Lower Newmarket Till, and Thorncliffe Silt and Clay/Sunnybrook drift.

The key aquitard within the study area is the Lower Newmarket Till, which separates the shallow part of the flow system from the deeper part of the flow system contained within the Lower Sediments. This till aquitard is considered the protective layer for underlying aquifers occurring within Lower Sediment (Gerber, 1999; Rashtchi, 2020). Hydrogeologic investigations conducted by M. M. Dillon Ltd. (1990) and Interim Waste Authority (1994a, 1994b, 1994c, 1994d, 1994e, 1994f, 1994g, 1994h, 1994i) and continued by Gerber (1999), Gerber and others (2001), and Gerber & Howard (1996, 2000) suggest that the Lower Newmarket Till aquitard can be considered a dual porosity—and therefore a dual hydraulic conductivity—medium with bulk hydraulic conductivity (K) controlled by non-matrix structures or pathways (Figure 35).

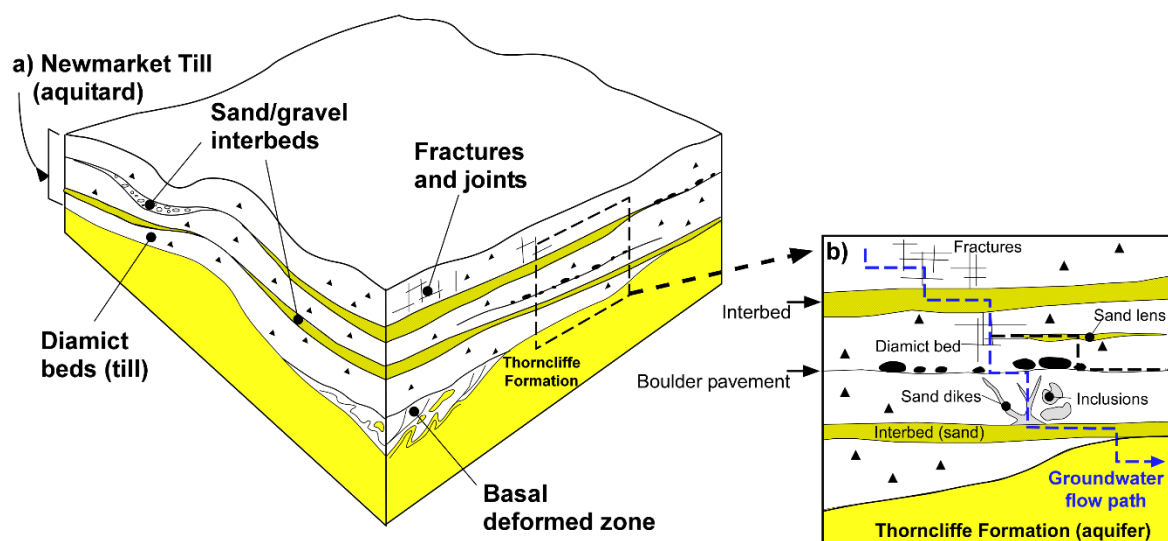


Figure 35 - a) Large-scale composite internal architecture of the Newmarket Till (also known as the Northern Till) aquitard; b) small-scale sedimentary heterogeneities identified in core and outcrops. Elements are not shown to scale (modified from Gerber et al., 2001).

Horizontal pathways include sand and gravel interbeds and boulder pavements marking erosional surfaces. These have been identified in the Newmarket Till in outcrop and shallow seismic reflection profiles (Boyce, 1998; Boyce et al., 1995). Vertical pathways include fractures, sand dykes, and steep dipping shear surfaces. Further discussion on heterogeneity in glacial sediments, including development of the poly morphological

concept to map and assess glacial heterogeneity, can be found in Klint and others (2013). Isotopic data (^2H , ^{18}O and ^3H) and regional water balance/groundwater flow modeling (Gerber, 1999; Gerber & Howard, 2000) suggest vertical bulk K values on the order of 5×10^{-10} to 5×10^{-9} m/s. Hydraulic conductivity estimates for the Newmarket Till matrix material, which were obtained from triaxial permeability and slug testing, in contrast, yield much lower estimates ranging from 1×10^{-11} to 1×10^{-10} m/s (Figure 36). Based on the K estimates and on modeling studies, the vertical leakage through the Newmarket Till to the underlying Lower Sediments is estimated at 30 to 40 mm/year on a regional basis. The amount of vertical leakage will differ spatially depending on vertical hydraulic gradients, the presence or absence of secondary permeability features—e.g., fractures, coarse grained sedimentary heterogeneities—within the till, or whether, and by how much, the till has been eroded by channelization—including the nature of channel infill sediments. Desbarats and others (2001) provide a statistical analysis of leakage through the Newmarket Till for much of the study area and illustrate the variability in leakage estimates provided by heterogeneity, including the presence of windows through the aquitard. Recent modeling studies suggest that where the Lower Newmarket Till overlies silt-clay rhythmites of the Thorncliffe Formation, vertical bulk K values may reduce to 1×10^{-10} to 5×10^{-10} m/s (Golder, 2021). Anisotropy, that is, the ratio of horizontal hydraulic conductivity (K_h) to vertical hydraulic conductivity (K_v), has historically been assumed to range from approximately 10 to 100 (K_h/K_v).

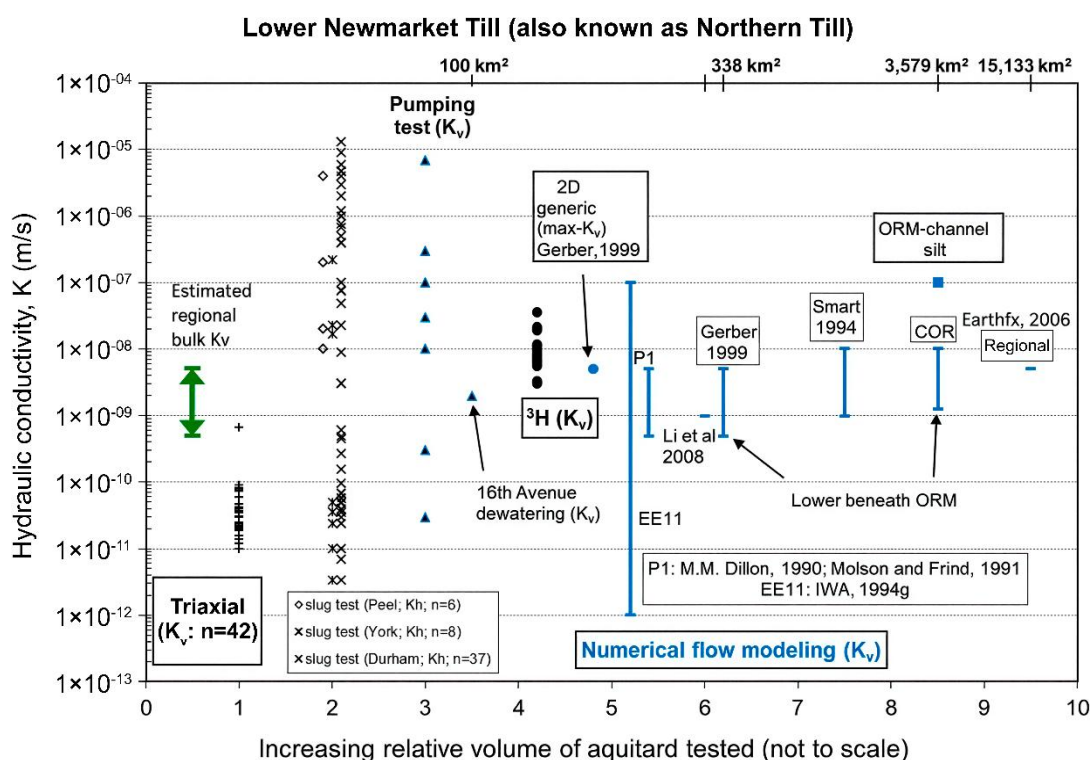


Figure 36 - Summary of hydraulic conductivity estimates for the Lower Newmarket Till (estimates from Earthfx Inc., 2006; Interim Waste Authority, 1994a, 1994b, 1994c, 1994d, 1994e, 1994f, 1994g, 1994h, 1994i; Gerber, 1999; Gerber & Howard, 2000; Li et al., 2008; M. M. Dillon, 1990; Molson & Frind, 1991; Smart, 1994).

Choosing representative hydraulic conductivity estimates for aquitards can be difficult and largely depends on the application. For regional modeling investigations that aim to estimate water budgets or wellhead protection areas, bulk estimates can often be utilized. However, where contaminant transport through aquitards is being investigated, more detailed analyses are needed. In such cases, the effect of heterogeneities at all scales needs to be considered along with their hydraulic properties including properties that influence matrix diffusion (Jørgensen et al., 2022; Jørgensen et al., 1998).

6.3.3 Estimates of K and T from Specific Capacity

The study area and surround has seen many numerical groundwater flow model investigations that have necessitated an estimate of the regional hydraulic conductivity field (Beckers & Frind, 2000, 2001; Earthfx, 2006; Li et al., 2008; Martin & Frind, 1998). While numerous methods can be used to estimate hydraulic conductivity (Woessner & Poeter, 2020), the local modeling investigations have used different methodologies to assign typical hydraulic conductivity values (Figure 34) based on geologic material descriptions contained within water-well and borehole records. Some investigations (Li et al., 2008) have assumed homogeneity of hydraulic conductivity within each hydrostratigraphic unit. To assist with future numerical modeling initiatives, the ORMGP recently completed an analysis of the short-term flow and drawdown data collected by well drillers to improve upon the assignment of hydraulic conductivity values.

In Ontario, following installation of a water well, a short-duration—generally less than 4 hours—single-well pumping test is often conducted so that the well driller can determine well yield, or the rate at which the well can be pumped. The data collected from this test allows specific capacity (SC) to be calculated. Specific capacity is defined as the pumping rate (Q) divided by the maximum drawdown in the well (Freeze & Cherry, 1979). The SC values can vary in accuracy and are subject to various sources of error—e.g., discharge rate differences, consistency of pumping rate, measurement and transcription errors, among others. None-the-less, they provide regional coverage because of the thousands of measurements present across the study area. Use of SC measurements to derive transmissivity (T_{SC}) and hydraulic conductivity (K_{SC}) utilized the methodology outlined in Bradbury and Rothschild (1985) that allows correction for partial penetration of well screens. Hydrostratigraphic unit thicknesses have been obtained from the most recent version of the ORMGP three-dimensional geologic model (www.oakridgeswater.ca). Regional T and K from specific capacity (T_{SC} and K_{SC}) can then be compared to local T and K obtained from slug and pumping tests in wells. Figure 37 shows the cumulative probability distribution and illustrates the comparison of SC with the derived transmissivity (T_{SC}) that currently exists within the ORMGP database. The geometric mean (cumulative probability=50 percent) T_{SC} value is approximately an order of magnitude greater than the geometric mean SC. Utilizing the screen length as the formation thickness

leads to derived T_{sc} values closer to SC. The K_{SC} values derived from SC are illustrated in Figure 38 and compared to K from slug test data. The geometric mean of K from slug tests within aquifer units is lower than the K derived from SC, which is not surprising given that drillers choose to screen the most permeable interval within an aquifer complex to maximize well yield. Also, an SC test will sample a larger aquifer volume than a slug test so therefore has a higher likelihood of accessing higher K sediment if there is heterogeneity. The method of correcting for screen partial penetration is explored further in Figure 39, where SC and associated T_{SC} values based on geologic formation thickness are compared to values calculated using screen length. Average conditions for pumping rate (Q), maximum drawdown, and screen length are used for both 2" wells—typical monitoring well diameter—and 6" wells—typical private water supply well. The average aquifer complex thickness from the ORMGP three-dimensional geologic formation model is approximately 29 m, with a median aquifer complex thickness of approximately 20 m. Substituting the average screen length (1.5 m) for the interpreted aquifer formation thickness leads to the following relationships.

- Quaternary sediment: $T_{sc} = 1.7 SC$ (2"-diameter well; aquifer thickness=screen length);
- Quaternary sediment: $T_{sc} = 1.3 SC$ (6"-diameter well; aquifer thickness=screen length); and
- Paleozoic bedrock: $T = 1.5 SC$ (rock units along Niagara Escarpment, Priebe et al., 2018).

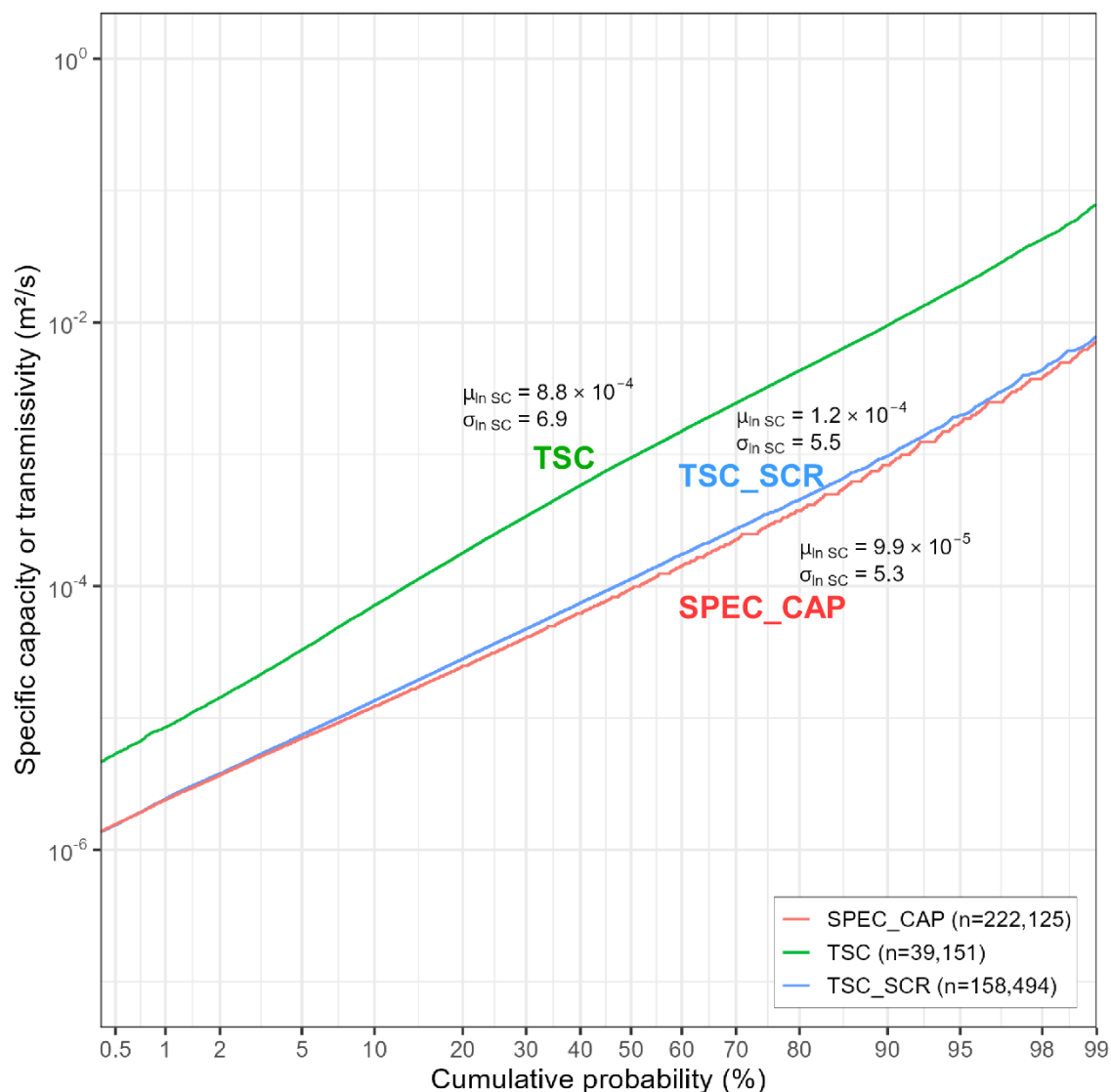


Figure 37 - Cumulative probability comparison of specific capacity from short-term (<4 hours) pumping tests in m²/s (SPEC_CAP), transmissivity derived from specific capacity using hydrostratigraphic unit thickness in m²/s (TSC), and transmissivity derived from specific capacity utilizing the screen length as the hydrostratigraphic unit thickness in m²/s (TSC_SCR). Geometric mean (μ) occurs at a cumulative probability of 50 percent. σ=standard deviation.

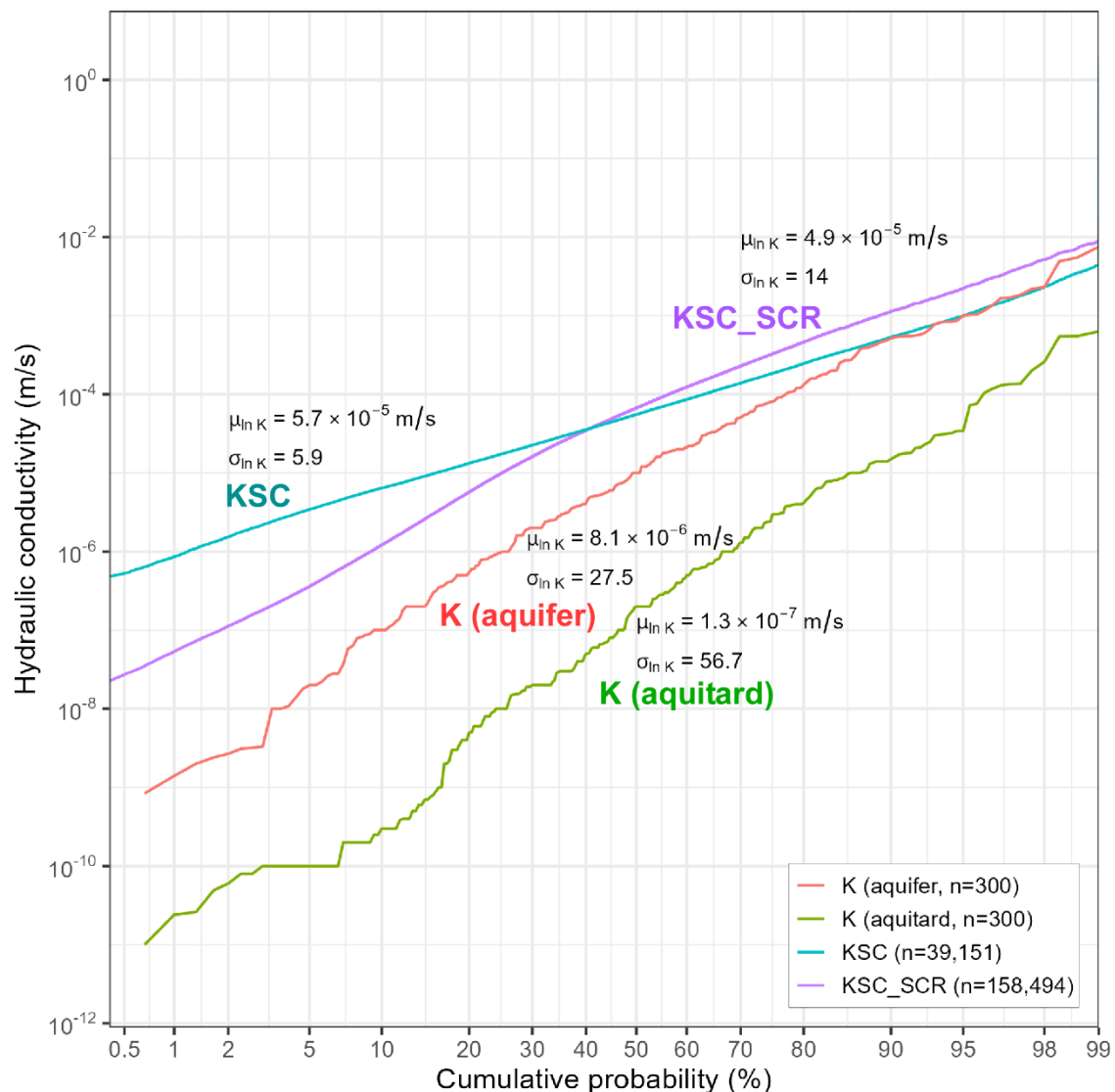


Figure 38 - Cumulative probability comparison of hydraulic conductivity from slug testing in m/s (K), values of hydraulic conductivity derived from specific capacity utilizing interpreted formation thickness in m/s (KSC), and hydraulic conductivity values derived from specific capacity using screen length as the formation thickness in m/s (KSC_SCR). All four sets of values approximate the straight lines indicative of log-normal distributions, which is typical for the distribution of hydraulic conductivity, transmissivity, and specific capacity in a geologic material (Neuman, 1982). The geometric mean of hydraulic conductivity occurs at a cumulative probability of 50 percent. Further description of estimation of hydraulic conductivity from specific capacity is provided by Bradbury and Rothschild (1985) and Priebe and others (2018).

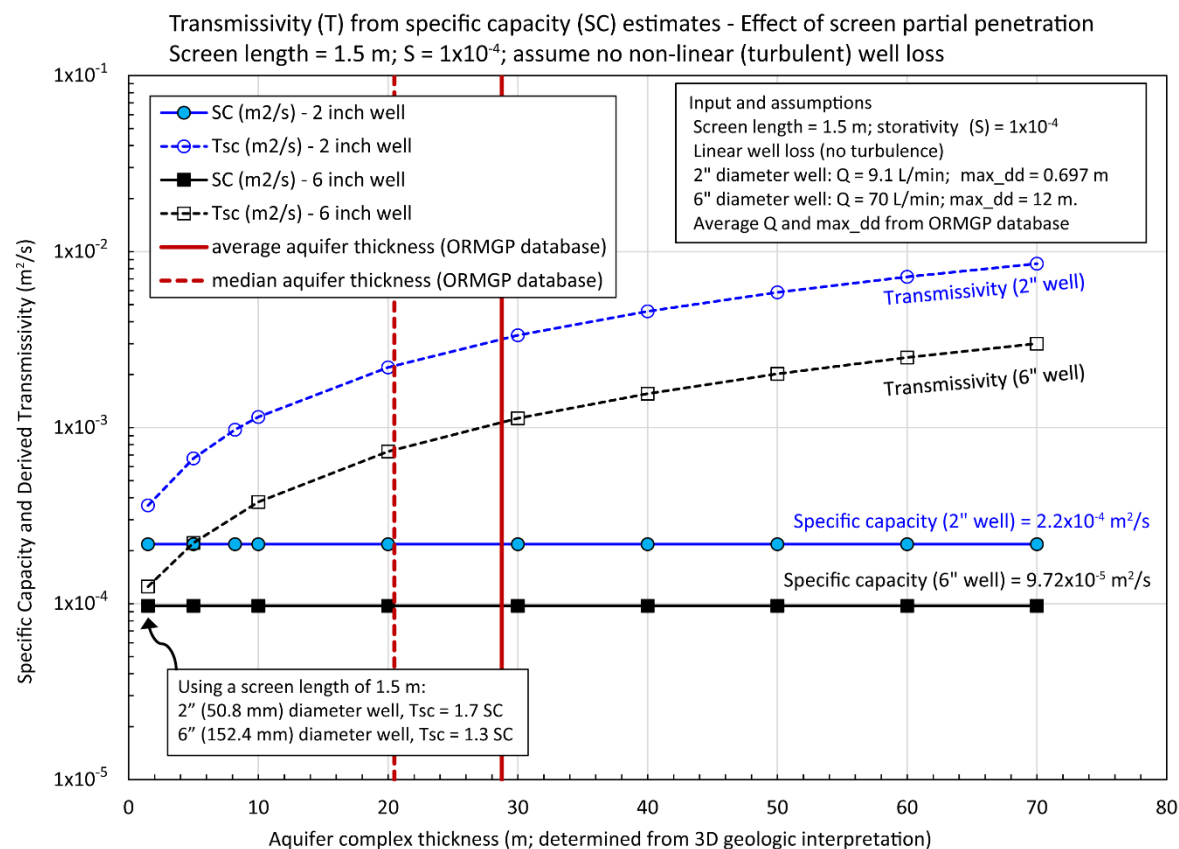


Figure 39 - Effect of screen partial penetration on values of transmissivity derived from specific capacity (T_{SC}) illustrating the effects of utilizing thickness of the aquifer complex versus length of screen. Average and median aquifer formation thickness from the latest ORMGP three-dimensional geologic interpretation are indicated in red. Input assumptions for these calculations utilize average pumping rates (Q) and maximum drawdown (dd) for 2" and 6" diameter wells in the ORMGP database. When the average screen length (1.5 m) is used as the aquifer thickness, $T_{SC} = 1.7$ SC for a 2" well and $T_{SC} = 1.3$ SC for a 6" well.

The ratios of T_{SC} to SC for a screen length of 1.5 m stated in bullets 1 and 2 of the previous paragraph apply to aquifers within Quaternary unconsolidated sediments in the study area. Priebe and others (2018) provide an excellent summary of the considerations involved in estimating hydraulic conductivity from specific capacity data for rock units along and west of the Niagara Escarpment. The relationship between T and SC for rock units situated toward the western part of the study area along the Niagara Escarpment (Priebe et al., 2018; bullet 3) is similar to the Quaternary sediment relationship when aquifer thickness is approximated with a 1.5 m screen length. The study area Quaternary deposits are characterized by large facies changes over short distances and therefore exhibit a high degree of anisotropy. It appears that utilizing the screen length as the effective aquifer thickness provides values of T_{SC} and K_{SC} that compare more favorably with values obtained using slug and pumping tests conducted in wells. An interactive map of SC, T_{SC} , K_{SC} , and K values within the ORMGP database can be explored at www.oakridgeswater.ca (at Data Snapshots/Hydraulic Properties).

A summary, with interactive maps, of hydraulic property currently contained within the ORMGP database can be found at www.oakridgeswater.ca (Data

Snapshots/Hydraulic Properties). Hydraulic property collation and refinement is an ongoing task for ORMGP staff. A summary of current hydraulic conductivity values from slug tests and specific capacity is illustrated in Figure 40. Many of the KSC_SCR values in the figure apply to aquitard formations—e.g., Lower Newmarket Till. The ORMGP classifies screens according to formation by comparing screen elevation to the latest geologic model interpretation. KSC_SCR values for aquitard formations are treated as part of the program’s QA/QC process, which includes testing and refinement of the three-dimensional geologic unit interpretation. Specific capacity values are from the reported flow rate and drawdown during testing at the time of well completion. While heterogeneities exist within study area aquitards, it is considered low probability that domestic water wells will be installed within aquitards. Similarly, while many private wells may be installed with screens straddling aquitard–aquifer boundaries—within the upper part of an aquifer—specific capacity estimates are considered to be representative of aquifer units. Areas with KSC_SCR values for aquitard formations are subject to further inspection and refinement of the three-dimensional geologic/hydrostratigraphic unit interpretation where necessary.

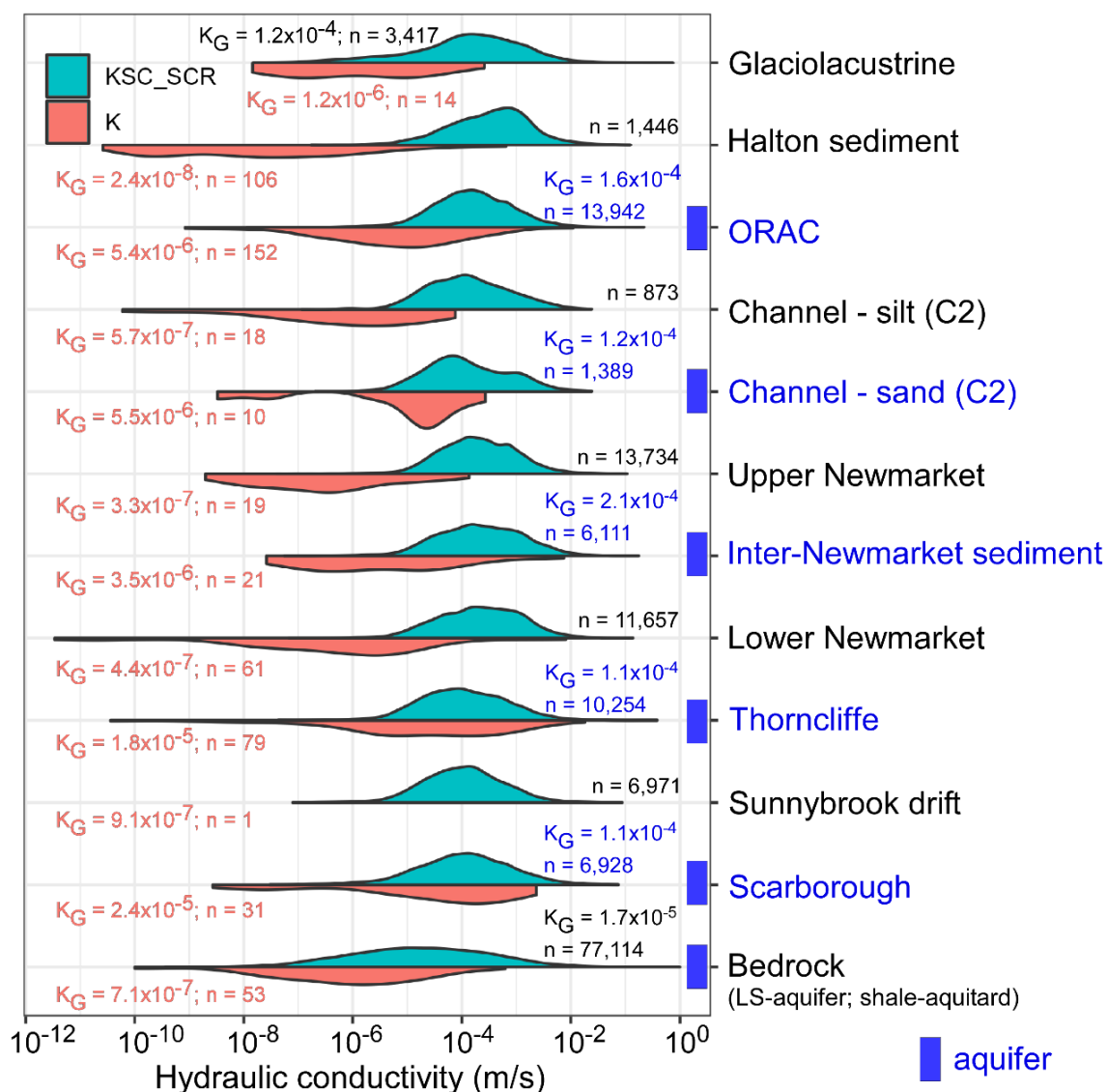


Figure 40 - Violin plot summarizing distribution of hydraulic conductivity (m/s) by formation for estimates contained within the ORMGP database illustrating the range of values present within aquifer and aquitard complexes. Peaks represent a higher density of data at that value. Upper distribution (KSC_SCR—blue/green color) reflects hydraulic conductivity values from specific capacity utilizing the screen length as the aquifer thickness. The lower distribution (K—orange/red color) reflects hydraulic conductivity values from slug testing, KSC for the ORAC is skewed toward a higher value compared with the slug test values, reflecting the goal of private well drillers to target screen installation in more permeable facies. The large number of well screens associated with the KSC_SCR estimates for aquitard units—e.g., Lower Newmarket Till—indicate the need to refine the three-dimensional geologic interpretation in the area of these well screens since it is unlikely that wells draw a water supply from aquitards. The wide range in hydraulic conductivity values from slug tests reflects the high degree of heterogeneity present within study area hydrostratigraphic complexes, including sedimentary non-matrix heterogeneity and interbeds. Estimates of hydraulic conductivity from specific capacity (KSC_SCR) for bedrock aquifers compare favorably to similar methodology for estimating hydraulic conductivity of carbonate aquifers along and west of the Niagara Escarpment where geometric mean hydraulic conductivity ranges from 3×10^{-5} to 1×10^{-4} m/s as reported in Priebe and others (2018). Slug test values from bedrock skew toward lower hydraulic conductivity, reflecting the many slug tests conducted within wells screened across shale. Further discussion on hydraulic properties, including interactive mapping, contained within the ORMGP database can be found at [ORMGP-Data Snapshot-hydraulic properties](#).

6.4 Groundwater Flow

Groundwater moves in the subsurface from areas of high potential energy to areas of low potential energy. Hydraulic head or static water level at any given point in the subsurface is a measure of this energy. Therefore, groundwater moves from areas of high hydraulic head to areas of lower hydraulic head. By contouring hydraulic heads from wells within the same aquifer, hydrogeologists can estimate the direction and magnitude of groundwater movement in the subsurface. It must be highlighted that water levels measured at different depths in the subsurface can be very different. For example, in regional groundwater discharge areas, groundwater is rising to the surface from depth. In such areas, water-level measurements in the shallow subsurface will be lower than measurements made at depth, and groundwater will flow upward in response to this vertical hydraulic gradient. Conversely, in regional groundwater recharge areas, water flows downward in response to decreasing hydraulic head with increasing depth. Where aquifers are confined beneath lower hydraulic conductivity clay or till layers, especially in lower elevation discharge areas, the high hydraulic head due to gravity driving groundwater flow from upland areas can cause water levels to be above the ground surface, leading to flowing well conditions.

A water table map reflects the uppermost saturated surface and therefore must be prepared by using water levels measured in shallow wells. This can be problematic, especially in areas where the near-surface sediments have low permeability so do not yield much water such that very few, or no, shallow wells exist. This is frequently the case in the study area where lower permeability tills occur at the surface. In such areas, wells are drilled through these lower-permeability materials to deeper more permeable aquifers, and the water levels in the wells do not accurately reflect the water table. In these areas, the water table occurs in the lower-permeability till sediments. If a hole were to be drilled in the shallow till unit, groundwater would enter the well screen, but it would seep into the hole slowly, perhaps taking several months to reach a static level, because of the fine-textured, low-permeability soils. To prepare the water table map shown in Figure 41, precautions were taken to not use water levels from deeper in the subsurface, since these water levels could introduce erroneous water table measurements. In addition, when considering some parts of the study area, particularly in the vicinity of the ORM, where there are areas with locally perched water table conditions, care was taken to avoid incorporating anomalously high perched water table measurements. Despite these efforts, there are undoubtedly some erroneous water levels in Figure 41. Seasonal water table fluctuations can be on the order of meters, thus the observation date needs to be considered because a map of values in one season may show different flow directions than one from another season and mixing the values can produce a meaningless flow pattern. None the less, the prevalence of many water levels that truly reflect the water table results in Figure 41 reasonably reflecting the average water table across the study area. The figure continues

to be updated as new data are added to the database. The water table elevation is a subdued replica of the ground surface topography (Desbarats et al., 2002). The ORM functions as a groundwater divide with flow north to Georgian Bay, Lake Simcoe, and the Kawartha Lakes and flow south to Lake Ontario. Although difficult to discern on a regional scale, the shallow groundwater moves toward coarser ORM grained channels (C2). Shallow groundwater flow moves towards the many streams that have incised through the shallow sediments. Although the elevations of the water table are lowest along the shore of Lake Ontario, Marchildon and others (2022) found that very little groundwater discharges directly to Lake Ontario, with the bulk discharging to the many streams that wind their way to Lake Ontario.

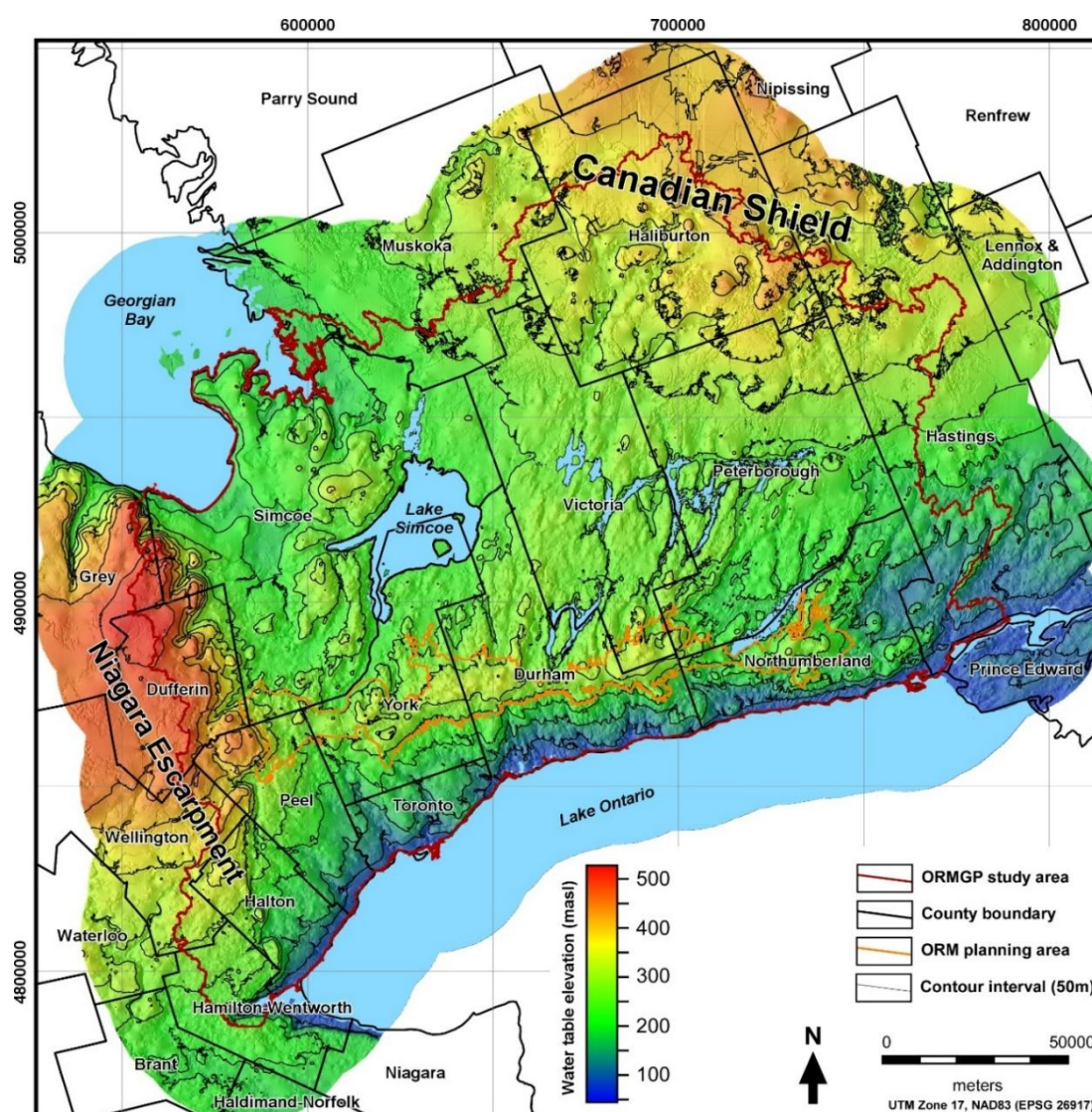


Figure 41 - Water table elevation prepared from groundwater levels measured in wells screened less than 20 m below ground surface. The water table is a subdued replica of ground surface topography, which is typical of humid climates. Further exploration of the interpreted water table surface, including wells used to prepare the surface, are available at [ORMGP-Maps-water table theme](#).

The interpreted water table depth is shown in Figure 42. For much of the study area, the water table is within 5 m of the ground surface; however, some elevated areas, particularly beneath parts of the ORM, have a water table elevation 20 to 30 m below ground surface.

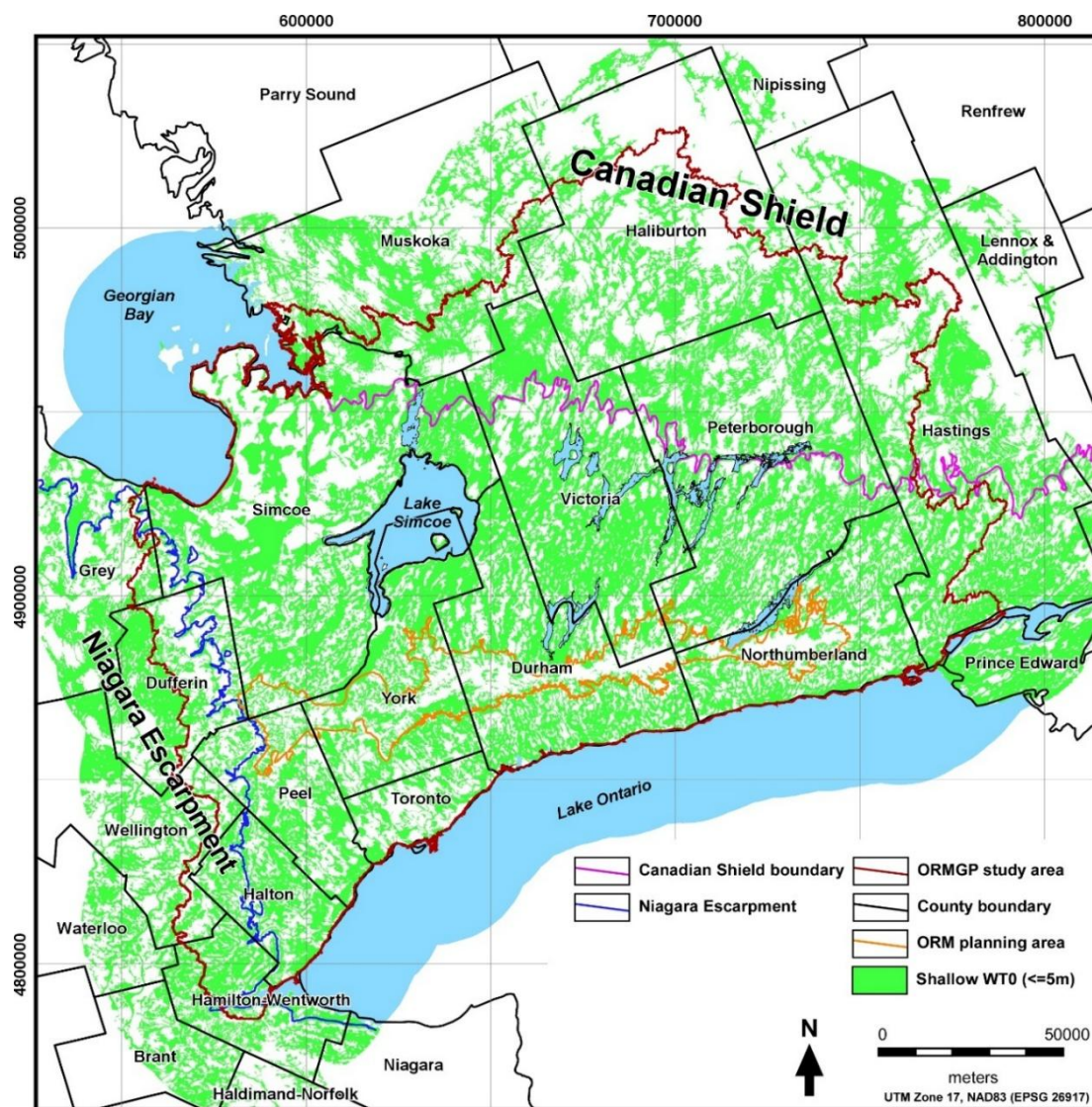


Figure 42 - Interpreted depth to water table—m; Shaded green areas are where the interpreted water table is within 5 m of ground surface. In some upland areas, such as beneath the Oak Ridges Moraine, the water table is 20 to 30 m deep. The water table map based on ORMGP data is available at [ORMGP-Maps-water table theme](#).

In addition to making use of the water levels from wells, in southern Ontario, rivers and/or lakes can indicate water table elevation. The ORMGP program has constructed two series of water table maps: those based on groundwater levels measured in wells where the bottom of the well screen is less than 20 m below ground surface (mbgs) alone (WT0), and those that incorporate other factors such as stream elevations and deeper wells in areas where the water table is greater than 20 mbgs, such as beneath the ORM (WT1). Both water table surfaces (WT0 and WT1) have been corrected so they are not above ground surface.

The maps are available for exploration at [ORMGP-Maps-water table theme](#) along with associated metadata.

The data that have been used to prepare these maps is of variable quality, so the maps need to be used with some caution. Uncertainty associated with the prepared water table maps, and also with the potentiometric surface maps for deeper aquifer complexes, results from several sources; that include the following.

- **Screen depth:** Water levels are from wells with a specified screen depth. As a result of complex sediment deposition during Ontario's glacial past, the hydraulic setting can be quite different in different areas. For regional maps, small geological nuances cannot be investigated to arrive at an ideal well depth to reflect water table conditions. The depth selection criterion might, in some areas, incorporate water levels that are not representative of the water table—e.g., water levels in shallow wells may reflect perched groundwater conditions and thus be anomalously high.
- **Sparsity of data:** There are many regions within the study area where few shallow wells are available for measuring the water table. In these areas, the estimated water table is more uncertain.
- **Poor water level measurements:** Much of the water level data used to create the water table maps comes from well drillers, who record the static water level on the well record form. It can take a long time for the well to recover to a static water level (hours to months depending on the transmissivity of the zone), so often the drilling crew has to leave the well before the water level fully recovers. If the water level has failed to reach the final static level when the driller records the static water level, then the measurement might be anomalously low.
- **Temporal variability of measured water levels:** The water levels in the database have been measured in different years and in different seasons—e.g., wet spring versus dry summer. For wells where more than one water level is available, the average water level has been used. Ideally, to produce the best water table map, the water level in all wells would be measured on the same day to acquire a snapshot in time of the water table surface. Unfortunately, this is not practical and therefore a surrogate approach, whereby the available water levels are aggregated, has been taken. This method assumes that the available water levels over the years would reflect average conditions over time and that the resultant regional water table map reflects a reasonable representation of the average water table. The water table rises and falls throughout the seasons—generally high in spring, winter, and fall months and low in summer months—in some cases by 2 to 3 m or more depending upon the geology and the physical setting. Water table fluctuations in till deposits which occur over a large portion of the study area have been observed to range up to 5 to 6 m seasonally depending on climatic conditions—e.g., drought. This range of water table fluctuation within till deposits has also been observed elsewhere in Ontario (Ruland et al., 1991),

and in Denmark (Jørgensen et al., 2022). Groundwater takings—e.g., pumping for water supply—can also lead to variability in groundwater levels both spatially and temporally.

As a result, the water table maps presented herein are considered to reflect a reasonable estimate of the average water table position. In general, when looking at a local scale, site-specific information would be considered more accurate than the regional overviews provided in Figure 41 and Figure 42. An analysis of groundwater level variability, both seasonal and longer-term, using data from active monitoring wells is available at [ORMGP-Data Snapshot-groundwater level variability](#).⁷

Groundwater flow within the study area is topographically driven. An approximate overall ground surface horizontal gradient, while not uniform, is approximately 0.004 to the north of the ORM, and at least double that (0.008 to 0.02) to the south of the ORM. Water table horizontal gradients are similar to ground surface topographic gradients (Figure 43). Higher horizontal hydraulic gradients occur in areas with steeper topographic slopes—e.g., ORM slopes, Niagara Escarpment, river valleys, the glacial Lake Iroquois shoreline—often where groundwater discharge occurs.

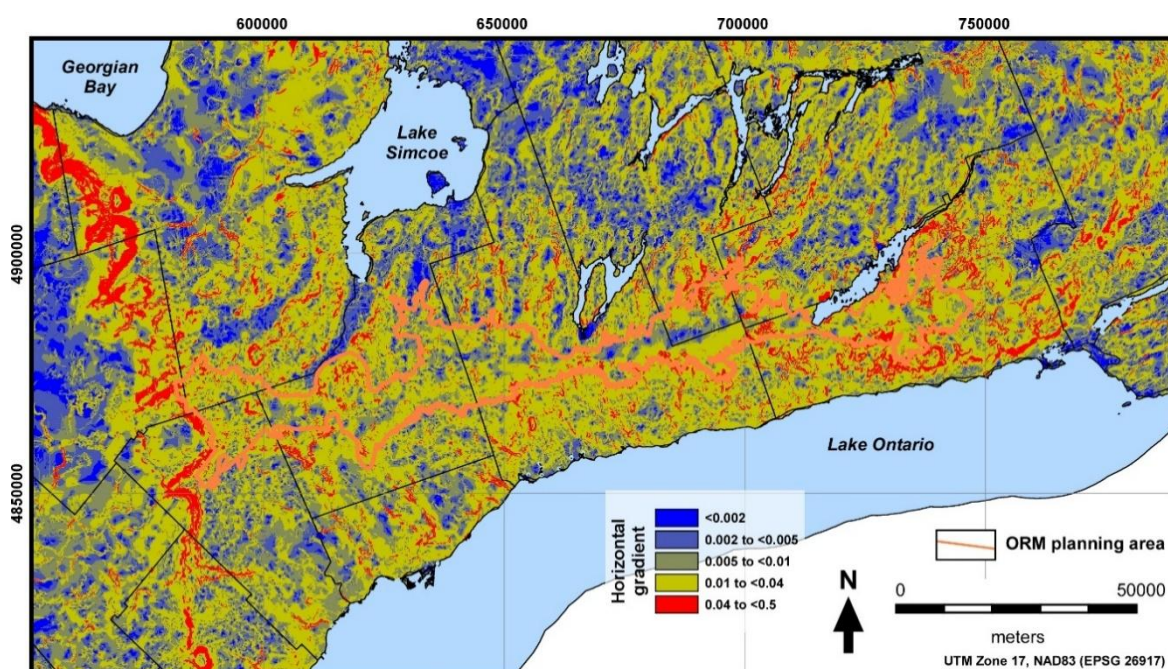


Figure 43 - Horizontal hydraulic gradients for the interpreted average water table. Average hydraulic gradients are between 0.001 and 0.1. Areas of lower horizontal gradient occur over extensive lowlands and in some upland areas. Horizontal hydraulic gradients increase near and in discharge areas along steep slopes and along river valleys. The coverage area shown is less than the entire study area to allow for comparison to horizontal hydraulic gradients shown for groundwater levels within Lower Sediment presented in subsequent figures.

Groundwater flow within the deep flow system—i.e., generally within the Lower Sediments situated beneath the Lower Newmarket Till aquitard—was constructed by using water levels from deeper wells, where the bottom of the well screen was deeper than 40 m below ground surface. Figure 44 shows that the deeper flow system is like the shallow flow

system in that groundwater level elevations are also a subdued replica of ground surface topography with a flow divide beneath the crest of the ORM. Like groundwater flow in the shallow system, groundwater within the deeper system also moves toward the coarser, lower parts of the Thorncliffe channels (C1), and where the deep system is intersected by streams, the flow preferentially moves toward these discharge locations. Horizontal hydraulic gradients for groundwater flow within the Lower Sediment are lower than the water table gradients and range from generally less than 0.005 to the north of the ORM to less than 0.04 to the south of the ORM (Figure 45; [Exercise 9](#)).

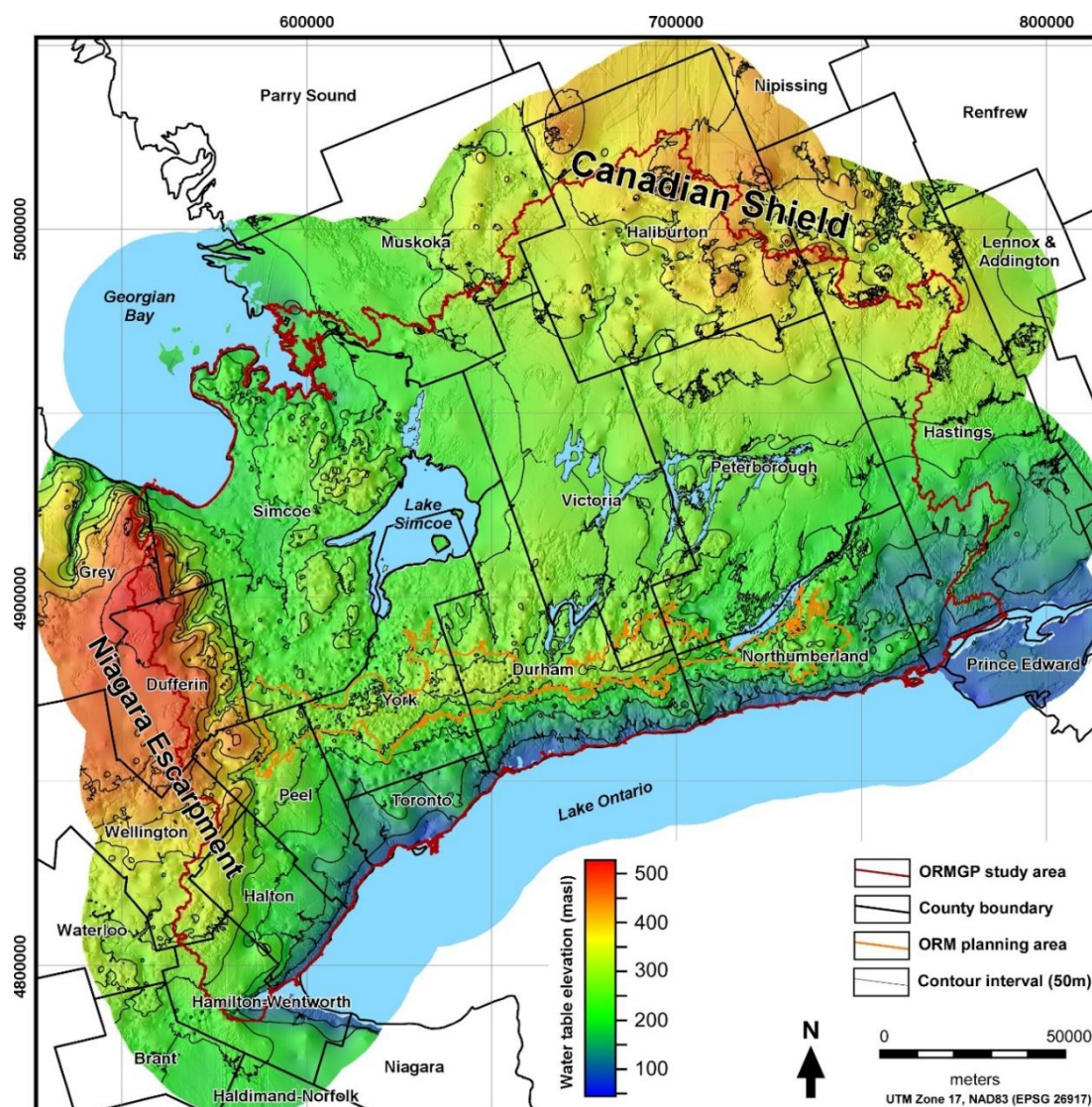


Figure 44 - Potentiometric surface of the deep flow system (Lower Sediment), constructed from wells where the bottom of the screen is greater than 40 m below ground surface. Groundwater flow patterns and directions are similar to those of the water table for all aquifers within Quaternary sediments above bedrock—e.g., groundwater flow divide beneath the ORM. The interpreted potentiometric surface, including wells used to prepare the surface, are available for viewing and exploration at [ORMGP-Maps-water table theme](#). Vertical hydraulic gradients occur within Lower Sediment aquifer complexes (TAC and SAC) with the magnitude of hydraulic head difference generally less than 5 m.

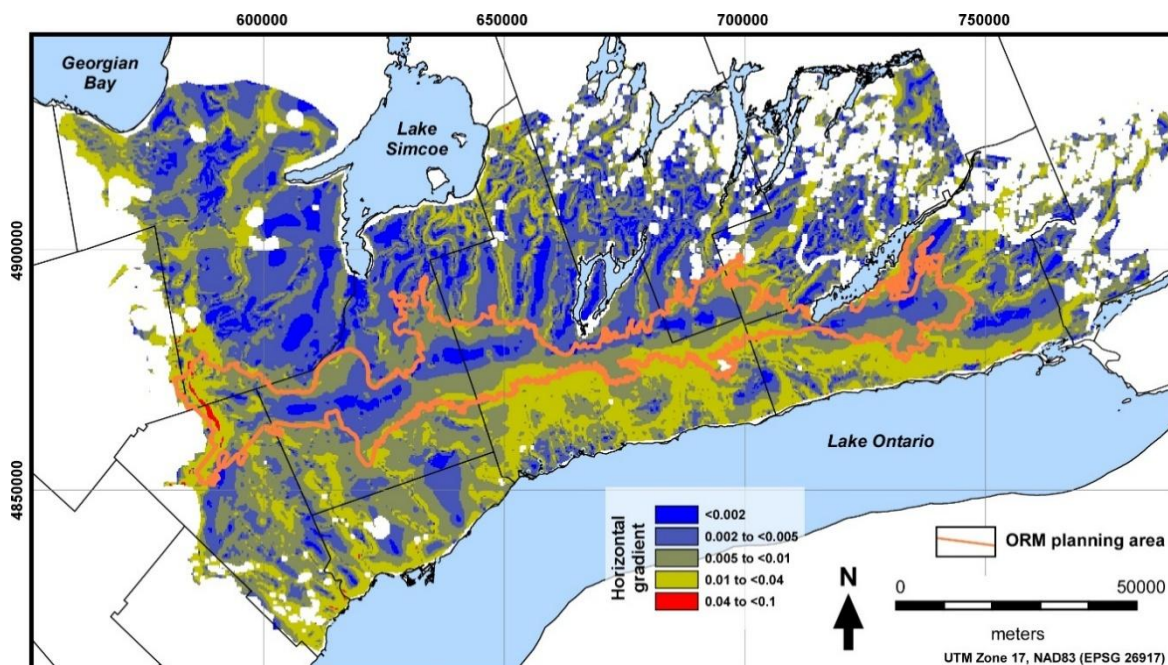


Figure 45 - Horizontal hydraulic gradients for groundwater flow within the Lower Sediment. Gradient calculations were conducted on the simulated deep flow system hydraulic head from Earthfx Inc. (2006). Horizontal hydraulic gradients increase along steep slopes—e.g., ORM south flank—and along river valleys.

The deep flow system within the Lower Sediment is replenished by vertical groundwater flow, as these sediments do not generally outcrop in the study area except in lowland discharge areas. The principal control on vertical groundwater flow to the Lower Sediments is the two-component regional aquitard consisting of Lower Newmarket Till and/or underlying Thornccliffe silt-clay rhythmites. Vertical leakance controls groundwater flow through this aquitard and is defined as the average vertical hydraulic conductivity of the confining unit (K'_v) divided by its thickness (b'). Direction of flow through the aquitard is either upward or downward depending on the vertical hydraulic gradient (i_v). Areas with downward vertical hydraulic gradients from the shallow flow system to the deep flow system are shown in Figure 46 (colored areas). The magnitude of the hydraulic head difference between shallow and deep aquifers generally reflects the integrity or bulk vertical hydraulic conductivity of the intervening aquitard—i.e., the Lower Newmarket Till. Areas with a hydraulic head difference of 20 m or greater (purple areas in Figure 46) reflect areas where the bulk vertical hydraulic conductivity is 1×10^{-9} m/s or less. Downward vertical hydraulic gradients through the Lower Newmarket Till generally range from 0.2 to 0.8, with the higher gradients occurring in topographically high areas, or areas where groundwater from Lower Sediment aquifers discharge to river valleys, and where significant groundwater pumping occurs from Lower Sediment.

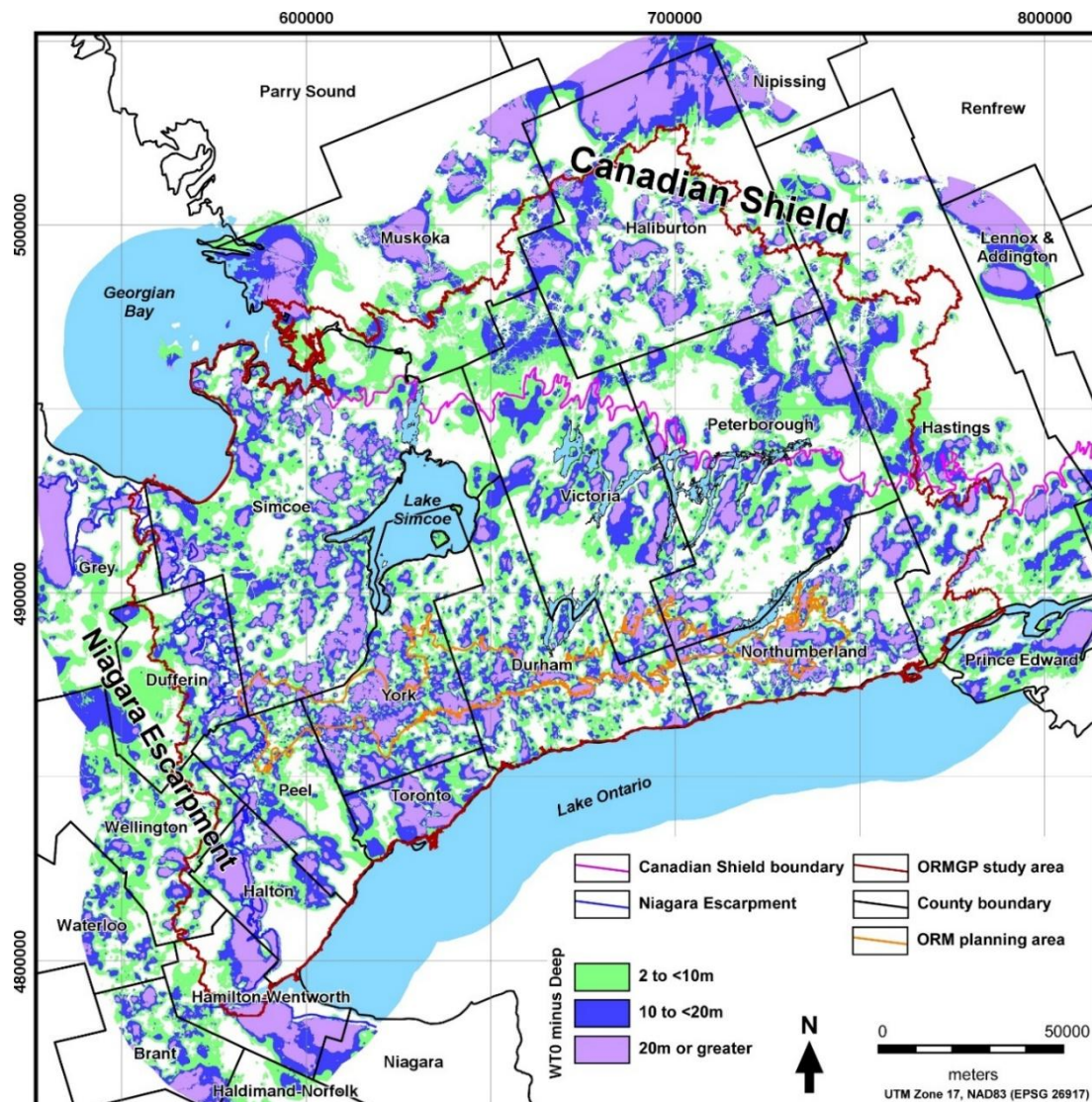


Figure 46 - Water table minus deep potentiometric surface. Shaded areas are where interpreted water table elevation is above the deep potentiometric surface elevation, indicative of vertical downward hydraulic gradients. White areas occur along stream valleys and other low topographic areas where upward vertical hydraulic gradients and groundwater discharge occur. Water table and potentiometric surface interpretations, including data points, are available for further exploration at [ORMGP-Maps-water table theme](#).

Numerous investigations state that there is relatively little groundwater flow within bedrock units—shale, limestone—beneath much of the study area and that few domestic water supplies exist within bedrock due to low yields and/or water-quality issues (Aravena et al., 1995; Funk, 1977; Haefeli, 1970; Ostry, 1979a; Sibul & Choo-Ying, 1971; Sibul et al., 1977; Singer 1981; Singer et al., 2003; Vallery et al., 1982). Exceptions to this occur.

- To the east and north of Lake Simcoe where glacial sediment is thin, many domestic wells tap both the Paleozoic bedrock units and many wells also tap the Precambrian rocks further north.

- Domestic wells exist in bedrock along the Lake Ontario shoreline to the east of Toronto, where the glacial sediment is thinner and permeability of the overlying sand and gravel aquifer material is slightly higher.
- Shallow bedrock wells are also common west of Toronto, across the south parts of Peel and Halton Regions, where lower permeability till sediments dominate thus providing little opportunity for domestic wells to tap aquifers above the bedrock surface.

In each of these three areas, the bedrock units do not yield great volumes of groundwater, but may produce 3 to 5 imperial gallons per minute (20 to 33 m³/d), which is sufficient to supply a private residence. Many of these bedrock wells have slightly saline water quality owing to the sluggish flow system within these lower permeability rocks. Across the entire study area, many of the wells that penetrate to the bedrock surface, tend to be screened across the sediment/bedrock interface. It appears that this interface zone frequently contains weathered and fractured bedrock that can provide enough water to serve as a domestic supply. The bedrock wells are shown in Figure 13a.

The area west of Lake Simcoe also contains karst regions where enhanced recharge and, by extension, enhanced groundwater flow occurs within bedrock (Figure 47) (Brunton, 2019; Brunton & Dodge, 2008). Karst mapping is being updated by the Ontario Geological Survey for the northeastern part of the study area along the edge of the Grenville Geologic Province (Brunton, 2019). The Niagara Escarpment occurs along the western boundary of the study area, which is also a known karst region. Karst mapping for this area has been updated recently (Brunton & Brintnell, 2020) as part of regional Paleozoic geology mapping refinement (Carter, Forter et al., 2021; Carter, Logan et al., 2021). Significant regional aquifers exist within rocks associated to the west of and along the Niagara Escarpment (Brunton & Brintnell, 2020; Figure 48) and are used for municipal water-supply purposes—e.g., the City of Guelph. Further information on bedrock aquifers situated to the west of the study area is provided by Priebe and others (2019, 2021). The observed depth of fresh water within bedrock is relatively shallow for this study area (Carter, Forter et al., 2021).

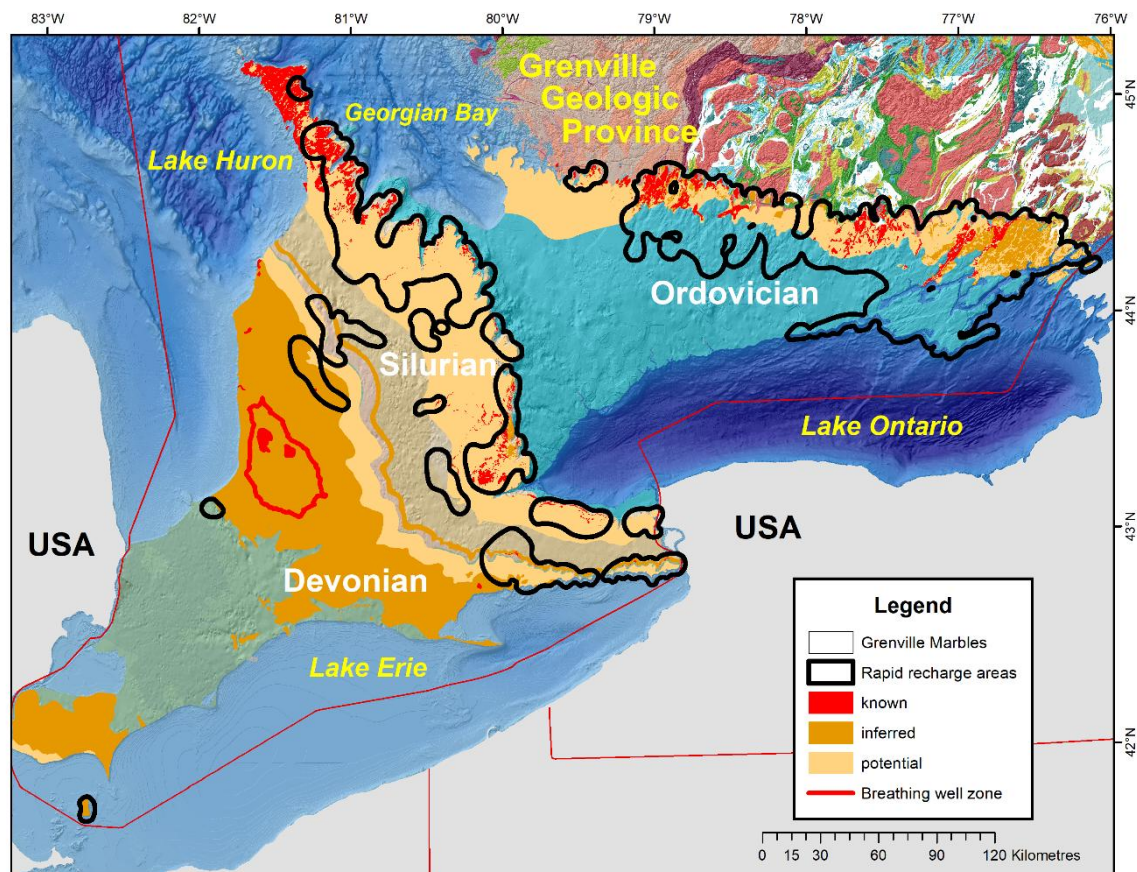


Figure 47 - Distribution of karst within southern Ontario; areas outlined in black are assumed to have rapid recharge. Karst mapping for the Ordovician cuesta area—Lake Simcoe to Napanee—Kingston—along the edge of Grenville Geologic Province is in the process of being updated (from Brunton, 2019; reproduced with permission).

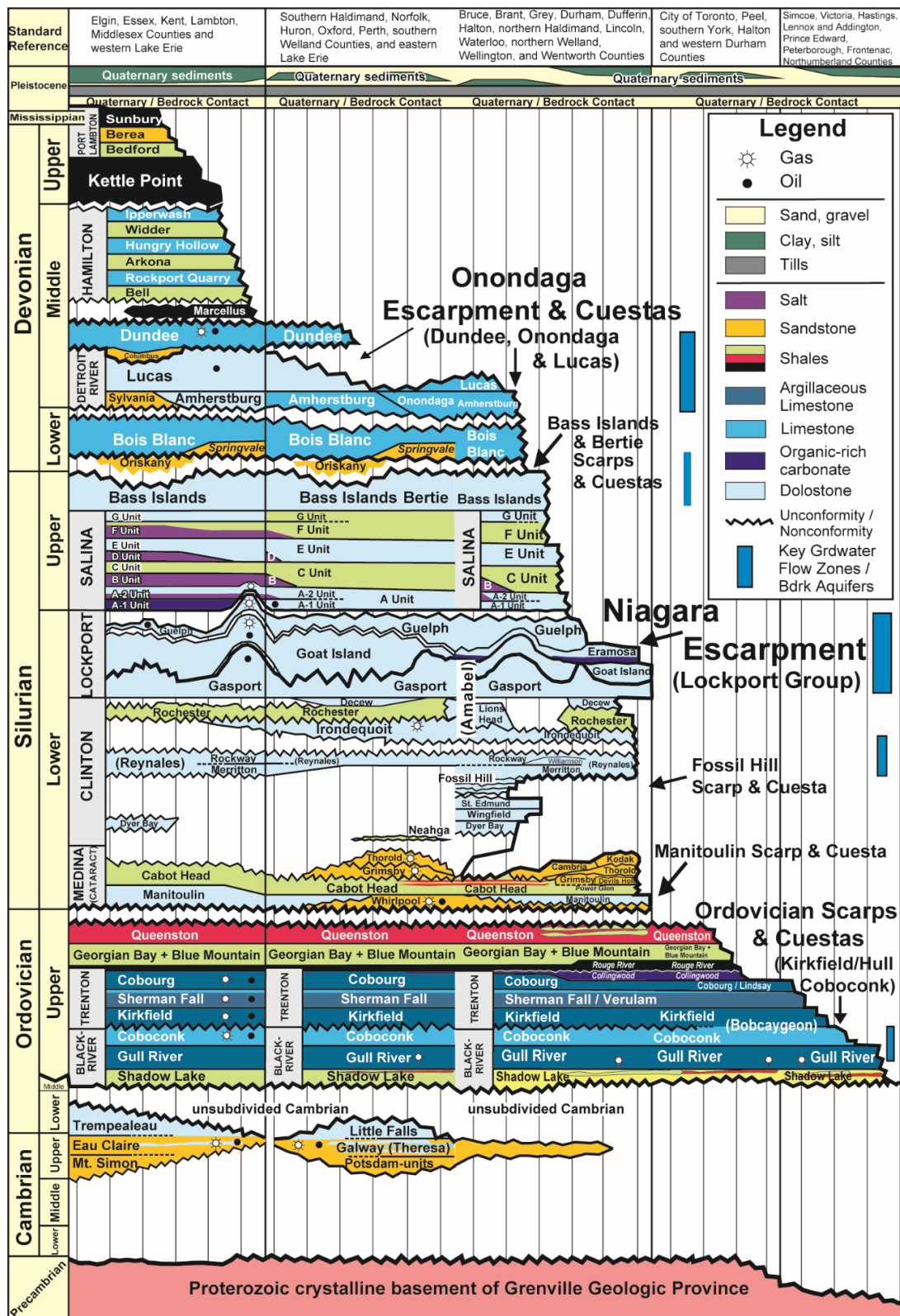


Figure 48 - Paleozoic stratigraphy for south-central and southwestern Ontario with key bedrock aquifers delineated. The stratigraphic framework for the Paleozoic geology of southern Ontario is in the process of being updated through a collaborative effort over the last decade (Brunton et al., 2021) (from Brunton & Brintnell, 2020; reproduced with permission).

In summary, regional groundwater flow directions within both shallow (ORM sediment) and deep parts of the flow system (Lower Sediment) mimic ground surface topography. The system is replenished by infiltration of precipitation with the highest recharge rates occurring over sandy upland areas, e.g., the ORM. Discharge zones occur within lowland areas and along topographic breaks in slope such as along the north and south flanks of the ORM and along river valleys that drain into Lake Simcoe, Lake Ontario, and Georgian Bay. Regional horizontal hydraulic gradients for the water table and deeper aquifer complex potentiometric surfaces generally range from 0.001 to 0.01 with increased gradients occurring in areas of steeply sloped topography associated with the flanks of the ORM and along river valleys. Vertical hydraulic gradients from the shallow to the deep parts of the flow system through the Lower Newmarket Till generally range from 0.4 to 0.8 (Gerber & Howard, 2002). Regionally, the majority of groundwater flow volume occurs within Quaternary sediments compared to the underlying bedrock units—which are largely shale and limestone ([Exercise 8](#)) ([Exercise 9](#)).

6.5 Water Budget

A basin water budget is a summary of the components—precipitation, evaporation, recharge, runoff, discharge—of the hydrologic cycle for a hydrologic system. Water that falls as precipitation, can runoff to streams and lakes, infiltrate into the ground, or evaporate from the land and water-bodies. In humid regions, most of the precipitation that falls on land evaporates from free surfaces or is transpired by plants. The combination of these two processes is termed *evapotranspiration*. The potential evapotranspiration is the amount of water that would evaporate and transpire if water were available in unlimited supply. Unlimited availability of water is uncommon thus the term *actual evapotranspiration* is used. Infiltrated water may be retained as soil moisture, move laterally as interflow within the unsaturated soil zone, or provide groundwater recharge to the water table. Interflow quantities are considered negligible on a basin-wide scale (Domenico & Schwartz, 1998). The maximum moisture content that can be retained by unsaturated soil is termed the *field capacity*, or *wet limit*. When the moisture content exceeds the field capacity, surface runoff, interflow, and/or groundwater recharge can occur. Groundwater may move downward to deeper parts of the flow system, be transpired by plants, or move within shallow parts of the flow system and be discharged in short timeframes to springs and streams, where it may leave the basin and eventually evaporate to the atmosphere to complete the hydrologic cycle (Domenico & Schwartz, 1998; Singer, 1981). Figure 49 summarizes the components of a basin-scale hydrologic cycle.

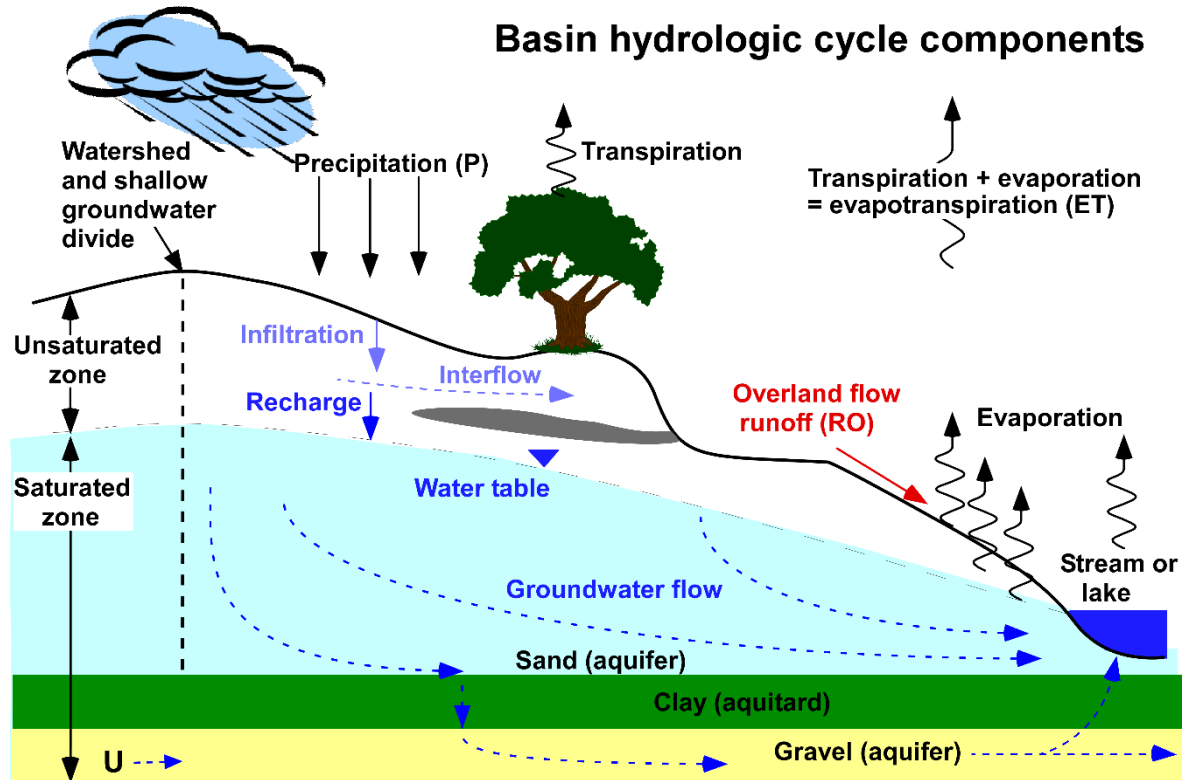


Figure 49 - Basin hydrologic cycle components. Transpiration includes three main steps, including plant root uptake of water from the soil zone, water moving through plant tissues, and water vapor released from plant leaves. Evaporation includes water evaporation from surface-water bodies, the soil surface, and the shallow subsurface—unsaturated zone including the capillary fringe above the water table (Hanson, 1991). Water vapor leaving the system via evaporation and transpiration are combined into a single parameter called evapotranspiration (ET). The watershed and groundwater divide (left side of the diagram) is a no-flow boundary. Shallow groundwater discharge (Q_s) is mostly baseflow to streams and lakes. Subsurface underflow (U) is groundwater flow in a deeper aquifer not affected by the groundwater divide.

The diagrammatic water balance for the watershed in Figure 49 can be expressed mathematically as shown by Equation (2).

$$A t (P - ET - RO) - t (Q_s + \Delta U) = A (\Delta sm + \Delta gw) \quad (2)$$

where:

- A = planimetric (map) area of the watershed (L^2)
- t = time duration of the budget period (T)
- P = precipitation (LT^{-1})
- ET = evapotranspiration (LT^{-1})
- RO = surface runoff per unit area (LT^{-1})
- Q_s = shallow groundwater discharge flow rate to surface water or the atmosphere (L^3T^{-1})
- ΔU = change in the deep aquifer flow rate (underflow) from left to right in the diagram; positive for increase in this direction (L^3T^{-1})

Δsm = change in soil moisture storage volume per unit area, controlled by changes in water content in the unsaturated zone; positive for increase (L)

Δgw = change in saturated groundwater storage volume per unit area, controlled by changes in water-table elevation; positive for water table rise (L)

The left-side of this equation represents the net volume of water that entered the subsurface during the time t , and the right-side is the net increase in water volume stored in the subsurface over the same period. The water parameters in this transient equation are typically annual averages for a duration of one year or more years.

Over long periods in an unstressed, natural-state basin, the natural inputs will balance the natural outputs so the change in storage will be zero (Domenico & Schwartz, 1998; Freeze & Cherry, 1979). In this case, the right side of Equation (2) is zero and the resulting steady-state equation becomes Equation (3).

$$A (P - ET - RO) = Q_s + \Delta U \quad (3)$$

In Equation (3), the left-side is the net flow rate of water entering the subsurface, and the right-side is the net flow rate leaving the system.

Figure 50 illustrates the long-term annual range of total precipitation (Figure 50a), streamflow (Figure 50a), and groundwater levels (Figure 50b) for select locations within the study area. Precipitation at the Toronto gauge station can vary annually by approximately 200 mm/year above or below long-term average values. Groundwater level variability is shown for several screened zones at a well location in north Pickering—site 1/94. The water table in the shallow screen is in till and can be up to 3 m above or below the long-term average. The year 2016 provides an example of the variability of a short-term drought year, with a noticeable low in precipitation, streamflow, and water table observations.

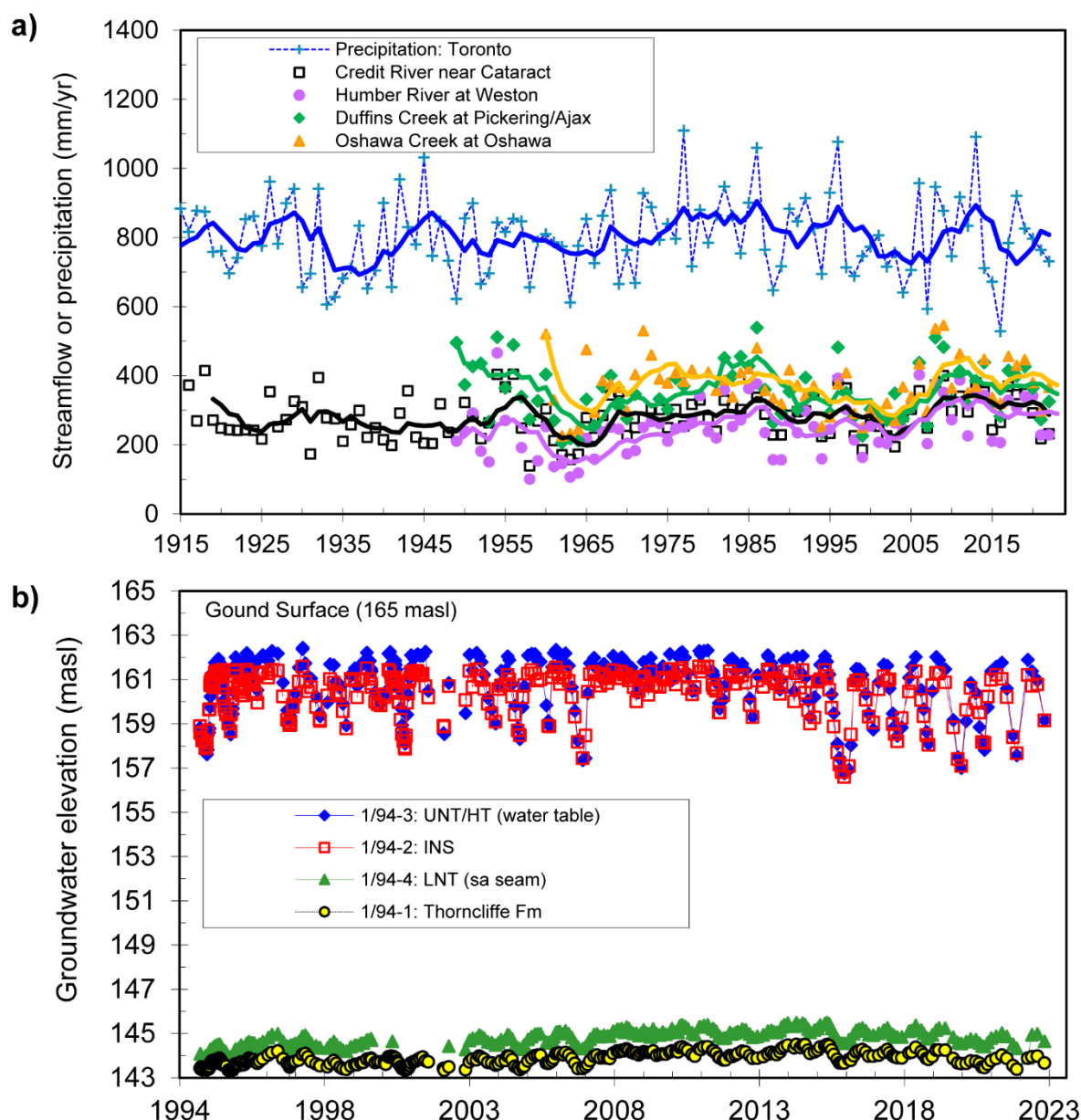


Figure 50 - Long-term hydrologic observations. a) Precipitation data from Environment Canada and streamflow data from Water Survey of Canada. Streamflow in mm/yr represents the volume of stream discharge for a year in terms of depth of water over the watershed area. Solid lines represent 5-year moving average. b) Groundwater levels from University of Toronto researchers and ORMGP staff, at location site 1/94 illustrating a downward vertical hydraulic gradient ranging from -0.8 to -1 . High vertical hydraulic gradients occur due to a low permeability aquitard—LNT—Lower Newmarket Till—between the upper and lower screens.

Figure 51 shows seasonal variability of groundwater levels and streamflow for two locations within the study area that can be subdivided into four periods. The length of each period may change for any given year and according to location. Period 1 occurs from approximately mid-December to the end of February. Precipitation is generally in the form of snow, with the snowpack increasing. The temperature is generally below freezing. Evaporation from the snowpack is effectively zero, and minimal recharge occurs during precipitation or snowmelt events. Groundwater storage is generally maintained depending on the amount of recharge received and groundwater discharge to streams.

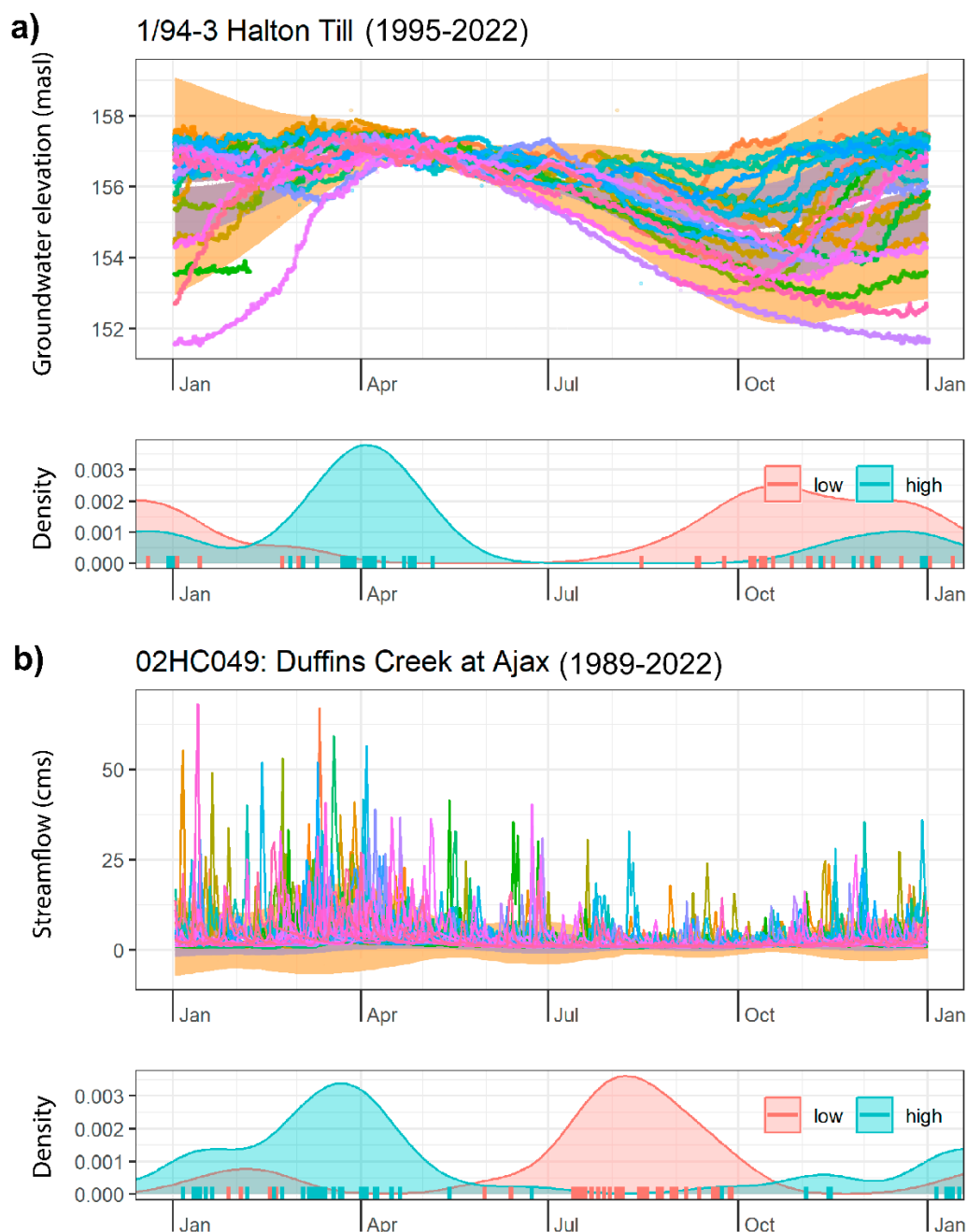


Figure 51 - Typical annual variability of groundwater levels and streamflow. a) Daily average water table elevation in till at Site 194-3 in north Pickering with groundwater with a different color line for each year. The density plot illustrates the date of the annual high and low groundwater levels for each year with tick marks at the bottom of the plot (blue for high and orange for low). The blue-filled density plot shows that groundwater highs occur most frequently in March and April whereas the orange-filled plot indicates lows occur most frequently in July through September. b) Daily average streamflow at 02HC049 Duffins Creek at Ajax with each year a different color. The density plot illustrates annual daily high and low streamflow. The highest streamflows occur most frequently in March and April and the lowest streamflows occur most frequently in July through September. There is a slight delay in peak groundwater levels relative to peak streamflow and a delay of a couple months between annual low stream flows in August and groundwater levels in October. Annual lows in streamflow occur earlier in the year due to groundwater storage effects. Four approximate periods of hydrologic behavior are shown by the variability and density readings. Period 1 from approximately mid-December to February represents a period of relatively stable to slightly rising groundwater levels and streamflow. Period 2 from approximately February to April during which groundwater levels and streamflow are rising to an annual peak. Period 3 from approximately May to September is characterized by declining groundwater levels and streamflow. Period 4 from approximately September to mid-December when groundwater levels and streamflow stabilize or slightly increase.

Period 2 spans February to April. The rise in temperature to above freezing means that most precipitation is in the form of rain and, along with melting of the snowpack, leads to high streamflow and the potential for floods. In Ontario, April is frequently the month when streamflow runoff and shallow groundwater levels are at a maximum (Sangal, 1984). There is a slight delay in groundwater level peaks compared to streamflow peaks due to groundwater storage effects (Figure 51). Percolating water exceeds the moisture capacity or wet limit of the soil as indicated by a water table rise. Evapotranspiration is insignificant; the temperature is still low and plant growth is minimal. This is a major period of groundwater recharge.

Period 3 occurs from May to September. This period is characterized by high temperatures and high evapotranspiration rates resulting from significant plant/vegetation growth. Precipitation is in the form of rain and most of it is retained by the soil to satisfy an increasing soil moisture deficiency. Percolation to groundwater storage occurs only during large storms when field capacity (i.e., the maximum water the soil can hold against gravity drainage) of the soil is exceeded. Minor groundwater recharge can occur during periods of soil moisture deficit through such features as fractures and surface runoff that collects in ditches and infiltrates (Rushton & Ward, 1979). The water table is steadily declining, as discharge to streamflow is greater than recharge. Streamflows generally decline to their lowest levels during this time.

Period 4 occurs from September to mid-December. Precipitation is still in the form of rain with some snow. The growing season is finished, and evapotranspiration is low. Soil moisture has returned to field capacity—the wet limit—as shown by a water table rise. This is the second major period of the year where groundwater recharge exceeds discharge.

Along with seasonal variation in groundwater levels, observed groundwater levels within the study area also exhibit longer-term trends. These longer-term trends can occur due to changes in large groundwater pumping centers or to changes in climate such as variable precipitation or snowmelt. Examples of longer-term groundwater level variability are provided in Figure 52. Data analysis tools to review various datasets have been constructed and are available at www.oakridgeswater.ca⁷. The broad spectrum of available tools allows users to characterize various watersheds and hydrogeological settings by viewing, interacting with, and evaluating statistical graphs and calculations for the long-term temporal records—climate data, streamflow, and groundwater-level data—held in the ORMGP database. One example of an important streamflow analysis statistic is the cumulative discharge curve, where changes in slope reflect both natural and/or anthropogenic changes within a drainage area (Figure 53a).

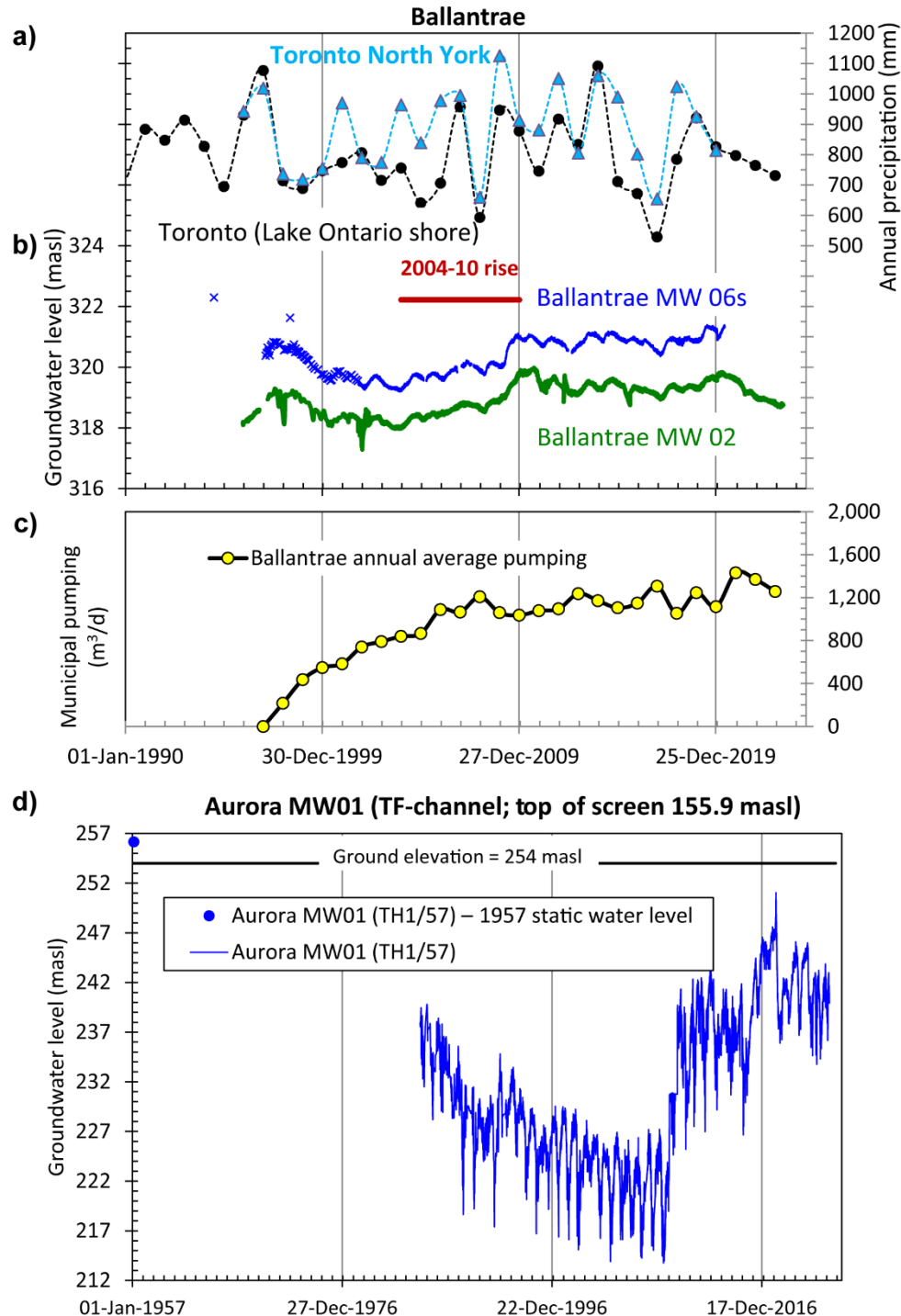


Figure 52 - Two examples (natural and anthropogenic) of longer term (beyond seasonal) groundwater level trends at Ballantrae on the ORM and at Aurora on the north slope of the ORM. a) Total precipitation at two long term climate stations, one with lower total annual precipitation at Toronto along the Lake Ontario shore and another at the Toronto North York station, situated to the north between Lake Ontario and the ORM. b) The increasing precipitation causes natural groundwater levels to rise in the ORAC between 2004 to 2010 as exhibited by two shallow ORAC monitoring wells in the Ballantrae area (MW 06s and MW 02). This rise in groundwater level is thought to be in response to climate, since local municipal pumping occurs from the deep Thornccliffe Aquifer Complex. The pumping rate (c) was increasing over this period, so if there was any response of the shallow water levels to pumping, they would have been decreasing. d) Illustrates the deep aquifer water level rise starting in 2008, as a response to the decline in municipal pumping from the Yonge Street Aquifer, near Aurora. Further details on this response are provided by Gerber and others (2018).

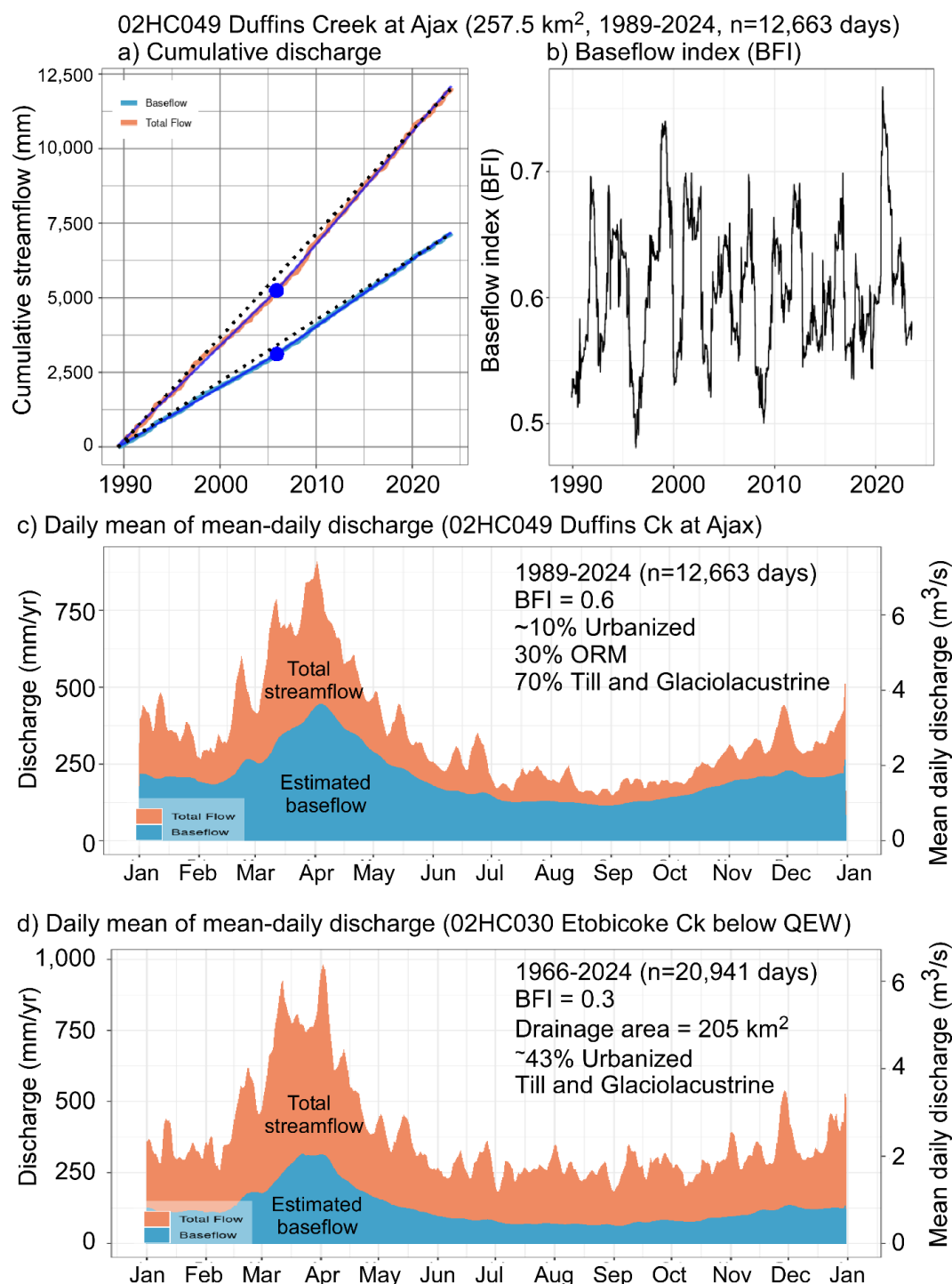


Figure 53 - Example of some of the streamflow hydrograph analysis tools (i.e., Hydrology analysis modules)—that are available at [ORMGP-Hydrograph explorer](#). The streamflow cumulative discharge curve is shown in a) for a gauging station along Duffins Creek situated near the Lake Ontario shoreline just east of Toronto. Slope inflections on cumulative discharge curves illustrate change in watershed characteristics. The slope inflection at around 2006 is likely due to increased urbanization and development within the southern part of the watershed. The baseflow index (BFI), which is the groundwater discharge component relative to total streamflow, for the same station is shown in b). Mean daily discharge summaries for two streamflow gauging stations are shown: c) shows mean daily discharge for the Duffins Creek station, a watershed with headwaters on the ORM and characterized by a higher average BFI of 0.6; while for comparison, d) shows mean daily discharge for a gauging station within the Etobicoke Creek watershed with headwaters south of the ORM. This watershed is characterized as more urban, with thinner glacial sediment, and bedrock close to surface across much of the lower part of the watershed. The result is a lower average BFI estimate of 0.3.

Estimates of the groundwater discharge component of total streamflow (i.e., the baseflow index, BFI) is important from a hydrogeologic perspective. For many streams in the study area BFI is greater than 50 percent and is approximately 60 percent in Figure 53b for the Duffins Creek station. Another way to make use of the extensive suite of online tools in the ORMGP is to compare responses at different streamflow monitoring stations to investigate how and why streamflow varies spatially. Figure 53c and Figure 53d shows the annual baseflow (in blue) as a percentage of the total flow (orange) for two streamflow monitoring stations. The Duffins Creek station (Figure 53c) is located farther away from Lake Ontario (closer to the headwaters on the Oak Ridges Moraine) where a larger portion of streamflow is derived from groundwater. In contrast, the Etobicoke Creek station (Figure 53d) is situated in a more urbanized watershed, closer to Lake Ontario, and as a result the streamflow has a higher surface runoff component. The higher surface runoff component of streamflow closer to Lake Ontario to some extent reflects the impacts of greater imperviousness in the watershed. In addition, the sediment thickness in the Etobicoke Creek watershed is also much thinner, and given the low hydraulic conductivity of the shale bedrock, groundwater flow in the watershed would likely have been low, even prior to urbanization.

6.5.1 Recharge

In humid regions, most of the annual groundwater recharge eventually discharges into streams or is removed by evapotranspiration processes from the water table (Pettyjohn & Henning, 1979). The rate of recharge depends on many factors including, but not limited to:

- quantity and intensity of precipitation;
- permeability of soils, and underlying sediment or rock;
- depth to water table;
- soil type and moisture conditions within the unsaturated zone;
- topography;
- vegetation type and density; and
- weather conditions including temperature, wind speed, solar radiation, and humidity.

The main sources of recharge to aquifers include infiltration of direct precipitation; depression-focused recharge where surface runoff accumulates; seepage from rivers, irrigation losses, and urban recharge such as leakage from water pipes, sewers, and stormwater collection ponds. For the study area, rain and snowmelt are the main source of recharge. Several recharge estimation methods exist, which are summarized by Lerner and others (1990) and Healy (2010). They include:

- empirical methods where recharge is correlated with other variables such as precipitation, soil type, and/or surficial geology;
- physical methods within the unsaturated zone—e.g., direct measurement by lysimeters, neutron probes, and tensiometers;

- physical methods within the saturated zone—e.g., water table fluctuation, Darcy calculations, and analytical models;
- water budget methods;
- surface water measurement methods—e.g., streamflow hydrograph separation analysis;
- chemical tracer techniques—e.g., chloride, isotopes ^{18}O , ^2H , and ^3H ; and
- numerical modeling methods.

Estimates of recharge by different techniques apply to different spatial and temporal scales and can yield substantially different values. Recharge estimation methods used in the study area include water budget, streamflow hydrograph separation, and numerical modeling. Limited chemical and isotope tracer techniques have been used in a small watershed investigation conducted just east of Toronto (Meriano et al., 2011). Estimates should be compared to those of other methods whenever possible and interpreted considering the hydrogeological characteristics of the area being studied. Rushton and Ward (1979) discuss the difficulties of estimating recharge using various methods. A particular disadvantage of water balance methods is that recharge, along with runoff, is a part of the residual between the large values of precipitation and evapotranspiration (Lerner et al., 1990). The water balance should be validated with multiple methods such as comparison to available groundwater level measurements and Darcian approaches including groundwater modeling.

A recharge-surface runoff water budget modeling routine has been developed and applied across the study area and is available at www.oakridgeswater.ca⁷. The net recharge distribution estimates are shown in Figure 54. Estimated recharge rates are discussed further in association with numerical modeling in Section 6.5.2.

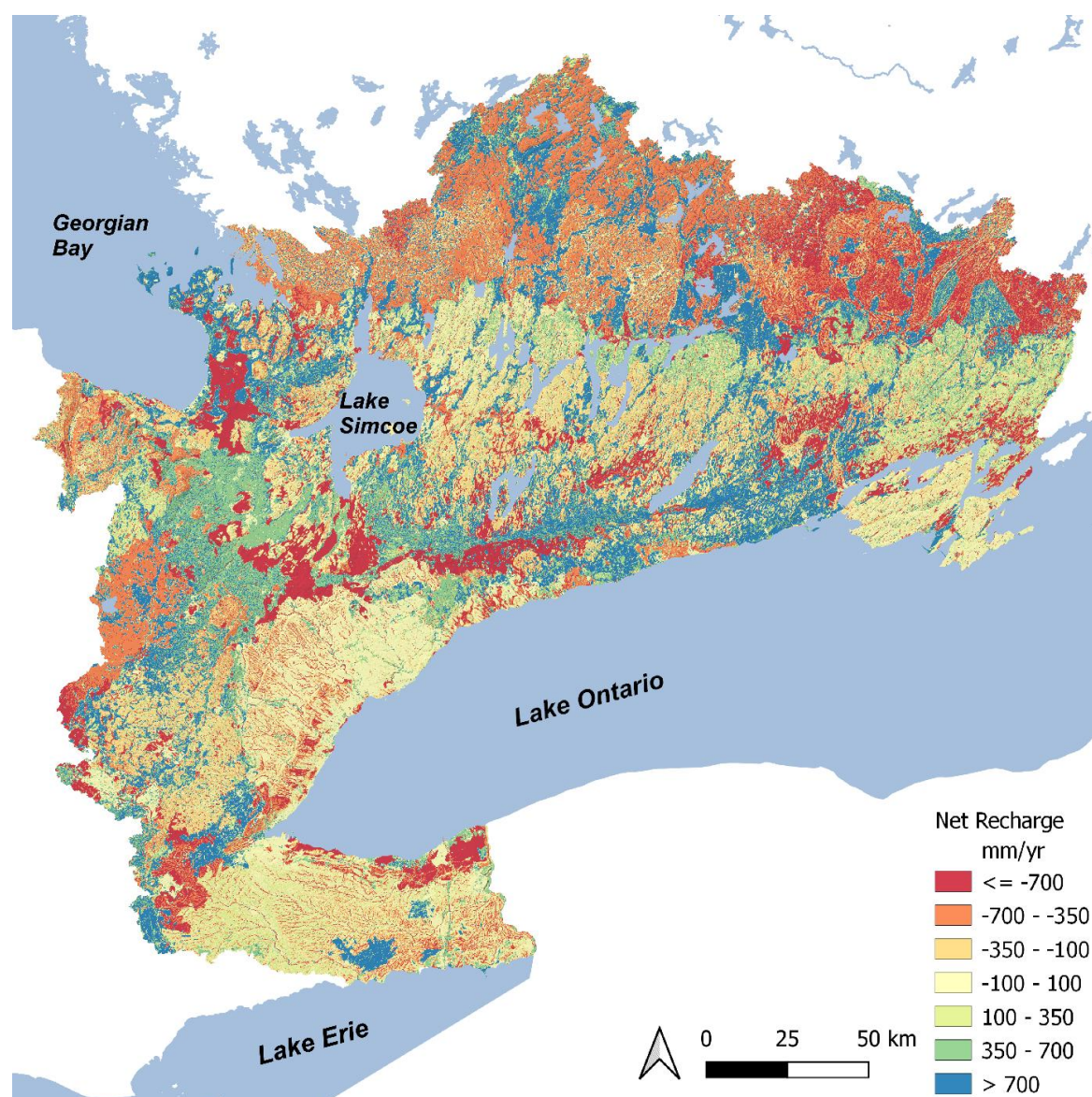
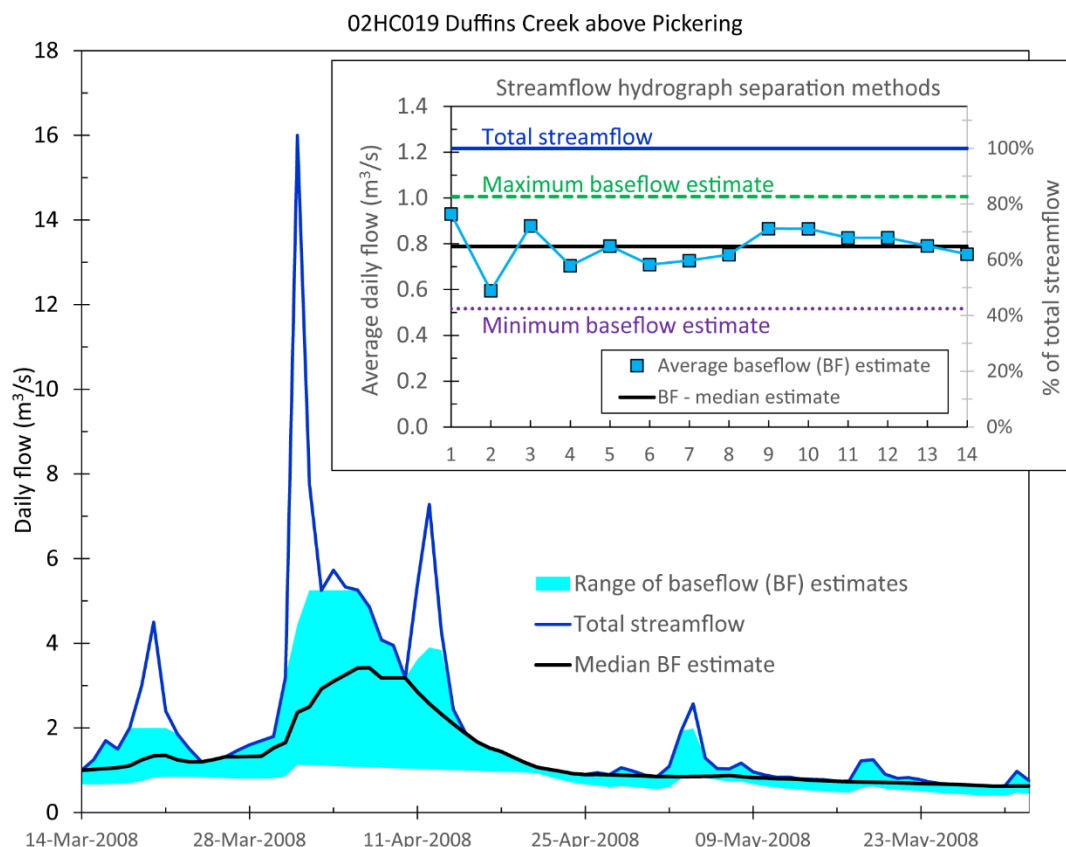


Figure 54 - Net recharge estimation results from the ORMGP regionally distributed surface runoff/recharge modeling routine for the study area. Model estimates are for 50x50 m cells on a 6-hourly time step for data since October 2001. High net recharge estimates occur in local areas such as hummocky terrain where local surface runoff ponds in depressions and seeps into the ground as well as along losing stream reaches. Negative net recharge areas are where processes other than recharge are dominant (e.g., discharge, evapotranspiration) such as areas where the water table is near or at the surface (e.g., rivers, wetlands) and highly urbanized areas where increased surface runoff and evaporation are the dominant surface processes. Maps of estimated recharge and further information including methodology for estimating recharge are available at [ORMGP-Tools-water budget](#).

In southern Ontario, as is typical of humid climates, there is an understanding that long-term groundwater discharge provides a preliminary estimate of long-term groundwater recharge. The flow rate in a stream is an important component of the water budget. Continuous collection of streamflow data and estimation of the base flow component provides insight into the volume of groundwater discharged. Station measurements of streamflow and stage are obtained by the Water Survey of Canada and the various ORMGP partner agencies—e.g., conservation authorities—and these data are updated regularly to the program’s database.

Using various baseflow separation techniques, streamflow has traditionally been split into two distinct components. The first portion occurs periodically during and after rainfall or snowmelt events where the water moves to streams in the form of overland flow—i.e., surface runoff; the second more consistent portion is referred to as baseflow, which is derived from groundwater discharge and persists yearlong. The latter typifies many streams that headwater on the ORM (Figure 53c). Figure 26 shows the spatial distribution of various stream-gauging stations within the study area. Various analyses performed on streamflow data (as, for example, in Figure 53 and Figure 55) are used to characterize the flow regime of many of the moraine’s larger tributaries. These characterizations, when combined with numerical groundwater flow models, provide powerful tools to enhance the understanding of watershed behavior, which is often linked to underlying Quaternary sediments, and to assess and quantify the impacts on water courses and groundwater levels, resulting, for example, from increased groundwater extraction or from urbanization. The annual median baseflow is derived using 14 different streamflow hydrograph separation routines (Figure 55). It is anticipated that by quantifying the groundwater recharge and improving the understanding of its link to discharge, and in turn its link to in-stream ecological flow needs, society can make better-informed water-management decisions—e.g., regarding the appropriate magnitude of groundwater that might be withdrawn for consumptive use from any watershed.



References

- | | |
|-----------------|--|
| 1. BF.LH | The Lyne-Hollick digital filter (Lyne & Hollick, 1979) as discussed in Chapman (1999); |
| 2. BF.CM | The Chapman-Maxwell digital filter (Chapman and Maxwell, 1996); |
| 3. BF.BE | The Boughton-Eckhardt digital filter (Boughton, 1993; Eckhardt, 2005); |
| 4. BF.JH | The Jakeman-Hornberger digital filter (Jakeman and Hornberger, 1993); |
| 5. BF.CI | The method of Clarifica Inc. (2002); |
| 6. BF.Ukn | The UK Institute of Hydrology (1980), sweeping minimum of Piggott et al. (2005); |
| 7. BF.Ukx | The UK Institute of Hydrology (1980), sweeping maximum of Piggott et al. (2005); |
| 8. BF.Ukm | The UK Institute of Hydrology (1980), sweeping median; |
| 9. BF.HYSEP.FI | The HYSEP fixed-interval method (Sloto and Crouse, 1996); |
| 10. BF.HYSEP.SI | The HYSEP sliding-interval method (Sloto and Crouse, 1996); |
| 11. BF.HYSEP.LM | The HYSEP local minima method (Sloto and Crouse, 1996); |
| 12. BF.PART1 | The PART method (Rutledge, 1998), pass 1 of 3 antecedent recession requirement; |
| 13. BF.PART2 | The PART method (Rutledge, 1998), pass 2 of 3 antecedent recession requirement; and |
| 14. BF.PART3 | The PART method (Rutledge, 1998), pass 3 of 3 antecedent recession requirement. |

Figure 55 - Streamflow hydrograph separation from a select time interval for the Duffins Creek above Pickering gauging station showing envelope and median of 14 baseflow estimation methods. The inset graph illustrates comparison of the 14 baseflow methodologies for the period June 1960 to October 2023 ($n=21,498$ days). All data collected by the Water Survey of Canada ([Water Survey of Canada](#)). References for the various methodologies are listed beneath the figure. Further exploration of streamflow hydrographs and associated statistical analyses can be found at [ORMGP-Hydrograph explorer](#). Further discussion of the results and data are available at [ORMGP-Data Snapshot-streamflow-hydrograph separation](#). For a regional investigation of baseflow estimation in the Great Lakes Basin of the US and Canada, Neff, Day, and others (2005) used similar methods to this program—HYSEP, UK and PART—along with the BFLOW method of Arnold and Allen (1999).

In addition to streamflow measurements at gauged locations, over 13,000 spot-flow—or low-flow—measurements have been collected across many of the watersheds that drain off the ORM and around Lake Simcoe. Low-flow or spot-flow surveys are conducted during summer months and measure streamflow during a dry period, free from rain or snowmelt events, to focus on the groundwater component of

streamflow. Typically, the surveys are conducted across a watershed in a short time interval, often over one day, and provide hydrogeological insight by:

- providing an indication of how significantly, and where, a particular stream is connected to the groundwater system by determining in the field where, and at what elevations, streams start flowing;
- allowing greater insight into the linkage between the groundwater and surface water systems by allowing both losing and gaining reaches of streams to be identified;
- understanding the spatial patterns of streamflow and their relationship to catchment geology, groundwater flow, drainage pathways, and ecosystem connectivity; and
- providing a snapshot of regional hydrology that helps overcome the sparse distribution of existing long-term stream-gauging stations.

While gauged streamflow locations can provide a quantitative indication of groundwater discharge and surface runoff, low-flow streamflow surveys can provide a powerful synoptic snapshot of the distribution of watershed-wide groundwater discharge. A good summary of low-flow streamflow survey methodology applied within the study area can be found in Hinton (2005). A summary map of stream profiles can be viewed at maps.oakridgeswater.ca⁷. The results of low-flow streamflow surveys—i.e., gaining/losing/neutral flow stream reaches—can provide a check on the rendering of the three-dimensional hydrostratigraphic or geologic surfaces since higher baseflow would be expected to be associated with delineated aquifer units rather than till and other aquitards. The results of low-flow surveys can also be compared to cold-water fisheries mapping—fish and stream-temperature surveys—and thermal surveys (Dyke et al., 1997), if available.

Examples of low-flow streamflow surveys conducted within the study area are documented in Hinton (1995) for the Duffins Creek watershed and in Hinton and others (1998) for the Humber River watershed, two large watersheds within the study area. In the Duffins Creek watershed, spot-flow surveys have been conducted over many years by the Toronto and Region Conservation Authority. Figure 56 illustrates the results of the 2005 survey conducted for the Duffins Creek watershed. Stream reaches with significant gains in flow (shown in blue), presumably from groundwater discharge, occur either on the moraine, or along the flanks of the ORM, just south of the mapped moraine boundary, and represent groundwater discharge from the ORAC. Increases in flow further south in the watershed, represent groundwater discharge from both the shallow part of the flow system—coarser grained glaciolacustrine sediment linked to the Lake Iroquois shoreline—and also from deeper aquifers that occur within Lower Sediments (Thorncliffe and Scarborough aquifer complexes; Figure 57). The resulting spatial patterns of groundwater discharge are like those of the historical survey presented in Hinton (1995).

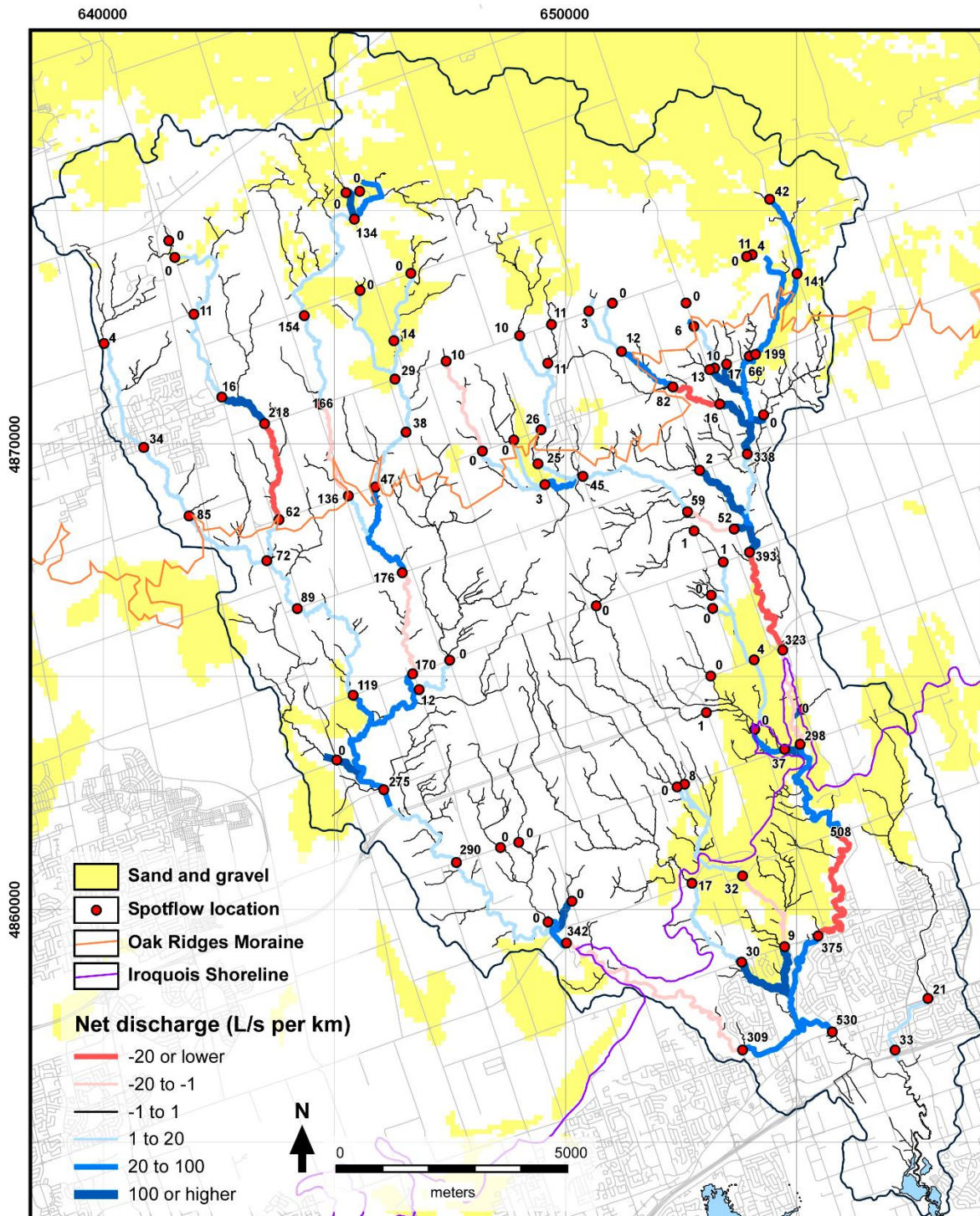


Figure 56 - Low-flow streamflow survey example from the Duffins Creek watershed. Plan view of stream-reach measurement points and flow values in L/s from a 2005 survey. Stream reaches in red are losing flow while stream reaches in blue are gaining flow. Data and analysis from the Toronto and Region Conservation Authority. Low-flow streamflow survey data can be explored at [ORMGP-Maps-locations theme](#) and also at [ORMGP-Tool-spot flow \(baseflow\)](#).

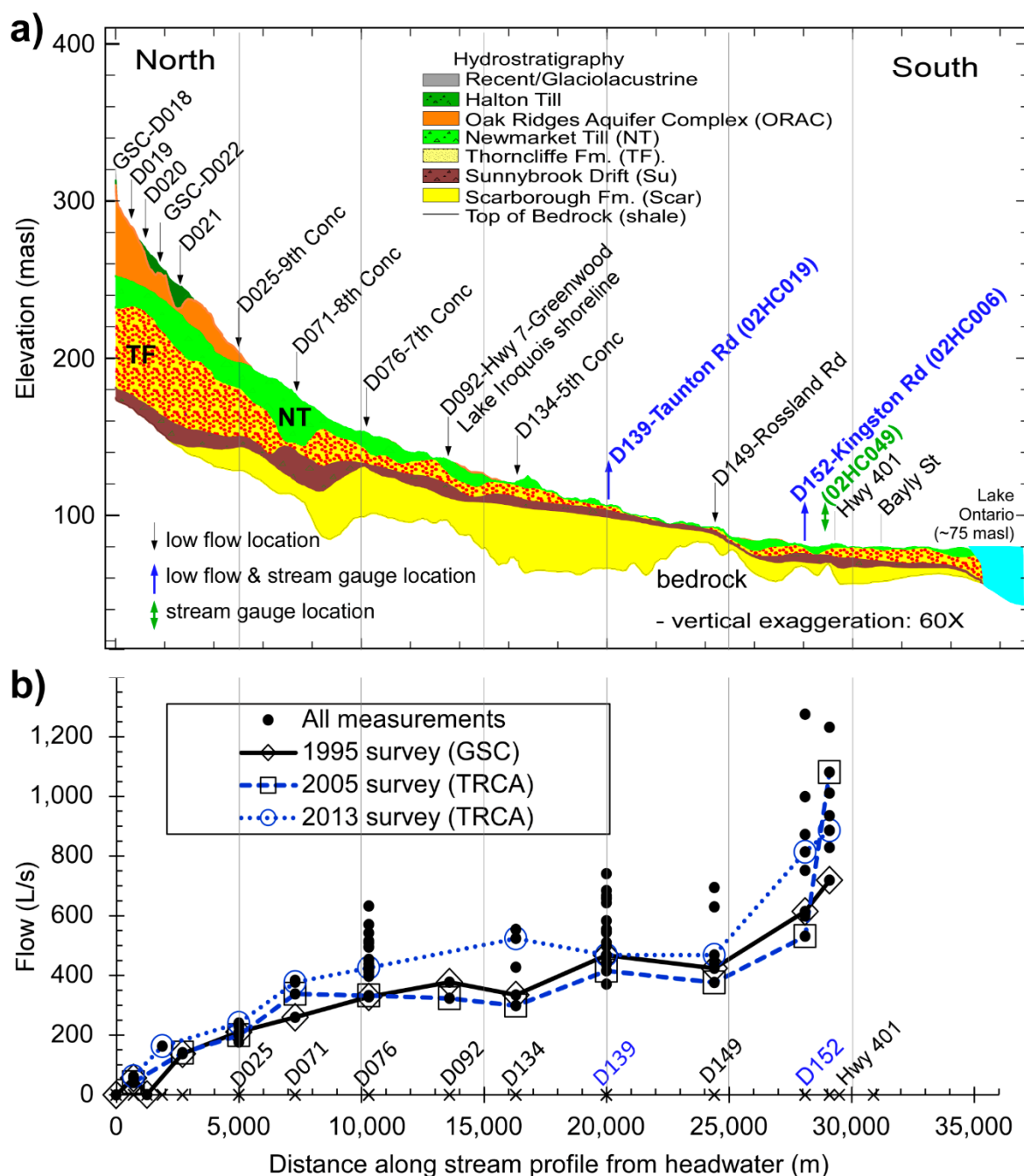


Figure 57 - Stream profile along east Duffins Creek illustrating locations and flow measured during low-flow streamflow surveys. Low-flow streamflow surveys have been conducted over many years. a) Stream profile along east Duffins Creek from headwaters on ORM (north) to river mouth at Lake Ontario (south). b) Low-flow streamflow measurements from low-flow surveys conducted by the Geological Survey of Canada and the Toronto and Region Conservation Authority. Initial stream flow pickup occurs due to groundwater discharge from the ORAC along the south slope of the ORM. Flow also increases closer to Lake Ontario due to additional discharge from Lower Sediment (Thorncliffe and Scarborough aquifers) and from the west branch of Duffins creek, which joins the East Duffins Creek just north of D152. Low-flow streamflow survey locations and results are available for exploration at [ORMGP-Maps-locations theme](#) and [ORMGP-Tools-spot flow \(baseflow\)](#). Stream profiles within the study area can be viewed at [ORMGP-Maps-streamflow profiles theme](#). The example shown here is ORMGP stream profile 10 (Duffins Creek East Branch) situated just east of Toronto in Pickering.

In summary, long-term streamflow gauges that measure continuous—hourly or a shorter time interval—discharge can provide estimates of the quantity of groundwater discharge through streamflow hydrograph separation techniques, whereas low-flow streamflow surveys provide snapshots of the spatial distribution of groundwater discharge that provide insight into groundwater-surface-water connections.

6.5.2 Numerical Flow System Modeling

The numerical models held within the ORMGP model archive system are important tools that are used to explore water budgets more holistically in the study area. Three important components of the flow-system—the water budget, groundwater travel paths and travel times, and groundwater discharge directly to Lake Ontario—are explored below using available numerical models. Numerical models can be effective tools, and are regularly used, for integrating different data sets and estimates from many methodologies (e.g., recharge estimation) into a single holistic approach to better understand and refine the conceptual model and overall understanding of the flow system including both surface water and groundwater flow. A summary of the numerical models available within the study area was provided in Section 6.1.3, and details can be found at [ORMGP-Maps-numerical models theme](#)[↗].

Oak Ridges Moraine water budget

Many historical studies have provided estimates of various water budget components within the study area. Mean annual precipitation ranges between 700 and 1,200 mm/year with an average of approximately 1,000 mm/year (as discussed in Section 3.2). Evapotranspiration is approximately 60 percent of precipitation, with streamflow comprising the remaining approximately 40 percent (Sharpe, Hinton et al., 2014). Using streamflow hydrograph separation, it is estimated that at least 50 percent of the streamflow in the study area is comprised of groundwater discharge (Neff, Day et al., 2005). This translates to regional average recharge rates on a watershed basis of at least 175 to 275 mm/year within the study area (Neff, Pigott, & Sheets, 2005). This is thought to be a minimum recharge estimate, because some recharge moves to and within the deep system and might discharge to ungauged streams, wetlands, or large lakes—e.g., Lake Ontario, Lake Simcoe—bypassing gauged streams. Similar water budget estimates were obtained from a study of several watersheds within the central portion of the study area. The following estimates are based on soil moisture budget methods (from Gerber, 1994; Gerber & Howard, 1997) for the period 1980 to 1989:

- average annual precipitation is approximately 900 mm/year;
- average annual actual evapotranspiration is approximately 540 mm/year (60 percent of precipitation);
- average annual groundwater recharge is approximately 280 mm/year (31 percent of precipitation);

- average annual total streamflow is approximately 360 mm/year (40 percent of precipitation),
 - average annual surface runoff from hydrograph separation is approximately 120 mm/year (33 percent of total streamflow),
 - average annual groundwater discharge from hydrograph separation (i.e., recharge) is approximately 240 mm/year (66 percent of total streamflow).

Early ORM studies (Gerber & Howard, 1997) were conducted to estimate groundwater recharge using a variety of relatively simplistic methods, including soil moisture budget techniques and streamflow separation. Results were generally considered regional in extent and applied on a regional basis. A summary of estimated unit recharge rates for various types of surficial geology is provided in Table 4. Over the last decade, spatially distributed recharge estimation within the study area has evolved and is now largely conducted using sophisticated numerical models such as GSFLOW (or MODFLOW and PRMS run separately; Earthfx Inc., 2014b; GeoProcess & Papadopoulos, 2021; Markstrom et al., 2008; Markstrom et al., 2015;), HydroGeoSphere (Aquanty, 2019; Frey et al., 2019), and the ORMGP recharge/surface runoff model (Figure 54). Numerical modeling studies consider many factors—e.g., land use, soil type, and water table position—over areas smaller than watersheds (i.e., cells or elements). These models, both historical and more recent, have successfully tested or generated unit recharge rates that are generally consistent with historical estimates found in the soil moisture budget and/or streamflow separation studies. The exception is along the ORM, where recent model-estimated unit recharge rates are higher due to the water reallocation effect associated with hummocky terrain and depression-focused recharge (Table 4). In these areas, the depression that receives surface runoff from upslope areas has higher unit recharge rates at the expense of lower unit recharge rates on the adjacent upslope areas (Gerber & Howard, 2000, 2002; Greenwood & Buttle, 2020). Considered altogether, regionally, the average recharge rates from models—finer discretization scale—are similar to those described using soil moisture balance and streamflow hydrograph separation methods with a coarser discretization or more regional scale.

Table 4 - Summary of estimated and simulated unit recharge rates (mm/yr) by type of surficial geology.

a) Soil Moisture Balance, and/or Streamflow Separation							b) Numerical Model Tested					c) Model Generated* VL-WABAS PRMS		
general surficial geology	Singer 1981	Gerber 1994	Hunter 1996	Smart	Gerber	G&H	% of R	Mowatt	Meriano	Meriano	Earthfx Inc.	E&G, 2008	G&P, 2021	
	G&H, 1997			1994	1999	2002		2000	1999	2007	2006	320-420 360	500-700 360	
				G&H, 2000				M&E, 2003 M&E, 2009						
ORM	280-380	300-400	300-400	350	400	400	31%	350	400	263 -365	360			
hummocky till					325	325	25%	250	335					
North Slope of ORM														
till plain		200-300		170-250				200			90	120	150	
glaciolacustrine				50				100			60	90		
South Slope of ORM														
till plain	150-200	150-250		170-250	150	150	27%	200	150-200	100	90	90	150	
glaciolacustrine		50		50	50	50	5%	100	35	37-100	60	90		
Lake Ontario shore (Lake Iroquois plain)														
sand and gravel		200		150	200	200	9%	200	200	200	240	180	200-400	
clay and silt	50-100	50		40	25	25	2%	100		50	60	90		
diamict	50-100	50		40	25	25	1%	100				60		
Urban									50			60% of unit R		

Estimated and tested unit recharge rates (mm/yr) for various types of surficial geology.

ORM – Oak Ridges Moraine

%ofR – percentage of total estimated recharge for study area.

G&H, 1997 – Gerber and Howard, 1997; G&H, 2000 – Gerber and Howard, 2000; G&H, 2002 – Gerber and Howard, 2002.

M&E, 2003 – Meriano and Eyles, 2003; M&E, 2009 – Meriano and Eyles, 2009.

E&G, 2008 – Earthfx Inc and Gerber Geosciences, 2008; G&P, 2021 – GeoProcess Research Assoc. Inc. and Papadopoulos & Assoc. Inc, 2021.

*Other recent numerical model studies that estimate study area spatially distributed recharge include Earthfx Inc., 2014b and Frey et al., 2019.

Spatially distributed recharge estimates are also included at [www.oakridgeswater.ca/\(ORMGP-Tools-water budget\)](http://www.oakridgeswater.ca/(ORMGP-Tools-water budget)).

An early numerical model water budget exercise was conducted for the Duffins and Petticoat Creek watersheds situated to the east of Toronto to delineate flow system characteristics along and south of the ORM (Gerber & Howard, 2000, 2002; Figure 58). At the time of model construction, provincial efforts were focused on delineating a planning boundary for the Oak Ridges Moraine, both the 275 masl and the 245 masl ground elevation contour were being considered—the 245 masl contour was eventually chosen. This model was used as a tool to describe the importance of the ORM to the groundwater flow system. A key conclusion was that while the moraine ridge (>275 masl) primarily functions as a net groundwater recharge area, significant groundwater discharge also occurs on the moraine resulting in many headwater streams forming on the ridge. Discharge also occurs south of the moraine ridge along the south slope—between the 245 and 275 masl ground surface contours. Typical of humid climates, most of the groundwater recharge discharges to rivers and streams. This model also estimated that in the shallow flow system—above the Newmarket Till—groundwater discharge to streams was approximately 75 percent of total groundwater discharge from the watershed, with the remaining discharge—approximately 25 percent—occurring to streams further downgradient, where aquifers within the Lower Sediment intersect with stream valleys.

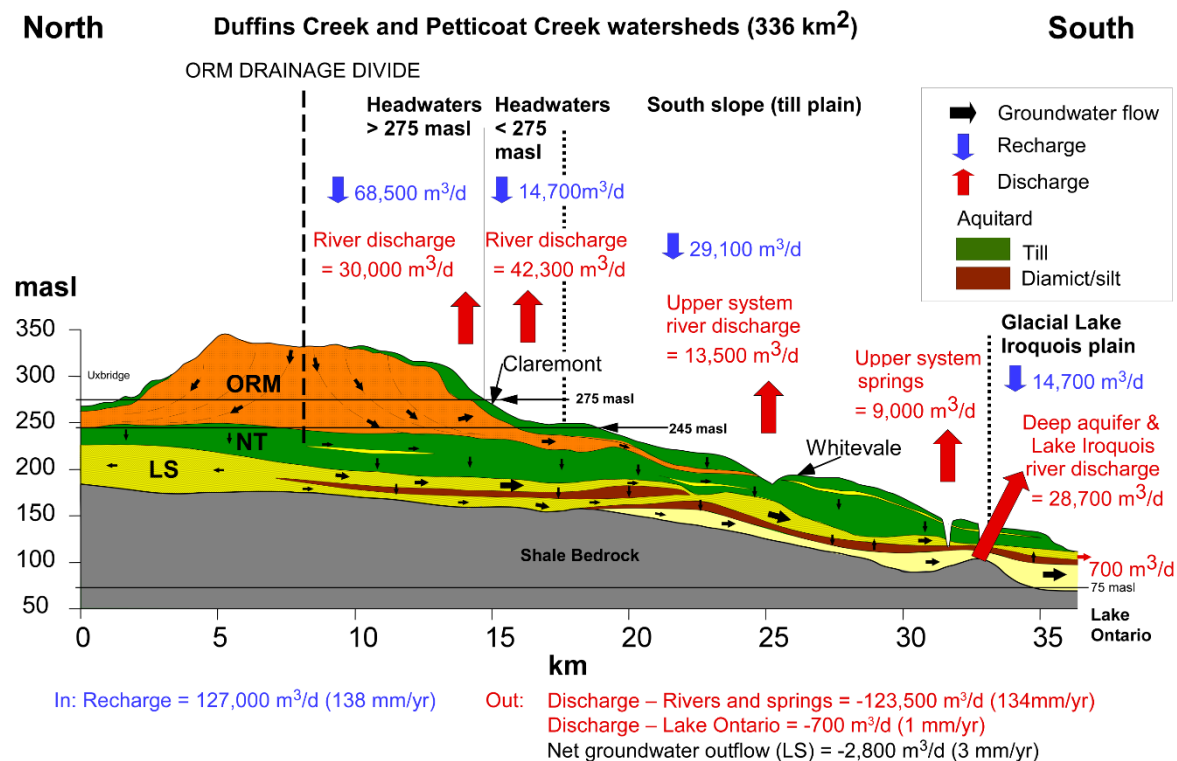


Figure 58 - Water budget for the Duffins Creek and Petticoat Creek watersheds. Quantities estimated using numerical groundwater flow modeling with details provided in Gerber and Howard (2002) (modified from Gerber & Howard, 2002).

Subsequent groundwater numerical flow modeling exercises have focused on the broader study area and have elucidated flow system behavior for various objectives (e.g., watershed water budgets, wellhead protection areas) including understanding of the role of the ORM as an elevated reservoir. The Regional Model (Earthfx Inc., 2006) was constructed for most of the study area, and water budget estimates for the western half of this model area are summarized in Figure 59, while the accompanying Figure 60 shows the relevant water budget zones. The ORM, which serves as a flow divide for both surface water and groundwater, functions as a major recharge area, having the highest unit recharge rates in the study area. Discharge from the ORM forms the headwaters of major rivers and streams flowing north and south from the ORM. Like the water budget for the Duffins-Petticoat watershed discussed earlier (Figure 58), most—approximately 90 percent—of the recharge to the groundwater system discharges to rivers and streams. Direct groundwater discharge to lakes, and large groundwater supply takings, generally account for less than 10 percent of the total discharge from the groundwater system. For the ORM elevated reservoir, a total of 7 m³/s recharges the flow system. Within the shallow part of the flow system—above the Newmarket Till—3.3 m³/s discharges to rivers and 0.7 m³/s moves laterally as groundwater flow to the north and south flank till plains. This leaves an estimated 3 m³/s, or a unit rate of 90 mm/year over the zone area of 1,061 km², which is estimated to flow vertically through the Newmarket Till to the Lower Sediments. Much of this flux then flows laterally away from the groundwater divide that occurs beneath the ORM. Spanning several watersheds associated with the ORM, this model analysis estimates that shallow—above the Newmarket Till—groundwater discharge accounts for 35 percent of the total discharge with deep aquifer—within the Lower Sediment—discharge accounting for 61 percent, and discharge direct to large lakes—Lake Simcoe and Lake Ontario—accounting for 4 percent of total discharge. Future modeling efforts will focus on refinement of the estimates of shallow flow system versus deep flow system discharge, and by extension the amount of water moving vertically through the Lower Newmarket Till. At the time, a recurring problem with some of the numerical models was that shallow system model cells would go dry, thereby forcing recharge to enter Lower Sediment model cells. Recent model code improvements have overcome this issue.

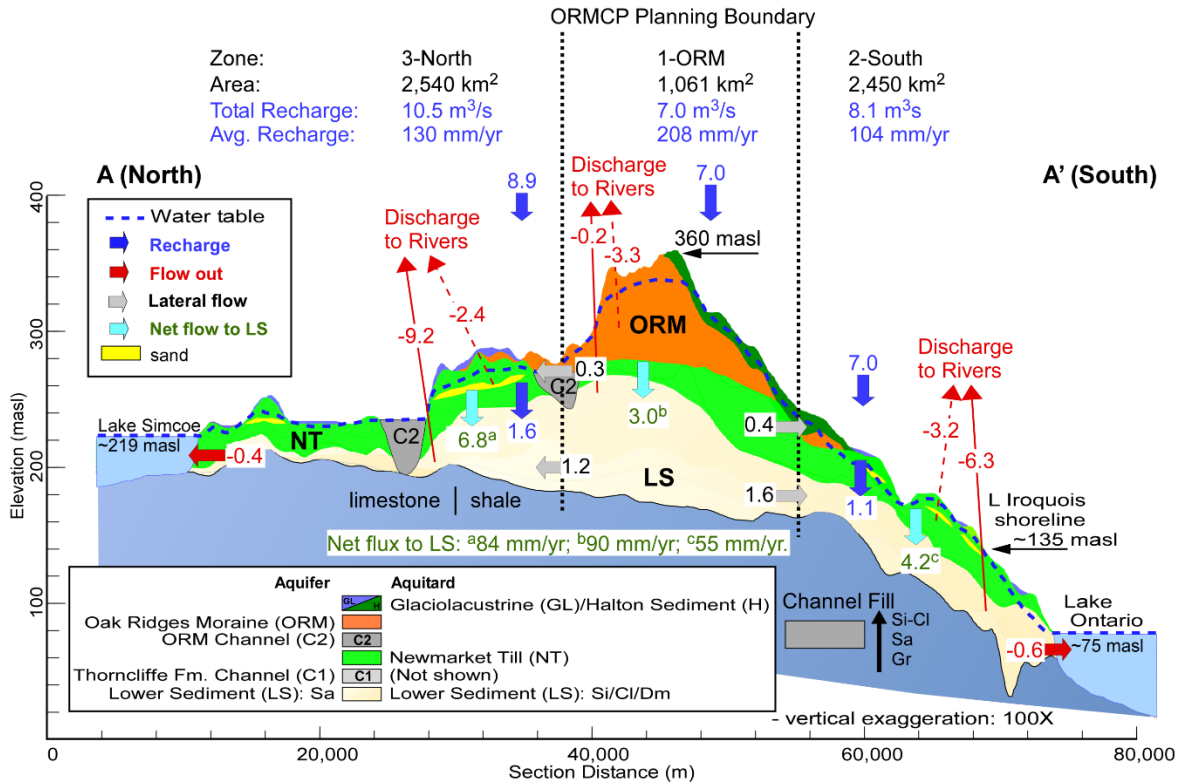


Figure 59 - Simulated water budget estimates for the western half of the Oak Ridges Moraine from a numerical model constructed by Earthfx Inc. (2006). Water budget tracking zones (3-North, 1-ORM, 2-South) are illustrated in Figure 60 and are set up to analyze the ORM as an elevated reservoir. C1 (Thorncliffe Formation channels) are not shown, as they function primarily as high-permeability zones with the Lower Sediments (LS). C2 (ORM channels) can be important to the water budget depending on where they occur. Those beneath the ORM can allow for enhanced vertical groundwater flow from the ORM to deeper aquifers within the Lower Sediment (LS). To the north of the ORM, C2 channels are largely in river valleys, which function as discharge areas.

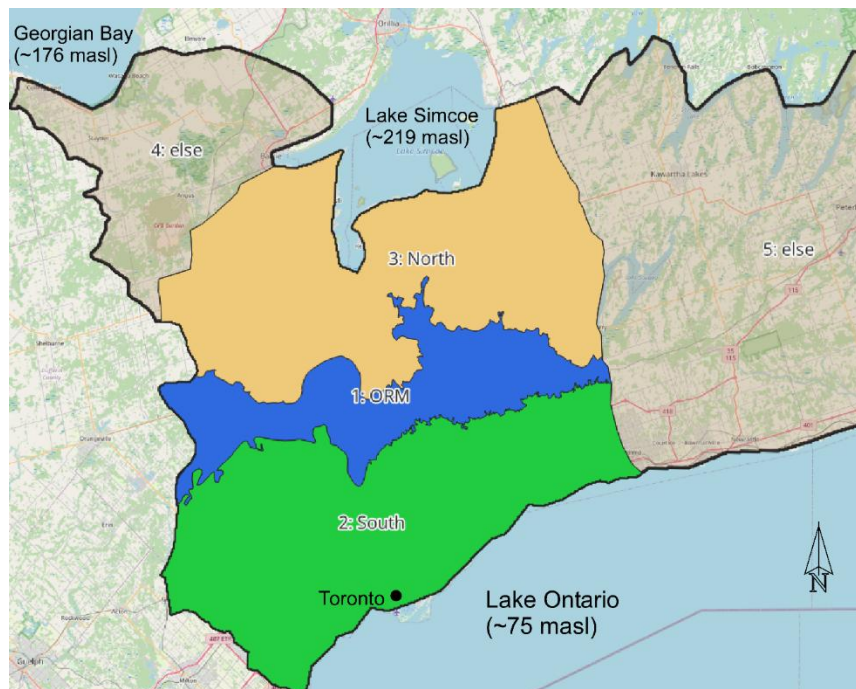


Figure 60 - Regional Model zones for tracking water budget quantities. Water budget model (simulated) estimates are summarized in Figure 59.

Particle tracking in the Regional Model (Earthfx Inc., 2006) is used to illustrate the ORM functioning as an elevated reservoir. Forward particle tracing involves introducing particles (green colored, as shown in Figure 61) within the Oak Ridges Moraine planning boundary and letting them move forward through the flow system. Reverse particle traces are shown in red where the introduction of particles is at the shorelines of Lake Simcoe and Lake Ontario. These reverse particles move upgradient within the groundwater flow system. Particle tracing illustrates that much of the recharge occurring over the ORM discharges to river systems that ultimately flow to these two large lakes. This is shown by very few green particle-trace lines reaching the lake shores. Reverse particle traces from the large lakes suggest that groundwater discharge directly to these lakes is provided by local recharge of groundwater, consistent with the estimates of minor volumes of discharge in various numerical models.

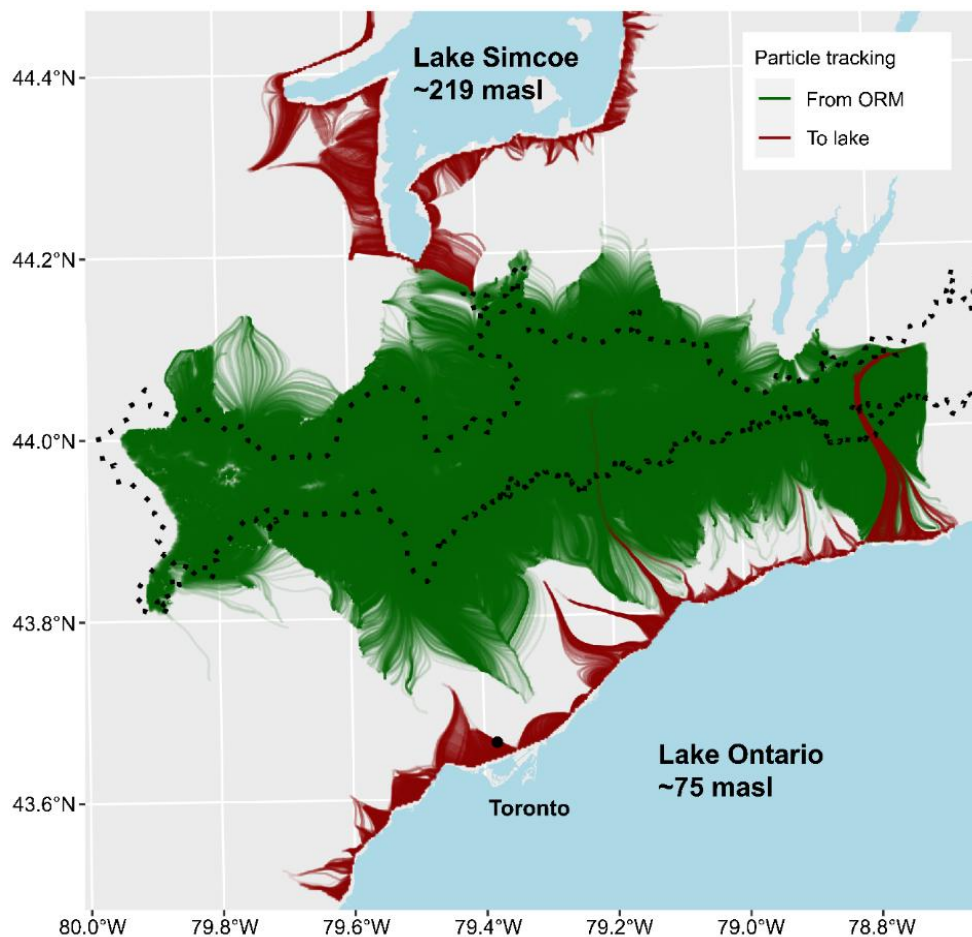


Figure 61 - Particle tracking of groundwater flow using the Regional Model (Earthfx Inc., 2006). Forward particle tracks (green lines) move in the direction of groundwater flow emanating from the Oak Ridges Moraine (dotted black line). Reverse particle tracks (red lines) are released at the Lake Simcoe and Lake Ontario shorelines and flow upgradient within the groundwater flow system. Forward particle tracks illustrate that most of the flow emanating from the ORM discharges to river systems that ultimately flow to the large lakes. Groundwater discharge to large lakes is largely provided by local recharge and, by extension, local groundwater flow.

The Newmarket Till—and, locally, the Thorncliffe Formation silt/clay rhythmite—functions as a regional aquitard that exerts a major control on the groundwater flow system

by limiting vertical leakage to deep aquifer complexes contained within the Lower Sediments. Numerical flow models are very sensitive to the bulk K_v of this unit separating the shallow from the deep flow system within Lower Sediment (Earthfx Inc., 2006; Gerber & Howard, 2000). The bulk vertical hydraulic conductivity (K_v) of this unit in numerical modeling studies is generally higher than the measured matrix K_v obtained from lab triaxial permeability tests. This is attributed to the presence of preferential pathways in the form of fractures and sand bodies and locally by windows eroded by channel activity beneath the ORM—ORM channels. Bulk K_v estimates generally range from 1×10^{-10} to 1×10^{-8} m/s, while the matrix K_v is consistently in the range of 1×10^{-11} to 1×10^{-10} m/s. These estimates have been generated by or verified in numerous numerical modeling investigations (Earthfx, 2006, 2014b; Earthfx & Gerber, 2008; GeoProcess & Papadopoulos, 2021; Gerber, 1999; Gerber et al., 2001; Gerber & Howard, 2000, 2002; Golder Associates, 2021; Meriano, 1999, 2007; Meriano & Eyles, 2003, 2009; Mowatt, 2000; Smart, 1994).

It has also been suggested, through various numerical model studies, that the bulk K_v of the Newmarket Till is higher beneath the flanking south slope till plain compared to beneath and north of the ORM (Earthfx, 2006; GeoProcess & Papadopoulos, 2021; Gerber, 1999), perhaps due to increased stress release over the south slope till plain following deglaciation, with the Newmarket Till being buried beneath a greater thickness of sediments along the moraine. Downward vertical hydraulic gradients through the Lower Newmarket Till generally range from 0.4 beneath the ORM to 0.8 along the adjacent till plains, the latter due to deep system (Lower Sediment) discharge to river valleys. For the Duffins Creek and Petticoat Creek study, the vertical leakage to Lower Sediment was estimated to average 35 mm/year with a lower leakage rate beneath the ORM (13 mm/year) than that estimated over the south slope till plain (51 mm/year). More regional vertical leakage estimates through the Lower Newmarket Till are approximately 30 to 35 mm/year for watersheds beneath and south of the ORM (Figure 58; Gerber & Howard, 2000; Meriano & Eyles, 2003, 2009). For watersheds extending beneath and north of the ORM, the vertical leakage estimates are higher and range from 50 mm/year (Gartner Lee Limited, 1986) to 100 mm/year (Earthfx & Gerber, 2008). The modeling results presented in Figure 59 suggest that vertical groundwater flow to the Lower Sediment averages 90 mm/year beneath the ORM, and 84 mm/year beneath the north slope till and glaciolacustrine plain. The latter higher vertical leakage estimates may represent the effects of increased vertical hydraulic gradients due to greater municipal water supply pumping and/or the presence of local tunnel channelization through aquitards (Earthfx & Gerber, 2008). Desbarats and others (2001) discuss the effect and importance of the presence of aquitard windows on leakage within the Newmarket Till, illustrating a bimodal distribution of K_v with a spread between modes—windows versus till blocks—of four to five orders of magnitude.

It is estimated that, 75 to 80 percent of the direct groundwater recharge in watersheds beneath and south of the ORM discharges to streams from deposits in the shallow-flow system above the Lower Newmarket Till, based on work that Gerber and Howard (2002) conducted within the Duffins Creek watershed. Meriano and Eyles (2003, 2009) suggest shallow discharge to streams in the adjacent Rouge River watershed is approximately 60 to 65 percent of total study area recharge. Groundwater discharge to streams from the deep flow system north of the ORM is estimated to be higher than to south of the ORM, due to increased downward leakage to the Lower Sediments through the Lower Newmarket Till and ORM channels beneath the moraine (Earthfx, 2014b; Earthfx & Gerber, 2008; Figure 62). North of the ORM, ORM channels generally occur in river valleys, which function as discharge zones.

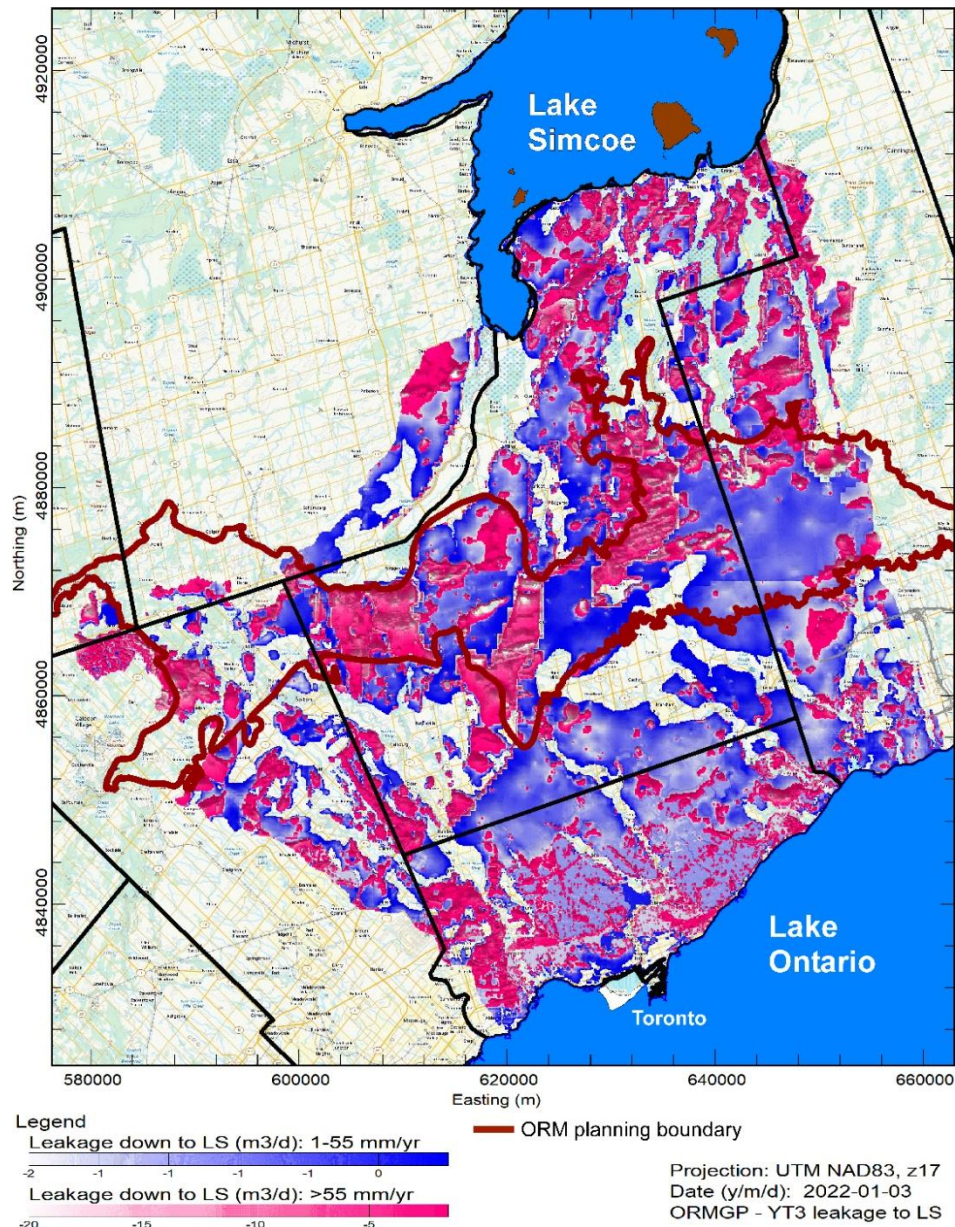


Figure 62 - Simulated downward leakage to Lower Sediments. These values are extracted from model output files developed by Earthfx Inc. (2014b). Nonshaded areas have upward hydraulic gradients from Lower Sediments to the shallow-flow system situated above the Lower Newmarket Till. Downward vertical hydraulic gradients occur over shaded areas, with blue representing lower flux (<55 mm/year) and red representing higher flux (>55 mm/year).

Numerical groundwater flow models are important tools to assess flow system function and to test and refine the understanding of the groundwater flow system. Future modeling exercises will refine the current water budget estimates, focusing on the key elements of the flow system including vertical flow through aquitards, as well as the role of channels and major bedrock valleys.

Groundwater travel times from recharging on the ORM crest to discharging

As described above, much of the groundwater recharge that occurs over the Oak Ridges Moraine discharges along the slopes of the moraine, creating headwaters for many

stream networks. Some recharge moves vertically downward through the Lower Newmarket Till to the deeper groundwater flow system, thereby following significantly longer travel paths. Recharge remote from headwater streams that occurs along surface and groundwater divides has an increased likelihood of recharging deeper aquifers (Gerber & Howard, 2002; Smart, 1994). The Duffins Creek study suggests that travel times from recharge to discharge are on the order of decades for north-to-southward flow in the shallow system, whereas travel times for groundwater flow that replenishes the deeper aquifers was determined to be as high as 2,500 years for recharge along the crest of the ORM before it discharges to stream reaches north of Lake Ontario (Figure 63).

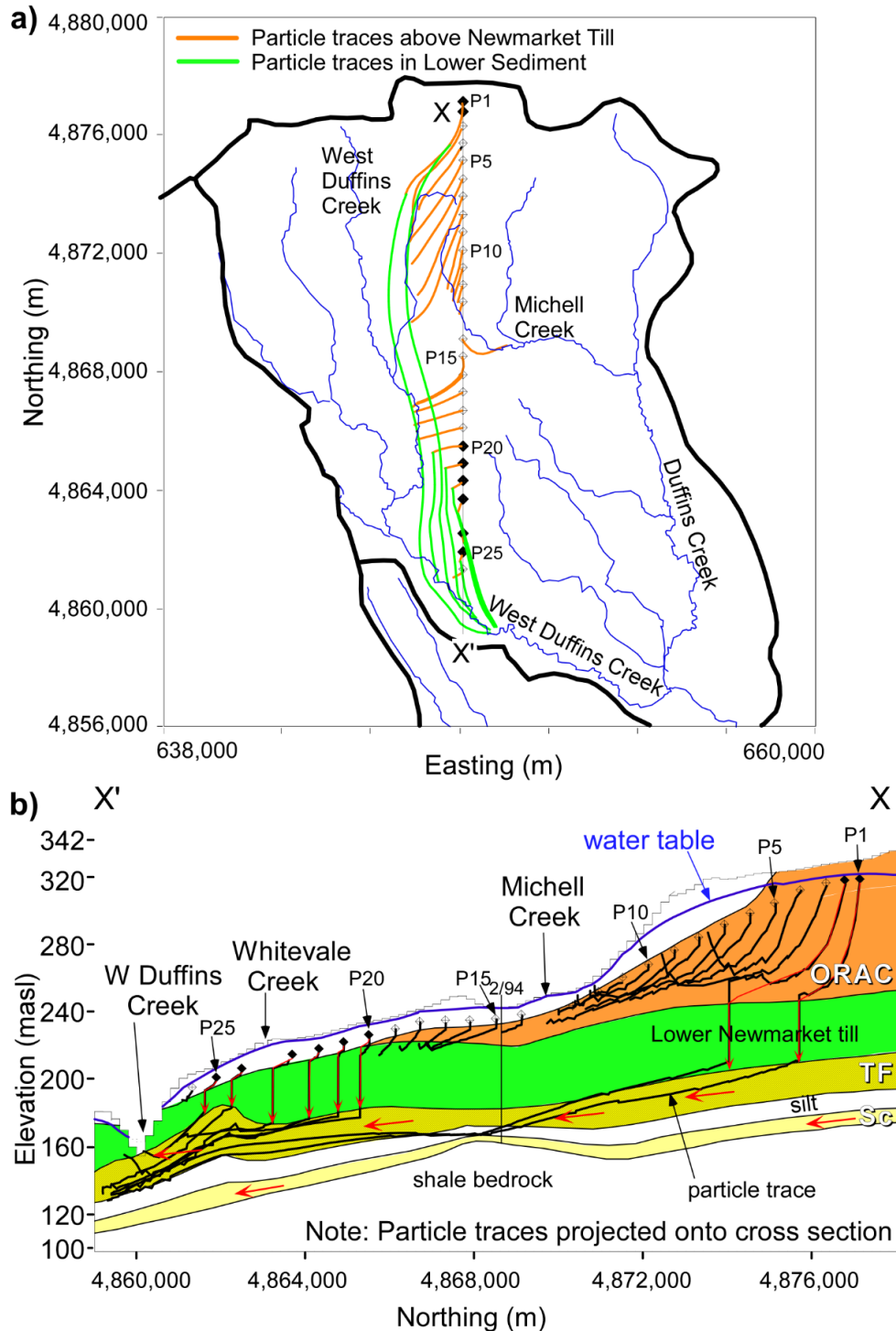


Figure 63 - Plan and profile of particle tracing, Duffins Creek watershed (modified from Gerber & Howard, 2002). Simulated travel times from recharge to discharge are on the order of decades for the shallow system—above the Lower Newmarket Till, also known as the Northern Till. Simulated travel times for groundwater flow that replenishes the deeper aquifers within the Lower Sediment can be up to 2,500 years for recharge along the crest of the ORM to ultimately discharge to stream reaches situated north of Lake Ontario.

Like the Duffins watershed example described above, a particle-tracing analysis is presented for the entire ORM area with forward particle tracking utilizing the Regional Model, that was shown in Figure 61 (Earthfx Inc., 2006). The Regional Model is a five-layer MODFLOW model with a 240x240 m cell size. Nine particles were released at the water table in each of the numerical model cells within the ORM planning boundary (Figure 64). In total, 300,000 particles were released using the simulated output of the Regional Model flow field. The path lines extend from the recharge area on the moraine, either north or south from the ORM, depending on their release location. As in Figure 61, few particles travel to major lakes—Lake Simcoe, Lake Ontario—with most particles discharging to streams and rivers that ultimately discharge to the large lakes. This is a significant result with implications for flow system delineation and the source areas for groundwater that directly discharges to Lake Ontario and Lake Simcoe. Histograms of simulated particle travel distance and particle travel times are presented in Figure 65. Most simulated travel distances from the water table beneath the ORM to ultimate discharge points are on the order of 1 to 10 km for recharge that occurs over the ORM. This can be compared to the distance between the ORM and the Lake Ontario shoreline which ranges from a low of about 4 km near Grafton in the east part of the study area to a high of nearly 40 km in the western part of the moraine. Generally, in areas north of Toronto and eastwards towards Port Hope, the moraine is about 15 to 30 km from the Lake Ontario shore. Also, most particles travel on the order of 100 to 1,000 years with some taking up to 10,000 years. This suggests the dominance of local to intermediate flow systems, with regional flow systems either in the deeper aquifer complexes or within bedrock, being of minor importance (Freeze & Witherspoon, 1967; Novakovic & Farvolden, 1974; Tóth, 1963). It was previously stated that approximately 75 percent of the total recharge to the system discharges from the shallow part of the groundwater flow system above the Lower Newmarket Till and that approximately 90–95 percent of the recharge to the system discharges to streams from flow within Quaternary deposits. This is consistent with analyses of regional flow systems in Alberta by Tóth (1963), who states that deep regional groundwater flow is not generally a significant contributor to streams in a basin because flow rates are low and a large portion of the recharge water—approximately 90 percent—never reaches this part of the flow system. The greater the topographic relief, the greater the importance of local flow systems. Except for the area in the west above the Niagara Escarpment, groundwater discharge from rock within much of the study area is considered negligible.

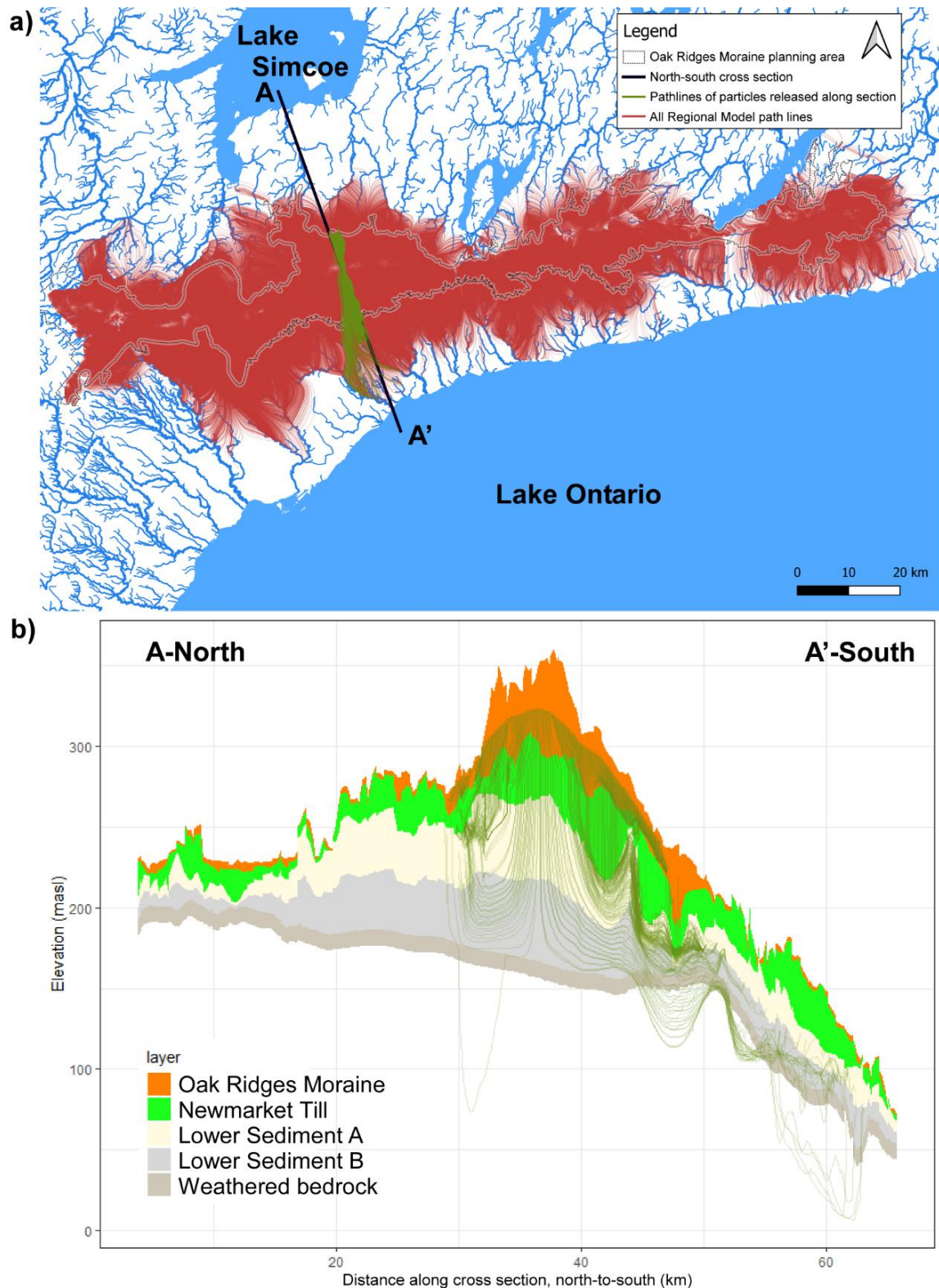


Figure 64 – a) Plan and b) profile of simulated forward particle path lines for groundwater particles released at the water table over the ORM planning area as simulated by the Regional Model (Earthfx Inc., 2006). The longest travel times and paths are for particles that originate along the ORM crest, or along a major groundwater divide. Relative travel times are similar to previous simulations included in Smart (1994) and Gerber and Howard (2002).

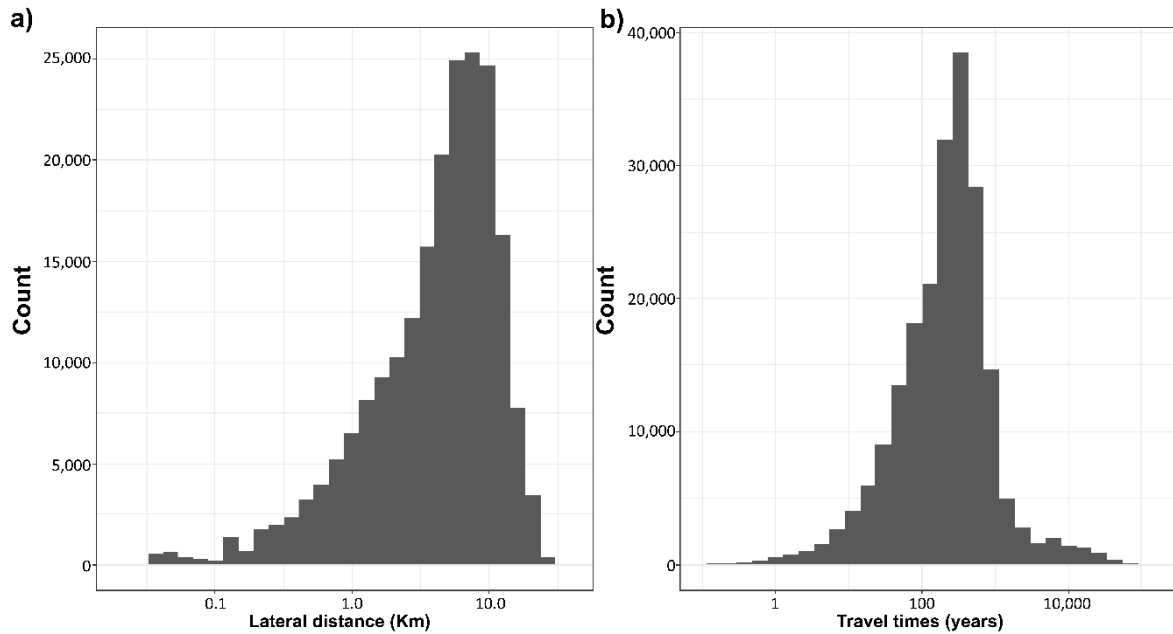


Figure 65 - Histogram of a) simulated particle travel distances and b) simulated particle travel times. Most simulated travel distances from the water table to ultimate discharge point are on the order of 1 to 10 km. Most particles travel on the order of 100 to 1,000 years with some taking up to 10,000 years.

Direct groundwater discharge to Lake Ontario

Canada and the US have been working together since 1972 to restore and protect the water quality and ecosystem health of the shared Great Lakes through the [Great Lakes Water Quality Agreement](#)[↗]. Efforts to address various issues have been organized into 10 issue annexes, one of which is groundwater ([Annex 8](#)[↗]). Although the Great Lakes have been well studied for decades, considerable uncertainty remains regarding the nature and magnitude of connection between the lakes and surrounding groundwater systems. To date, groundwater-surface water interaction research has generally focused on investigating localized discharge of groundwater and loadings via groundwater to streams and rivers. In the Great Lakes context, this groundwater is referred to as indirect discharge of groundwater to the Great Lakes, whereas groundwater that discharges across the littoral zone is referred to as direct discharge of groundwater. The importance of direct discharge to the lakes can be examined by addressing the following questions. How much groundwater moves directly into the lakes? Do the dissolved constituents in groundwater that discharges directly to the lakes have an impact on water quality along the shorelines and nearshore areas of the lakes?

The Great Lakes are experiencing increasing concentrations of anthropogenic contaminants (Baker et al., 2022; Earn et al., 2021), particularly chloride (largely from road-salting activities; Chapra et al., 2012) and nutrients (Van Meter et al., 2019). Figure 64a suggests that the source areas for direct groundwater discharge to Lake Ontario are closer to the lake shoreline. The north shore of Lake Ontario is also the most urbanized and therefore more heavily salted for road safety. A thorough review of road-salt issues along the north shore of Lake Ontario is provided in Mackie and others (2022). A comprehensive

presentation of chloride concentration and trends in surface and groundwater in Ontario is provided in Sorichetti and others (2022).

To capitalize on its comprehensive existing groundwater data and knowledge system, the ORMGP has recently been involved in a project with the Ontario Ministry of Environment, Conservation and Parks to estimate groundwater contributions to the north shore of Lake Ontario. Their report is available at www.oakridgeswater.ca/Lake Ontario shore⁷. The objective of the project was to provide improved scientific understanding and communication of

- regional direct and indirect groundwater discharge to the northern shore of the western Lake Ontario Basin, and
- associated estimated chloride loadings from direct groundwater discharge to Lake Ontario.

It is anticipated that this project will serve as input to future updates of the Great Lakes Water Quality Agreement Annex prepared by the US and Canada (Grannemann & Van Stempvoort, 2016), specifically the estimation of the role of groundwater in influencing water quality in the Great Lakes.

Historical estimates of direct groundwater discharge have suggested that the direct groundwater discharge to Lake Ontario is less than 5 percent of recharge for the various watersheds analyzed (Gerber & Howard, 2000, 2002; Haefeli, 1970, 1972; Kornelsen & Coulibaly, 2014; Meriano & Eyles, 2003, 2009; Ostry, 1979a, 1979b; Ostry & Singer, 1981; Singer, 1974). The direct groundwater discharge to the north shore of Lake Ontario was estimated using twelve select numerical models within the ORMGP model archive that have boundaries along the lake. Numerical model estimates are similar, with some exceptions (Figure 66). Most of the groundwater discharge along the north shore is received by streams and rivers that flow to Lake Ontario (Figure 67) and therefore is indirect to the Great Lakes. For the many rivers that drain into Lake Ontario along the north shore, the median estimated groundwater discharge component is 60 percent of total streamflow (Figure 68).

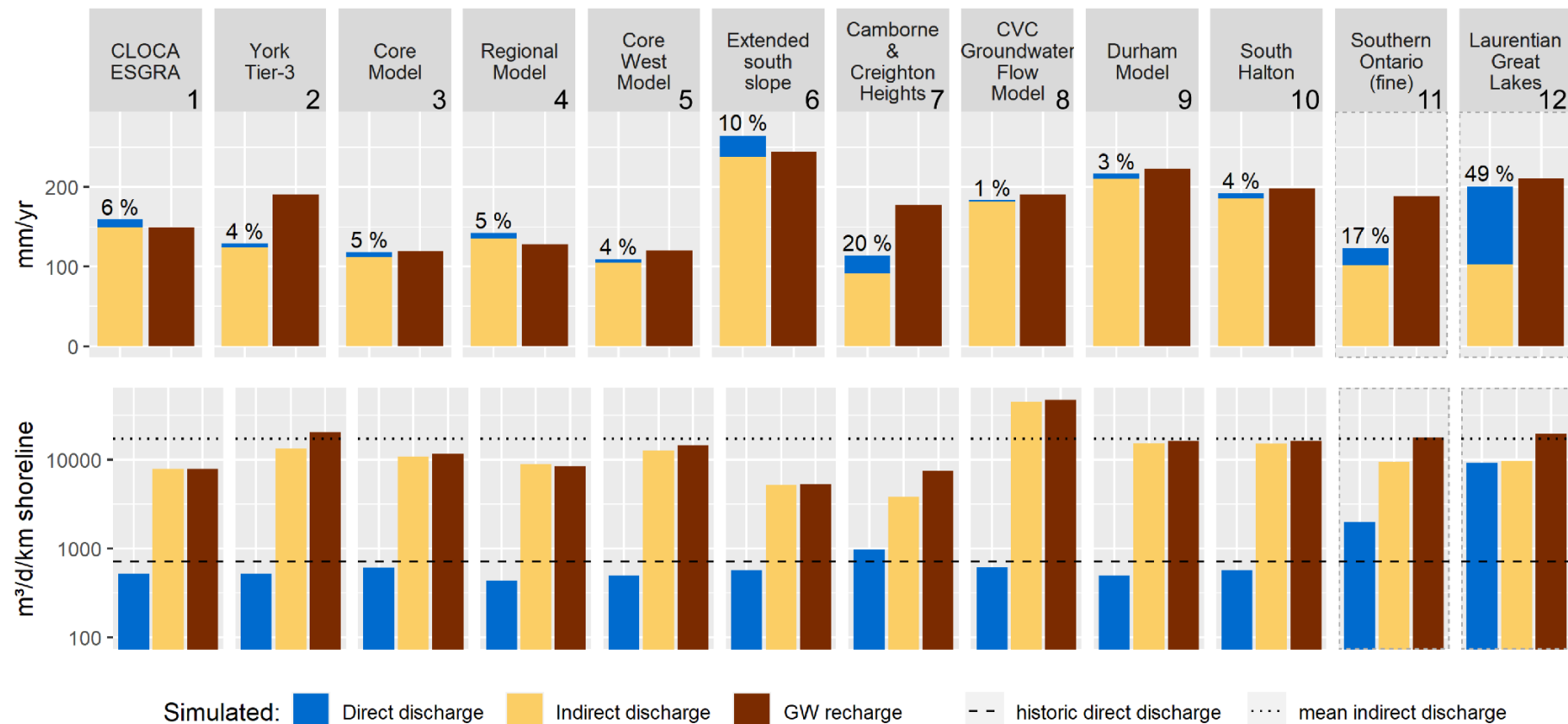


Figure 66 - Summary of inflow (recharge) and outflow (direct and indirect discharge) of twelve modeled groundwater domains within the Lake Ontario catchment area with boundaries along all or part of the north shore of Lake Ontario. Percentages indicate the proportion of simulated groundwater discharge that discharges directly to the lake. The dashed line shows the maximum of historical estimated direct discharge (715 m³/d per kilometer of shoreline; n=21), while the dotted line shows the mean indirect groundwater discharge which is discharge to streams that flow into the lake (figure from Marchildon et al., 2022). Further information on numerical models in the ORMGP model archive is available at [ORMGP-Data Snapshot-numerical models](#). The illusion of large imbalance of recharge and discharge in many of the models results from a couple of situations. Where discharge exceeds recharge there is groundwater inflow to the budget area, and where recharge exceeds discharge there is discharge to features other than the large lake or streams that flow to the large lakes, or to adjacent watersheds within aquifers beneath surface water drainage divides. Further information on each of the models can be obtained in the following references: 1 – Earthfx Inc., 2014a; 2 – Earthfx Inc., 2014b; 3 – Earthfx Inc., 2006; 4 – Earthfx Inc., 2006; 5 – Earthfx Inc., 2007; 6 – Earthfx Inc., 2010a; 7 – Jagger Hims Limited, 2007; 8 – Matrix Solutions, 2012; 9 – GeoProcess and Papadopoulos, 2021; 10 – Earthfx Inc., 2010b; 11 – Frey et al., 2019; and 12 – Xu et al., 2021.

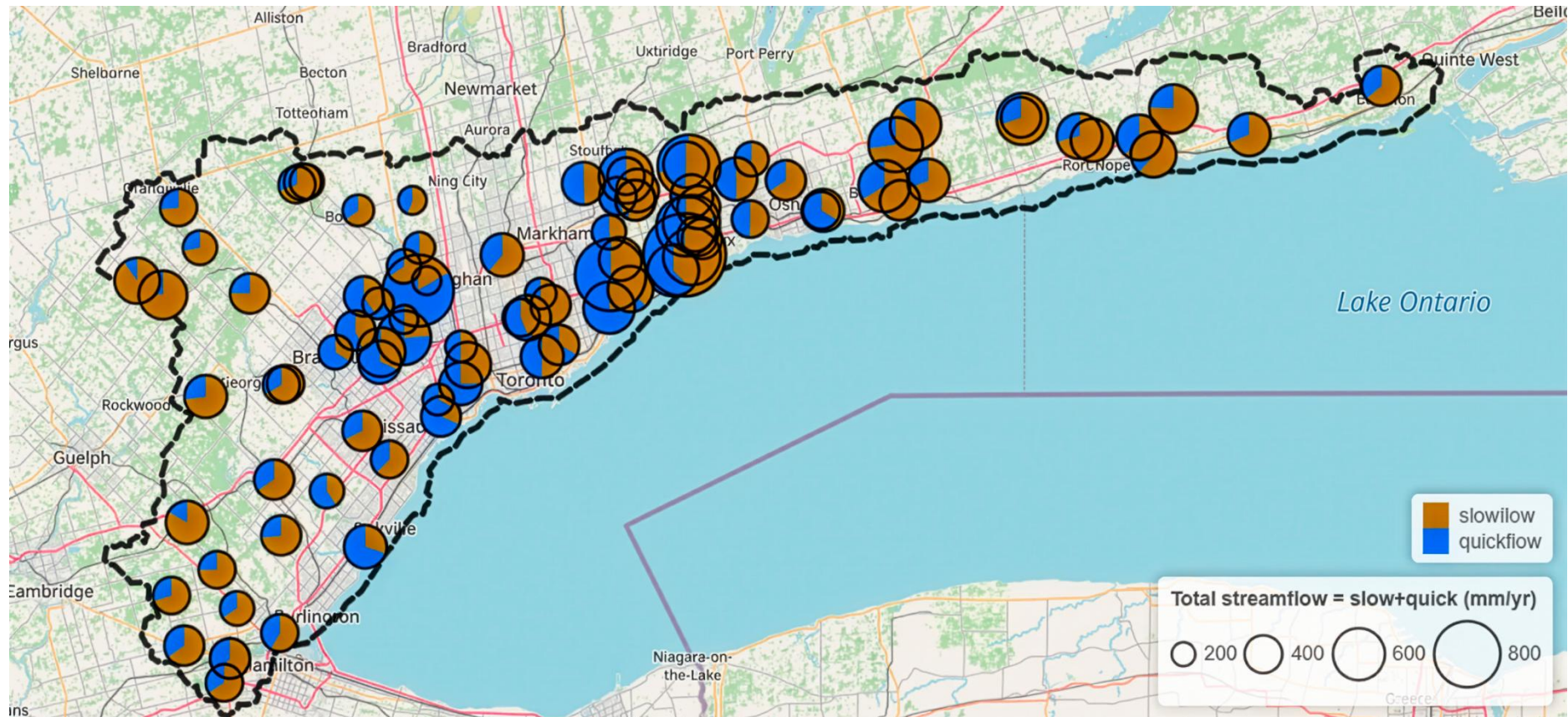


Figure 67 - Spatial distribution of total streamflow (mm/year) with estimated proportion of groundwater discharge (baseflow – slow flow) shown in pie charts for the north shore contributing area (figure from Marchildon et al., 2022; data collected by the Water Survey of Canada). The north shore contributing area is delineated by a black line and covers 6,520 km². Groundwater discharge is the median estimate from 14 streamflow hydrograph separation methods. Baseflow is the estimated volume of the groundwater contribution to stream flow. Quickflow is the estimated overland runoff (surface runoff). Total annual average streamflow has been normalized to the drainage area; hence units are in mm/year over the drainage area upstream from the streamflow gauge. There is wide variability in proportions of slow flow and quickflow. In general, slow flow accounts for at least half of the total streamflow except in heavily urbanized areas. The contribution of slow flow versus quickflow varies depending on surficial geology, the degree of urbanization, and the presence of streamflow regulation devices (e.g., dams). The presence of dams tends to increase the apparent slow flow contribution to total streamflow. This figure can be explored further at [ORMGP-Data Snapshot-streamflow - hydrograph separation](#).

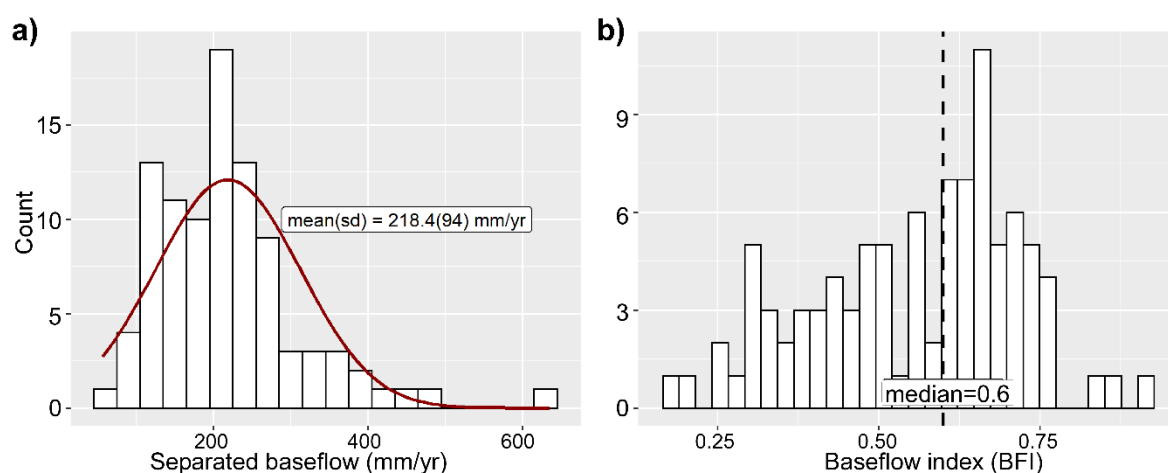


Figure 68 – a) Histogram of separated estimated baseflow to streams which is indirect groundwater discharge to Lake Ontario; and b) baseflow index (BFI) at the 95 streamflow gauges in the north shore drainage area of Lake Ontario that is shown in Figure 67. BFI was analyzed using Hydrology hydrograph analysis tools available at [ORMGP-Hydrograph explorer](#) and [ORMGP-Data Snapshot-streamflow hydrograph separation](#) (figure from Marchildon et al., 2022).

Road-salting activities, undertaken to increase transportation safety during winter months, introduce a significant amount of sodium (Na) and chloride (Cl) to the study area. The result is that all water reservoirs—groundwater, streams, and lakes—within the study area are experiencing increasing salt concentrations. Groundwater quality within the study area is quite variable depending on location and proximity to contaminant sources. Large changes in contaminant concentrations can occur over short distances. It has been estimated that only slightly more than half of the road salt applied in any year is flushed from the system with the bulk of this flushing occurring during the spring—April/May—snowmelt period (Howard et al., 1993; Howard & Haynes, 1993; Perera et al., 2013). This, along with the variable distribution of road salt sources and groundwater travel times (Figure 65b), suggests that steady-state maximum concentrations in receiving water bodies will likely not be realized for decades to centuries (Howard et al., 1993). Road-salt application rates for many municipalities are summarized in Figure 69. The ranges of chloride concentrations in wells for which data exist within the ORMGP database are provided in Figure 70 and range from background level of 5 to 10 mg/L, to thousands of milligrams per liter, again depending on proximity to contaminant sources. Based on the simulated groundwater discharge flux directly to Lake Ontario and the median chloride concentrations observed, the estimated salt loading directly and indirectly to Lake Ontario is provided in Figure 71. Additional details are available in the final project report (Marchildon et al., 2022; www.oakridgeswater.ca/Lake Ontario shore).

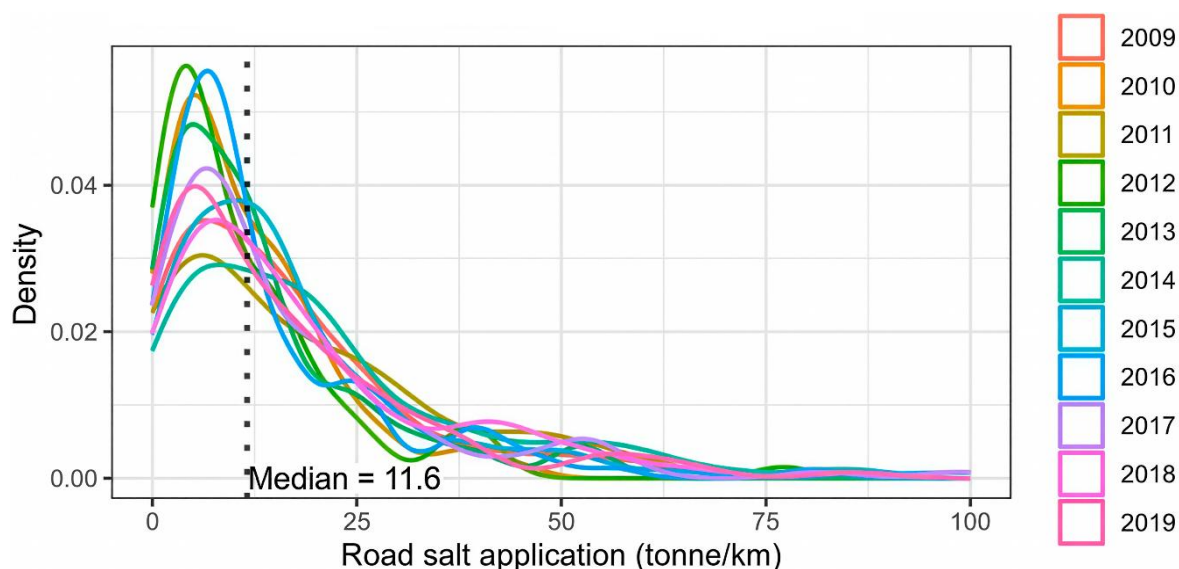


Figure 69 - Annual density distributions of road-salt-application rates from approximately 100 municipalities in southern Ontario (Data provided by Environment and Climate Change Canada, personal communication, 2021). Median application rate is 11.5 tonne/km, where a tonne is a metric ton, equivalent to a mass of 1,000 kg. A ton (imperial unit) is equivalent to 1,016.047 kg (figure from Marchildon et al., 2022).

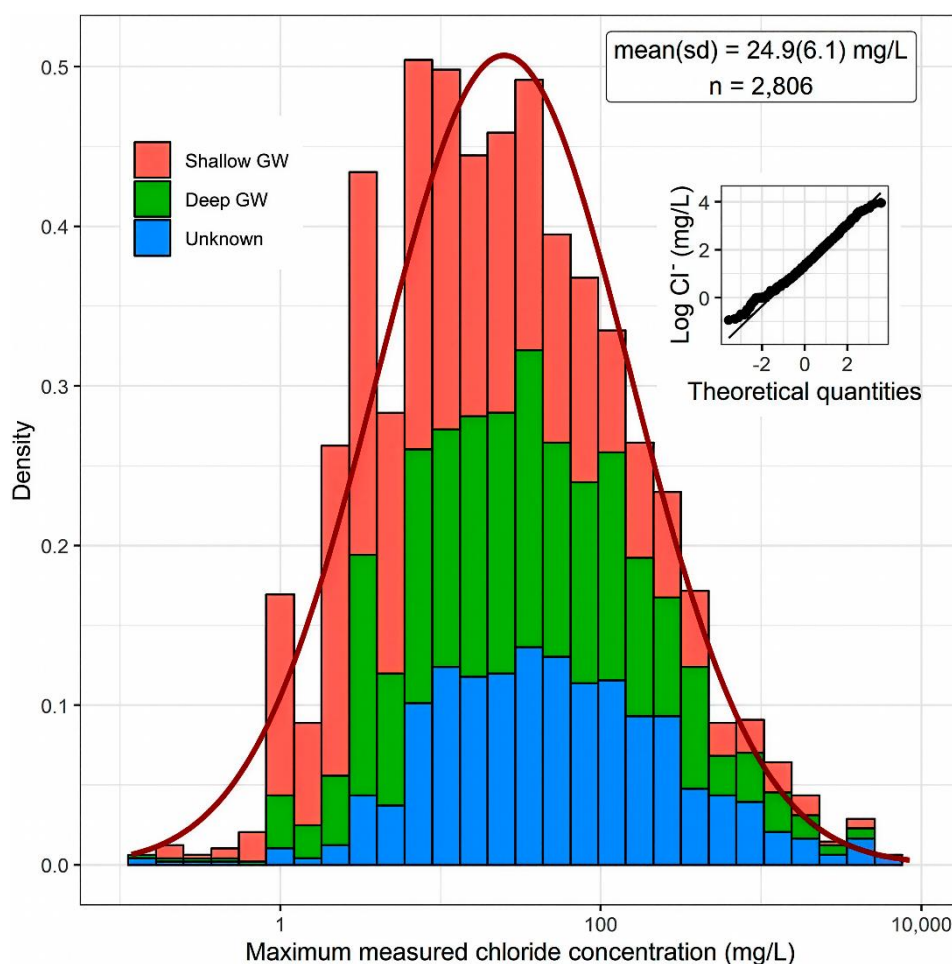


Figure 70 - Distribution of maximum chloride concentrations measured in wells of the Lake Ontario north shore contributing area. The fit to a log-normal distribution is shown as a brown line. Data presented are contained within the ORMGP database (modified from Marchildon et al., 2022).

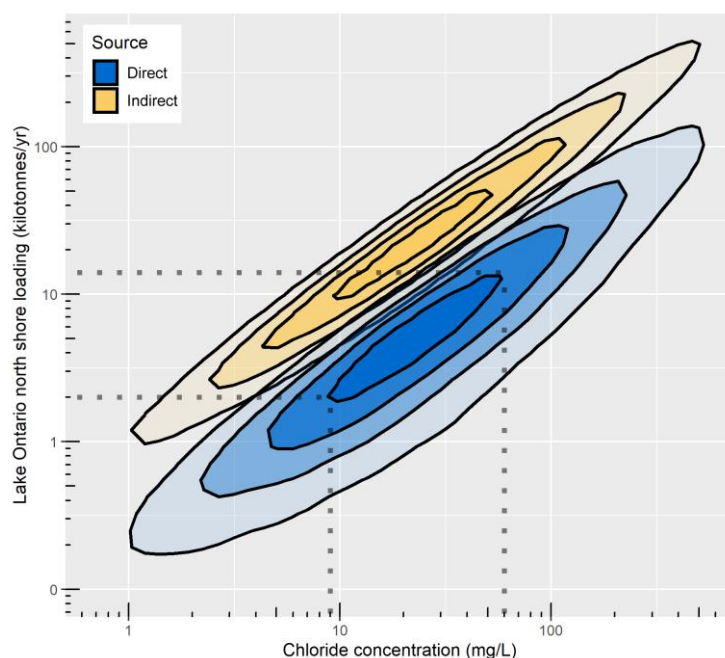


Figure 71 - Projected chloride loadings derived from the joint probability distribution of background groundwater chloride concentrations and direct and indirect groundwater discharge along the north shore of Lake Ontario. Distributions are based on a mean maximum observed chloride concentration of approximately 25 mg/L from data in the ORMGP database (Figure 70). It is estimated that approximately half of the chloride applied on an annual basis is flushed out of the system through surface runoff, and it will take decades to centuries for chloride concentrations to reach steady state in groundwater. This means that chloride concentrations will continue to rise. The variability in chloride concentrations has a greater impact on estimated direct groundwater discharge loading to Lake Ontario than variability in groundwater flow rates (figure from Marchildon et al., 2022).

Exercise 10 provides an opportunity to consider what is involved in preparing numerical models and in using existing models to analyze for other purposes and objectives ([Exercise 10](#)¹).

6.6 Groundwater Quality/Chemistry

The quality (i.e., chemical composition) of groundwater reflects the history of processes that have acted on the water since precipitation and snowmelt recharged the system. After water enters the subsurface, weathering and erosion of rock and soil adds solutes to the water, along with solution or precipitation reactions that occur within the subsurface along the groundwater flow path (Hem, 1985; Wood, 2025). Anthropogenic activities utilizing a myriad of chemicals—e.g., solvents, road salt, pesticides, herbicides, fertilizers—can change the chemical composition of groundwater and may lead to contamination issues. The study area comprises approximately 10 percent urban and 26 percent agricultural land use (Figure 6). Urban areas utilize and manufacture large volumes of chemicals that can make their way into the subsurface (Howard & Gerber, 2018). Agricultural areas typically involve the use and application of nutrients, pathogens, fertilizers, pesticides, and herbicides that can leach into the subsurface (Council of Canadian Academies, 2013). Road networks within both rural and urban areas receive road salt during winter in an effort to maintain ice free conditions. There are also groups of

chemical contaminants that are newly recognized as being hazardous to human and ecological health known as emerging contaminants. Types of emerging contaminants include, but are not limited to, pharmaceuticals and personal care products, per- and polyfluoroalkyl substances (PFAS), endocrine disruptors, pesticides and their metabolites, microplastics (nanomaterials), and other industrial byproducts and synthetic compounds (Bexfield et al., 2021; Cserbik et al., 2023; Divine et al., 2024; Divine et al., 2023; Levin et al., 2023; Wang et al., 2024). These contaminants come from both point and non-point sources and ultimately may enter surface water and/or groundwater.

Municipal water supply systems from groundwater are subject to regular quality analyses for organic and inorganic parameters—Ontario Drinking Water Surveillance Program; Ontario Minister’s Annual Report on Drinking Water. Private wells in Ontario have never been subject to comprehensive surveys of water quality, rather the homeowner is responsible for water quality (Novakowski et al., 2006). Regional groundwater quality investigations within the study area have largely focused on inorganic and bacteriological parameters (Hamilton, 2021). There is a lack of systematic widespread groundwater quality investigations for organic and emerging contaminants in the study area. A survey of farm drinking water wells in Ontario was conducted in 1991 and 1992 where 1,292 wells of the possible approximately 500,000 rural wells were sampled for nitrate, bacteria, and pesticides (Goss et al., 1998; Rudolph et al., 1998). From this study it was found that 34 percent of the wells had exceedances of maximum acceptable concentrations for coliform bacteria, 14 percent contained nitrate concentrations above 10 mg/L, and pesticides were detected in 7 percent (winter) and 11 percent (summer) of the wells sampled. Much of the study area is covered by extensive till plains, similar to surficial geologic conditions in Denmark. In detailed investigations in Denmark, it has been concluded that 20 to 40 percent of the groundwater beneath surficial clayey till aquitards is polluted with pesticide residuals and related metabolites (Jørgensen et al., 2004; Jørgensen & Spliid, 2016; Jørgensen et al., 2016). Contaminant transport of these pesticides through clayey till in the Danish studies is attributed to preferential flow along root channels, with lesser flow along fractures and joints (Jørgensen et al., 1998; Jørgensen et al., 2022). Detailed studies to investigate the contamination status, particularly for organic chemical parameters including pesticides and PFAS, of aquifers within the study area are lacking. Efforts have begun to collect organic chemical results for groundwater within the study area but comment on the results of the data collected to date is considered premature at this point in time. Therefore, the discussion below focusses on the organic chemistry of groundwater found within the study area along with two common tracers, namely chloride and tritium.

6.6.1 Data

Historically, there has been a paucity of regional groundwater-quality investigations and, by extension, readily available groundwater chemistry data within the study area. This has recently been rectified by provincial groundwater investigations—2007

to 2019—conducted by the Ontario Geological Survey where private wells were sampled throughout much of south-central Ontario, including the study area (Hamilton, 2021). The Provincial Groundwater Monitoring Network (PGMN) was established in 2001 and, although the monitoring wells are limited in number, the program provides for regular collection of groundwater level data and annual quality sampling at each well. Also, since 2008, geochemical and isotopic analyses have been conducted by the University of Waterloo and the ORMGP, utilizing long-term monitoring wells to supplement ongoing regular monitoring programs being undertaken by four municipalities—the regions of Halton, Peel, York, and Durham. Since the program’s inception in 2001, the ORMGP has incorporated a wide range of groundwater-quality data into the program database, including:

- historical groundwater chemistry data provided in Geological Survey of Canada water survey documents (Caley et al., 1947a, 1947b; Hainstock et al., 1948a, 1948b, 1948c, 1948d, 1948e; Hainstock et al., 1952);
- regional groundwater-quality and research investigations (Aravena & Wassenaar, 1993; Aravena et al., 1993, 1995, 2004; Gerber, 1999; Gerber & Howard, 1996; Howard & Beck, 1986, 1993; Sibul et al., 1977);
- landfill investigations (Interim Waste Authority, 1994a, 1994b, 1994c, 1994d, 1994e, 1994f, 1994g, 1994h, 1994i; M. M. Dillon Ltd., 1990);
- miscellaneous chemistry data found in consulting reports in the ORMGP library;
- municipal pumping and monitoring well groundwater-quality data from the regions of Halton, Peel, York, and Durham;
- data from the province of Ontario Drinking Water Surveillance Program (DWSP);
- Ontario’s PGMN groundwater-quality data;
- regional groundwater-quality surveys (2007–2019) conducted by the Ontario Geological Survey (Hamilton, 2021);
- surface water sampling by conservation authorities and the Geological Survey of Canada (1995/1996) conducted during low-flow surveys;
- historical surface water-quality sampling data from the PWQMN and conservation authorities; and
- ongoing University of Waterloo/ORMGP geochemical and isotopic analyses initiated in 2008.

Water chemistry data currently in the ORMGP database is available for exploration at www.oakridgeswater.ca⁷. Samples have been analyzed for a number of parameters including inorganic, organic, physical, and radiological, depending on the objectives of the sampling program. Data currently in the database is summarized in Table 5. The ORMGP has established one common database containing water-quality data alongside other pertinent information such as well-construction details, screen details, water-level data, and interpreted screened hydrostratigraphic units. Currently the database contains the

laboratory results and, when available field measurements, of over 290,000 samples. Drinking-water-quality standards for Ontario and Canada are found in Ontario (2006) and Health Canada (2020), respectively. Water-quality guidelines for the protection of aquatic life are sometimes different, and sometimes more stringent, than drinking-water guidelines and are known as Provincial Water Quality Objectives (PWQO; Ontario Ministry of the Environment and Energy, 1994). For example, for chloride, the drinking-water standard is currently 250 mg/L while the PWQO for the protection of aquatic life is 125 mg/L (Canadian Council of Ministers of the Environment, 2011).

Table 5 - Summary of groundwater quality readings in ORMGP database by parameter/compound group as of March 1, 2025.

Parameter/Compound Group	# of Readings	# Wells Sampled
General Chemistry	85,949,268	5,147
Metals	394,751	3,562
Bacteriological	241,429	996
Major Ions	211,172	4,066
Volatile Organic Compounds (VOC)	178,951	962
Miscellaneous Organics	141,029	1,045
Pesticides & Herbicides	113,822	572
Petroleum Hydrocarbon Compounds (PHC)	33,916	1,013
Semi-volatile Organic Compounds (SVOC)	9,955	564
Isotopes	7,102	1,077
Dissolved Gases	4,890	828
Per- and Polyfluoroalkyl Substances (PFAS)	1,861	50
Polyaromatic Hydrocarbons (PAH)	301	82

6.6.2 Regional Groundwater Quality Characterization

The groundwater quality data available in the ORMGP database exhibits local variability in water quality, however overall, groundwater quality does not vary significantly within any of the three unconsolidated Quaternary aquifer complexes above bedrock (Howard & Beck, 1986; Sibul et al., 1977) and is of generally good quality for domestic and municipal use.

Concerns, with respect to drinking water quality, are localized and are attributed to either naturally elevated parameters, such as hardness, manganese, and/or iron values, or to anthropogenically elevated parameters, such as bacteria, nitrate, and/or chloride (Sibul et al., 1977). Naturally occurring hardness, iron and manganese can be removed with common water treatment technologies. Nitrate and bacteria are associated with septic system effluent or agricultural fertilizer application and can enter shallow wells, or deeper wells with poor seals. High chloride values, frequently above the drinking-water criteria of 250 mg/L, occur in both shallow and deeper wells, often in wells close to salted roadways

or salt-handling areas/facilities. High chloride values are also common in surface water bodies. These anthropogenically-related parameters are more difficult to remove from water supplies.

Some of the earliest historical groundwater chemistry information available for the study area was collected in the mid-1900s by the Geological Survey of Canada and reported on in various water survey documents (Caley et al., 1947a, 1947b; Hainstock et al., 1948a, 1947b, 1947c, 1947d, 1947e; Hainstock et al., 1952). Subsequent detailed study of groundwater quality in the study area was conducted by the Ontario Ministry of the Environment in 1970 and 1974 in the Duffins Creek and Rouge River watersheds, situated in the central part of the study area along the north shore of Lake Ontario. The study involved the analysis of 44 groundwater samples (Sibul et al., 1977) and determined that elevated levels of chloride and nitrate were not uncommon. A subsequent analysis of 260 groundwater samples in the same area between 1982 and 1984 (Howard & Beck, 1986; Figure 72) also found elevated chloride and nitrate values which were attributed to road-salt and fertilizer contamination, respectively. Another important finding of these studies was that groundwater within the shale bedrock—Georgian Bay and Blue Mountain Formations—was of naturally poor quality with elevated concentrations of sodium and sulphate. Subsequent analyses conducted for landfill investigations (Interim Waste Authority, 1994g; M. M. Dillon Ltd., 1990) confirmed this finding. Two investigations conducted within the Duffins watershed near Whitevale provide insight into the natural chemical evolution of groundwater as it flows through the subsurface (Interim Waste Authority, 1994e; M. M. Dillon Ltd., 1990). The major ion chemistry from these investigations is plotted on a Durov diagram in Figure 72. Durov diagrams plot relative percentages of major ions and are useful for classifying water and delineating evolutionary trends (Zaporozec, 1972).

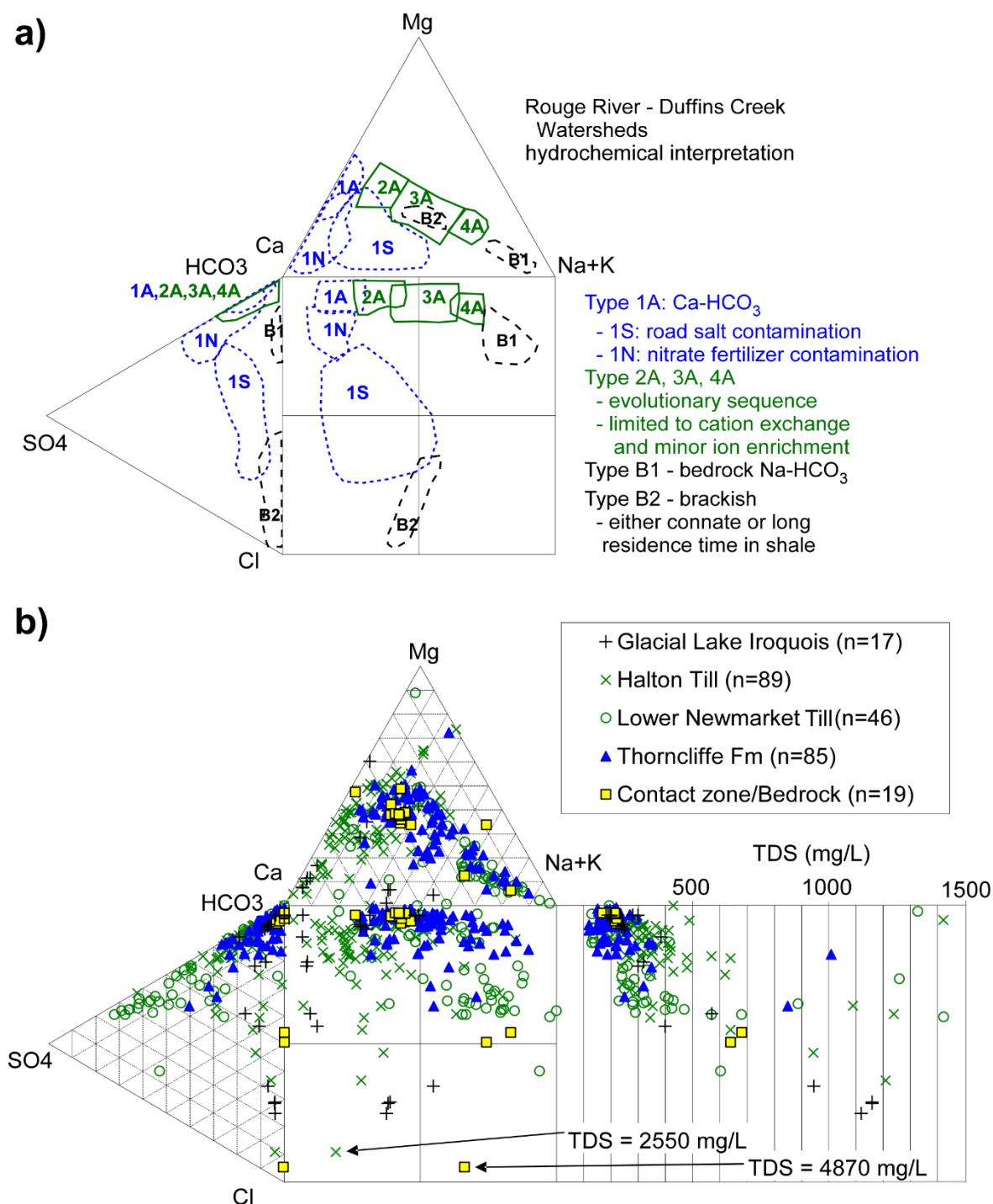


Figure 72 - Durov diagram representation of a) interpreted groundwater water types found in the Rouge River, Duffins Creek watersheds (From Howard & Beck, 1986, 1993); and b) data from studies within the Duffins Creek watershed. Duffins Creek data from M. M. Dillon Ltd. (Site P1, 1990), Interim Waste Authority (Site EE11, 1994g), and Gerber, 1999 (Site 194 and Site 294). Durov diagrams usually plot anions on the upper ternary diagram and cations to the left of the box. In (a) Howard and Beck (1986, 1993) use a modified form of the Durov diagram to show a better spatial distribution between common water types found in the study area. A similar modified Durov diagram is plotted in (b) to allow for comparison to the previous investigations of Howard and Beck (1986, 1993). Further information on Durov diagrams is available in Durov (1948) and general information on plotting water chemistry is provided by Zaporozec (1972) and Hem (1985).

Within the shallow groundwater system (i.e., above the Lower Newmarket Till) the water is generally dominated by calcium and bicarbonate ions. At greater depth within the Newmarket Till, groundwater becomes dominated by sodium and sulphate ions with lower relative concentrations of calcium, magnesium, and bicarbonate. It is not known whether the source of the sulphate is naturally occurring within the till or if it is introduced by anthropogenic activities. Natural sources of sulphate could include dissolution of gypsum or oxidation of pyrite, the latter of which has been observed in granitic boulders within the till. Anthropogenic sources of sulphate could include industrial air emissions or fertilizer application. The increase in sodium with depth is attributed to cation exchange reactions with clay minerals, which remove calcium and magnesium from solution. The sodium could be natural or related to the application of road salt.

Groundwater within the deeper flow system beneath the Newmarket Till is characterized by low sulphate concentrations, the dominance of sodium and bicarbonate, and the occasional presence of H₂S gas from sulphate reduction reactions. A slight increase in calcium and magnesium from renewed dissolution of carbonate minerals is also evident. Similar patterns were also reported for an investigation (Schwartz, 1974) west of the study area along the north shore of Lake Erie where cation exchange and sulphate reduction were found to be major reactions along the direction of flow. In that study, the reduction in concentrations of ionic species in the direction of flow was attributed to selective ion filtration through the surficial till units.

Howard and Beck (1986) distinguished eight water types (Figure 72), related to various reactions occurring in the subsurface. Six groundwater types were associated with the Quaternary sediment aquifers, ranging from calcium bicarbonate in character (1A) through to 4A representing a natural chemical evolutionary sequence dominated by ion exchange. Type 1A, calcium bicarbonate water, is typical of modern recharge water in sedimentary environments and formed by dissolution of calcite and dolomite by infiltrating mildly acidic recharge water. Water types 2A, 3A, and 4A are characterized by an increase in sodium at the expense of calcium. With increasing residence time, the water is also naturally characterized by an increase in iodide and fluoride, with only slight increases in chloride. In addition, water types 3A and 4A did not contain tritium. The last two remaining Quaternary-related water types were 1S and 1N, the first of which was interpreted to reflect contamination by road salt, and the second reflecting contamination by nitrate fertilizer. Two bedrock-related water was identified. Type B1 was sodium bicarbonate water, low in sulphate, whereas type B2 water had a high chloride content, were brackish, and were interpreted to be either connate or to have become mineralized through long-term contact with low-permeability shale deposits. Long flow lines with natural evolutionary sequences (Chebotarev, 1955a, 1955b, 1955c) to chloride-rich water do not exist (Howard & Beck, 1993). More generally, all groundwater samples within the Quaternary sediments were found to contain fresh water with total dissolved solids

generally less than 1,000 mg/L and electrical conductance less than 1,000 $\mu\text{S}/\text{cm}$ (Hamilton, 2021). Exceptions occurred where contamination from surface sources such as road salt was present or where groundwater interacted with higher salinity bedrock water such as shale.

Further exploration of groundwater-quality information throughout southern Ontario is provided by Hamilton (2021) for the locations shown in Figure 73. For the study area, the data can be explored at www.oakridgeswater.ca⁷. Most of the wells within the ORMGP database are within Quaternary sediments, with a dominance of Ca-Mg-HCO_3 water. The groundwater samples can be explored in several different ways on the ORMGP website (e.g., by water type, by the analysed parameters, by the driller's general water characterization, or by interpreted formation). A Piper plot, constructed for a user-selected number of wells, is shown in Figure 74.

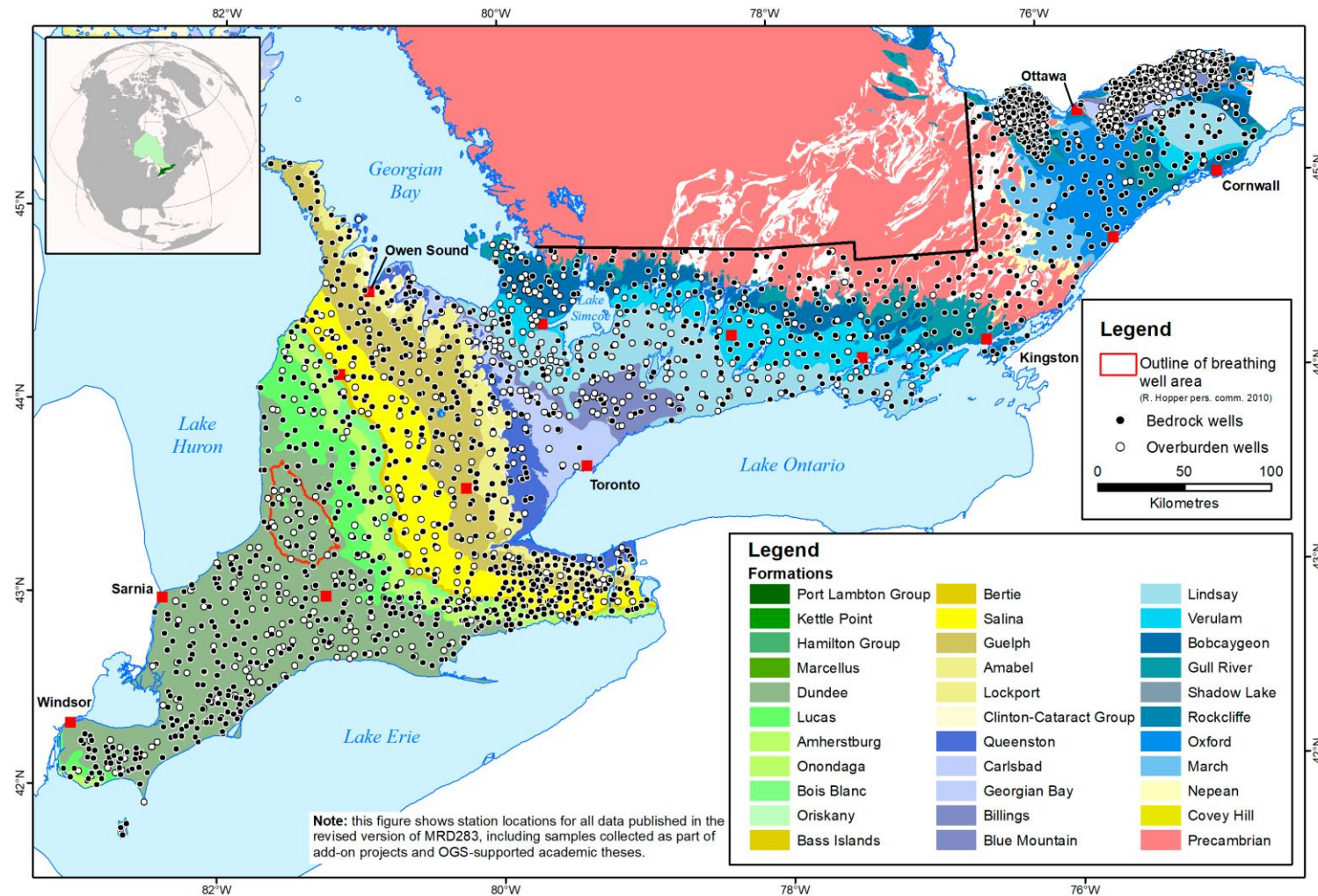


Figure 73 - Sampling locations 2007 to 2019 (bedrock and overburden) from the Ontario Geological Survey Ambient Groundwater Geochemistry Program (Hamilton, 2021). The Ontario Geological Survey database (Hamilton, 2021) contains 3,944 samples collected at 2,879 locations. The study area occurs in the center of the figure along the north shore of Lake Ontario. The data from the Hamilton study is incorporated into the ORMGP database (from Hamilton, 2021; reproduced with permission).

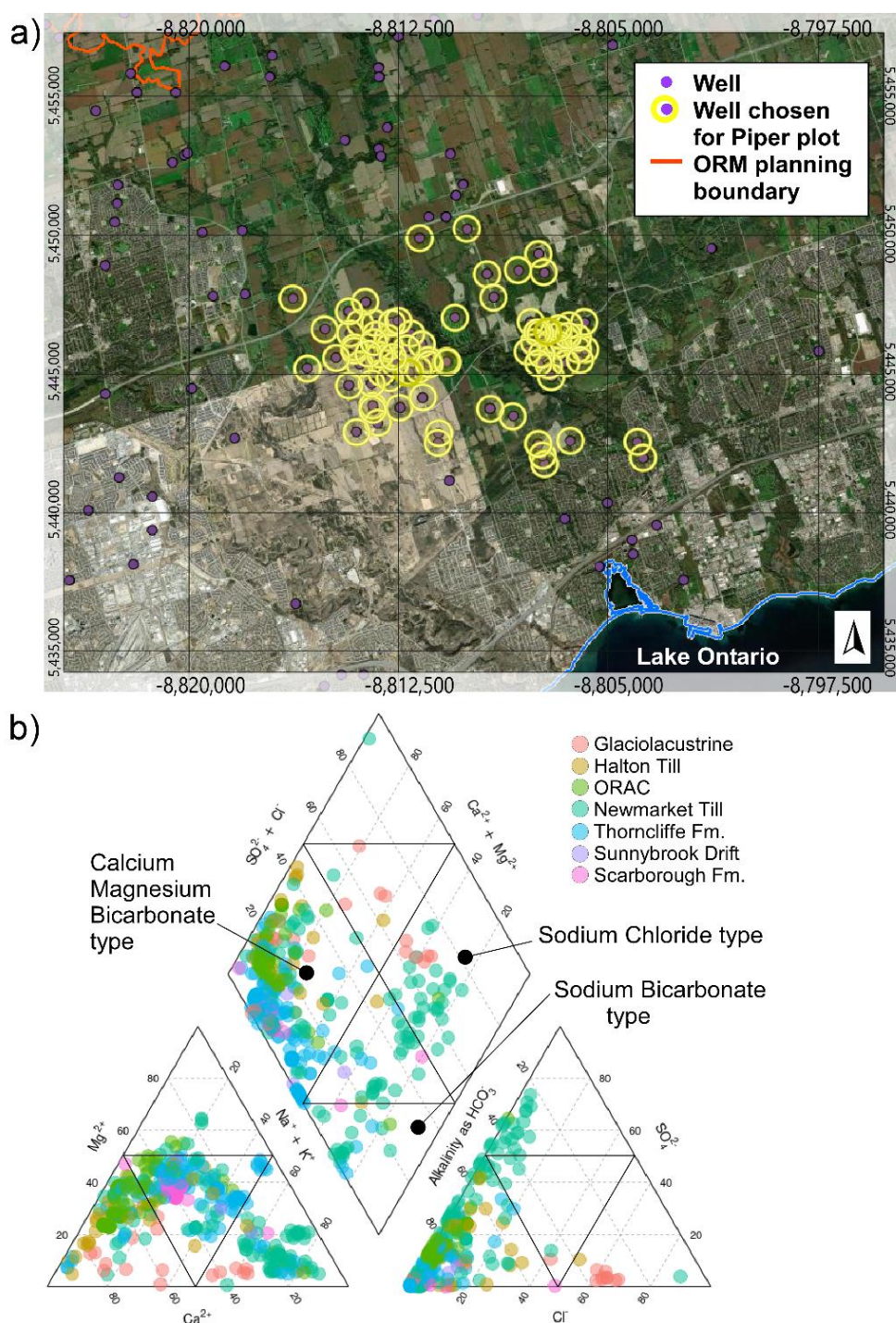


Figure 74 - Example Piper plot created on the ORMGP website, showing relative percentages of major ions in a sample. The data are from wells similar to those plotted in Figure 72 on the Durov diagram to allow for comparison. a) Location of wells chosen (yellow circles) and b) Piper plot of chemistry from chosen wells showing largely Ca-Bicarbonate water where recharging Ca-Bicarbonate water has been modified by cation exchange processes within till deposits. In this example, the wells are categorized according to hydrostratigraphic unit. The ORMGP database contains laboratory chemical analyses of over 290,000 samples. Groundwater chemistry data can be explored at [ORMGP-Maps-groundwater quality theme](#). The ORMGP Piper plot tool needs a password, which can be requested at [ORMGP-contact us](#). Further information on Piper diagrams is available in Piper (1944) and general information about plotting water chemistry analysis results is provided by Zaporozec (1972), Hem (1985), and Yang and others (2022).

6.6.3 Detailed Isotopic and Geochemical Study (Waterloo study)

The geochemical and isotopic discussion in this section provides a summary of work conducted since 2008 as part of the ongoing University of Waterloo/ORMGP geochemical characterization study (Henkemans, 2010), herein referred to as *the Waterloo study*. The objective of this ongoing study is to

- further test and refine the hydrogeological conceptual model (Figure 10) by providing an understanding of the groundwater mixing scenarios and the chemical end members of the groundwater; and
- analyze flow system dynamics, particularly aquitard unit integrity and aquifer complex vulnerability.

This study also explores possible chemical differences between the two flow systems that originate on the ORM, namely the southern flow system toward Lake Ontario and the northern flow system toward Lake Simcoe and other Kawartha lakes to the east. This division of flow systems is largely based on observation of a groundwater divide within all aquifer complexes along the crest of the ORM and by higher topographic gradients to the south of the ORM compared to the north of the ORM (Figure 10).

This section focuses on a summary of a representative suite of data generated through the Waterloo study that constitutes a subset of the geochemical data presently residing within the ORMGP database. Although the discussion focuses on this subset of the water-quality data, the results and interpretations presented apply broadly—that is, the water-quality data not considered in the discussion reinforces and supports the conclusions presented here. To date, University of Waterloo researchers have taken samples that have been analyzed for the following parameters:

- stable isotopes: ^{18}O , ^2H , and ^3H analyses conducted at the University of Waterloo;
- ^{37}Cl , ^{13}C , and $^{87}\text{Sr}/^{86}\text{Sr}$ (University of Waterloo);
- age-dating isotopes: ^{14}C (University of Arizona), CFC, SF_6 ; (University of Utah);
- passive sampling: noble gases, $^3\text{H}/^3\text{He}$ (University of Utah);
- field parameters: pH, temperature (T), conductivity, dissolved oxygen (DO), and oxygen reduction potential (ORP); and
- inorganic chemistry (York-Durham Laboratory).

Analyses for much of the above are in progress and therefore the discussion below focuses on the stable isotopes and the inorganic chemistry. Samples for stable isotopes are taken to compare with historical data and identify trends both spatially and over time. Tritium can provide insights regarding whether groundwater samples have been recharged in modern or recent times. ^{18}O and ^2H provide information regarding recharge sources and conditions such as temperature of recharge as well as potential differences and relative ages.

In the subsequent text, locations north and south of the ORM crest are deemed to be part of the northern and southern flow systems, respectively.

Key tracers – Tritium (^3H) and chloride

Analysis of water-quality results within the study area over time has led to the realization that two tracers, tritium and chloride, are the most useful for understanding flow system dynamics. More information about tritium is available at <https://www.sciencedirect.com/topics/earth-and-planetary-sciences/tritium>⁷. Historical sample locations with tritium data (using a broader sample set than the Waterloo study) are summarized for the shallow system in Figure 75 and for deeper groundwater in Figure 76.

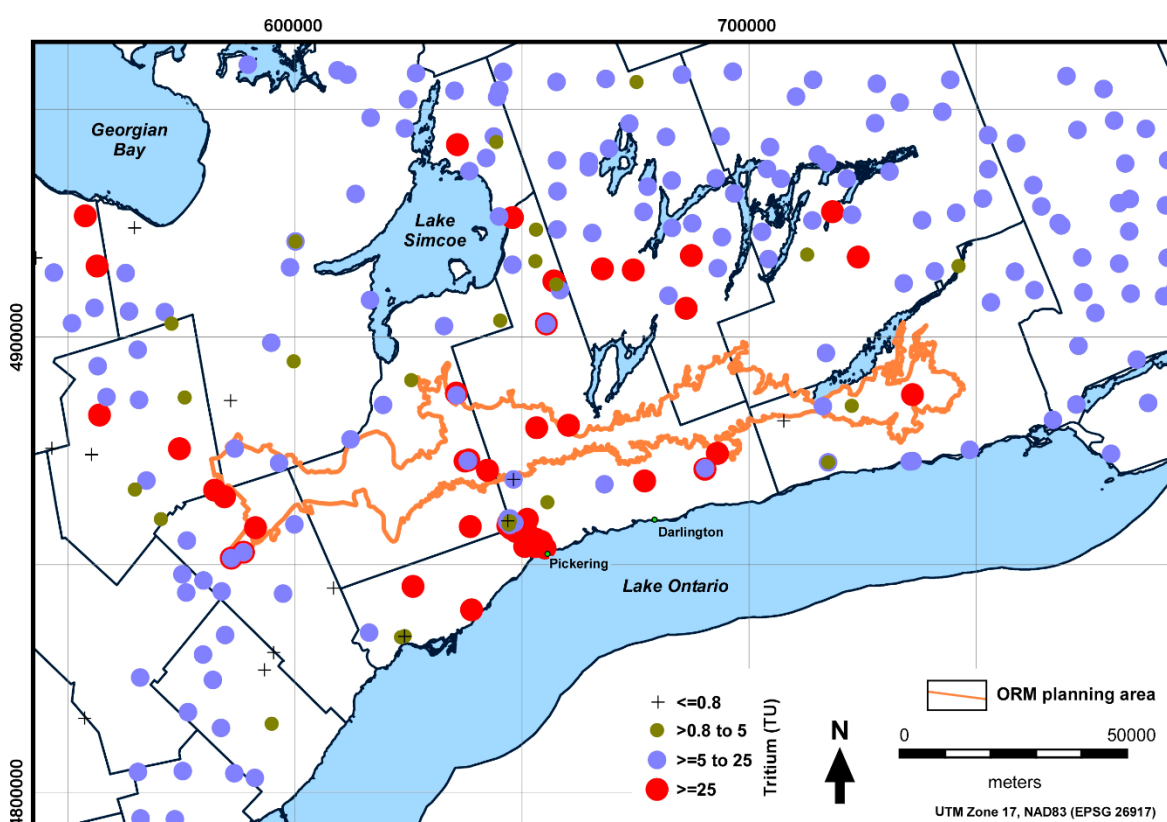


Figure 75 - Tritium results for shallow groundwater of the study-area taken from wells with screen tops less than or equal to 20 m below ground surface. Sources for plotted isotopic results are listed in Section 6.6.1 excluding analyses from the provincial DWSP. Data from 381 groundwater samples are shown; 92 percent ($n=350$) of the samples have detectable tritium (>0.8 TU). Canadian nuclear power generating stations are situated at Pickering and Darlington. Further information on the isotopic data (^{18}O , ^2H , and ^3H) is available at [ORMGP-Data Snapshot-chemistry isotope summary](#)⁷. Further information on sampling programs and tritium concentrations from samples of groundwater for all southern Ontario is described by Priebe and Hamilton (2022) and by Priebe and others (2023).

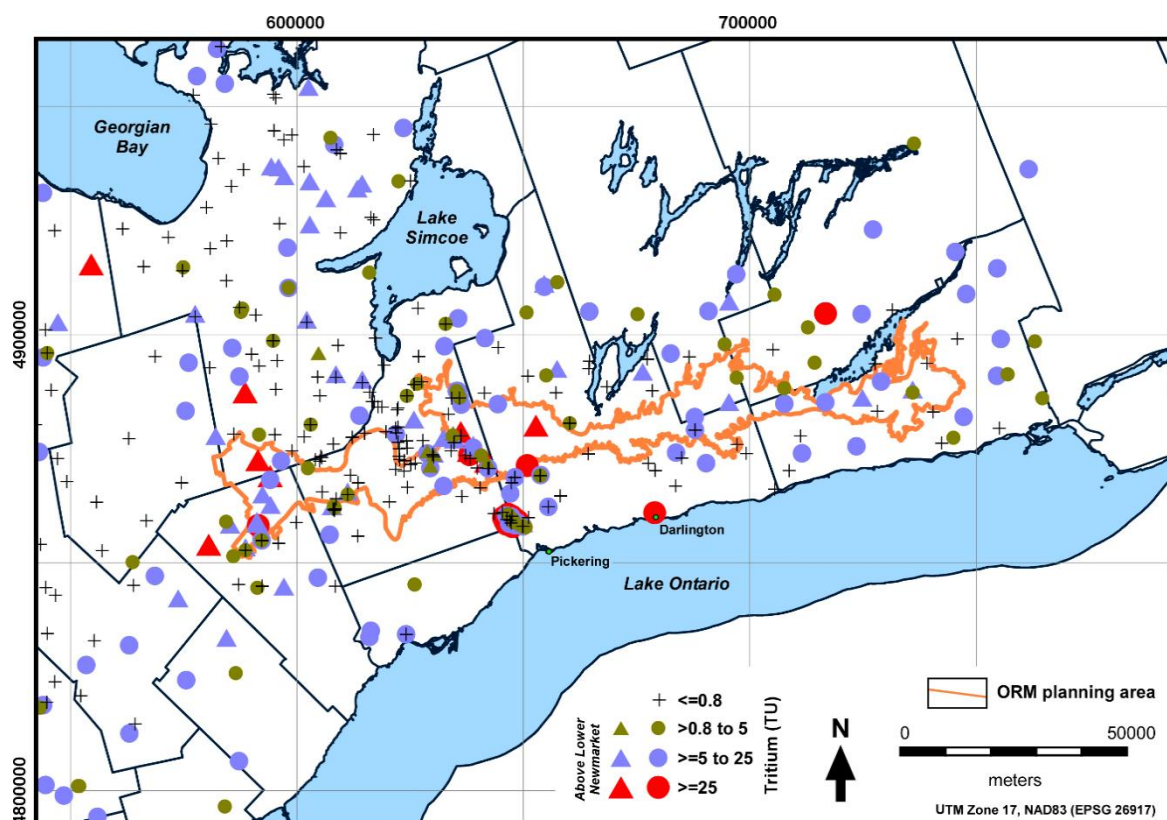


Figure 76 - Tritium results for deep groundwater of the study-area taken from wells with screen tops more than 20 m below ground surface. Triangles show wells screened within the upper part of the flow system—above the Lower Newmarket Till—whereas circles denote wells screened within the Lower Newmarket Till or Lower Sediment. Sources for plotted isotopic results are listed in Section 6.6.1 excluding analyses from the provincial DWSP. Data from 636 groundwater samples are shown; 55 percent ($n=349$) have detectable tritium (>0.8 TU). Canadian nuclear power generating stations are situated at Pickering and Darlington. Further exploration of isotopic data (^{18}O , ^2H , and ^3H) is available at [ORMGP-Data Snapshot-chemistry isotope summary](#). Further information on sampling programs and tritium concentrations from samples of groundwater for all southern Ontario is described by Priebe and Hamilton (2022) and by Priebe and others (2023).

Tritium is used as an important parameter to categorize samples because its presence indicates a component of the recharged water is less than 60 years old (Clark & Fritz, 1997; King-Sharp & Frape, 2020). The presence of tritium can therefore indicate the presence of younger fast flow paths or windows through aquitards, or the presence of a leaky well seal. Of the 270 samples included in the Waterloo study, 63 samples in the ORM isotopic database have undetectable tritium, which indicates that the water from these sampling locations is most likely more than 60 years old (Table 6). For the remaining samples, 79 had tritium values between 0.8 and 5 TU, while 45 samples had values between 5 and 25 TU and 83 samples had values greater than 25 TU, which indicates a component of young, recent recharge.

Table 6 - Select stable Isotope ($\delta^2\text{H}$, $\delta^{18}\text{O}$) and tritium (^3H) values from analyses of ORMGP isotope dataset (Waterloo study). Groundwater samples organized according to $\delta^{18}\text{O}$ value from more depleted (i.e., older water) to less depleted. *The map at the end of the table shows the location of the numbered samples. Select samples N-1 to N-5 (north of Oak Ridges Moraine divide) and S-1 to S-5 (south of Oak Ridges Moraine divide) represent select samples representing the range of water types, illustrated on Piper plots in Figure 79 and Figure 80.

ID#	Name	HS Unit	Depth (mbgs)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	^3H (TU)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	select	water types
North (N) of Oak Ridges Moraine divide															
1	Aurora MW 6 Beacon Hall	SAC	116.1	-15.5	-109.6	< 0.8	45.5	0.20	2.9	0.90	113	0.11	10.6	N-1	Na- HCO_3
2	Bradford 8th Line PW	SAC	88.4	-14.3	-99.2	< 0.8	84.9	0.70	17.4	9.7	179	< 0.5	87.8		
3	OGS 11-AG-122 (5711411)	BR	89.3	-14.0	-96.1	< 0.8	230	7.1	229	113	127	428	656		
4	Port Perry OW05-1-deep	SAC	118.9	-13.6	-100.5	< 0.8	153	4.4	57.9	46.3	417	1.1	243	N-2	Na- HCO_3 -Cl
5	PGMN-LSRCA-W071 (Ball MW 6s)	ORAC	36.7	-12.3	-84.7	< 0.8	3.3	2.0	48.5	10.9	206	11.50	1.24		
6	Mt Albert MW17i	TAC	37.2	-12.1	-82.9	2.2	4.0	0.96	70.4	17.8	252	216	8.0		
7	Mt Albert MW17d	TAC	80.8	-12.1	-82.0	3.5	4.8	1.1	75.5	20.2	219	35.7	14.9	N-3	Ca- HCO_3 - SO_4
8	Newmarket PW 14	ORAC	40.8	-11.5	-75.8	13.0	34.1	1.5	110	36.7	303	59.9	129		
9	Schomberg MW 4 Tower	SAC	128.2	-11.3	-76.0	< 0.8	19.7	2.3	76.1	28.4	852	0.10	1.1		
10	Ballantrae MW 6d	SAC	131.8	-11.2	-75.9	< 0.8	8.75	0.72	47.8	11.0	231	4.06	1.50		
11	PGMN-LSRCA-W298s	SAC	2.8	-11.1	-77.0	24.1	68.5	0.61	107	0.61	409	22.4	91.2		
12	Mt Albert MW 17s	INS	13.7	-11.0	-74.2	18.5	10.9	1.7	91.7	16.8	233	229	15.0		
13	Vandorf MW 2d	TAC	85.3	-10.8	-77.5	8.4	36.5	3.6	133	40.4	375	20.9	232	N-5	Ca- HCO_3 -Cl
14	PGMN-LSRCA-W298d	SAC	30.5	-10.8	-74.1	< 0.8	20.1	2.8	40.0	23.5	265	2.10	7.7		

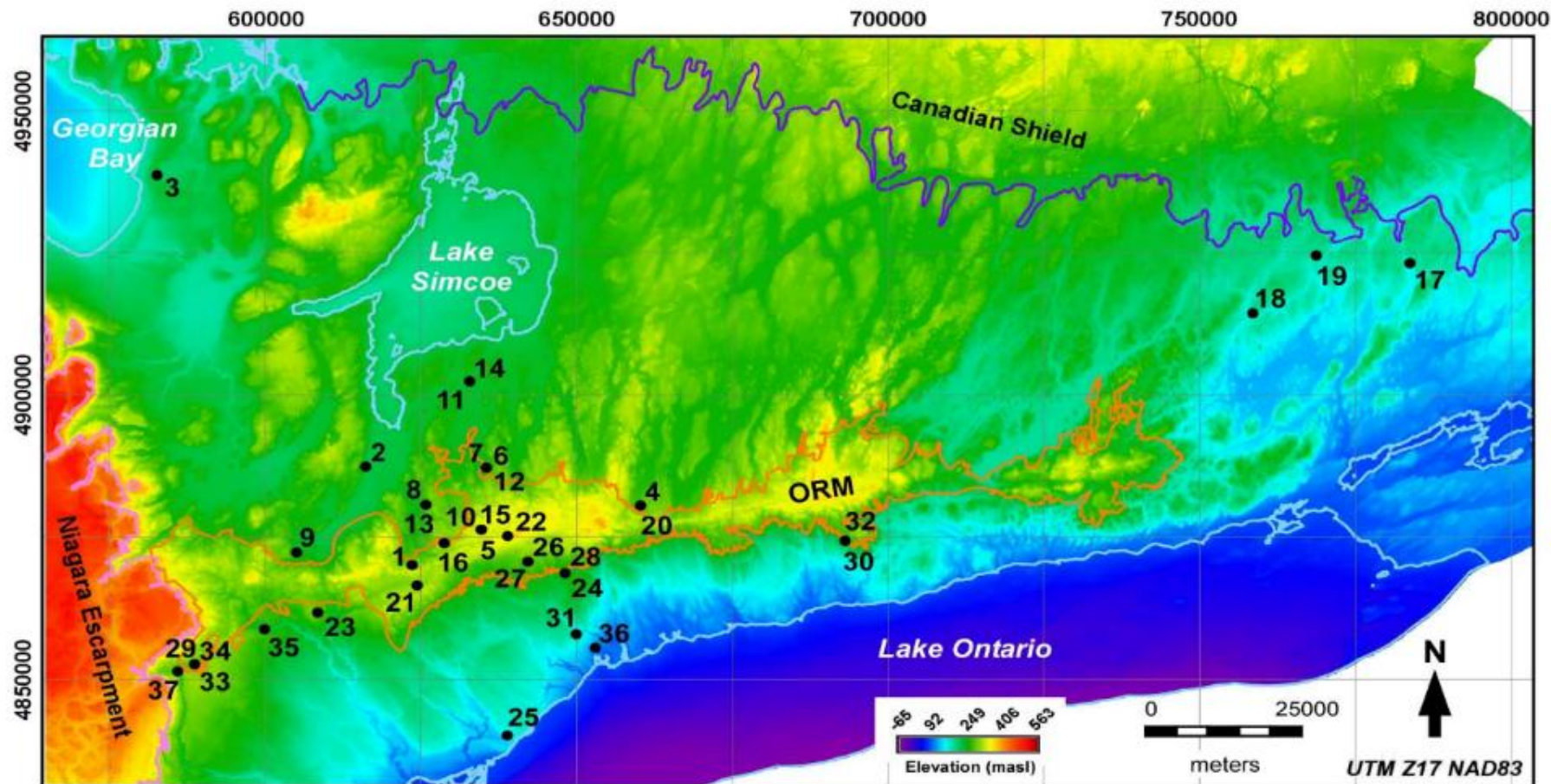
Table 6 - Select stable Isotope ($\delta^2\text{H}$, $\delta^{18}\text{O}$) and tritium (^3H) values from analyses of ORMGP isotope dataset (Waterloo study). Groundwater samples organized according to $\delta^{18}\text{O}$ value from more depleted (i.e., older water) to less depleted. *The map at the end of the table shows the location of the numbered samples. Select samples N-1 to N-5 (north of Oak Ridges Moraine divide) and S-1 to S-5 (south of Oak Ridges Moraine divide) represent select samples representing the range of water types, illustrated on Piper plots in Figure 79 and Figure 80.

ID#	Name	HS Unit	Depth (mbgs)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	^3H (TU)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	select	water types
15	Ballantrae MW 6i	ORAC	91.5	-10.7	-73.6	17.0	7.9	0.59	84.8	8.41	362	22.1	19.5		
16	Vandorf MW 2s	TAC	40.5	-10.6	-75.9	4.2	32.2	1.6	37.2	44.9	275	15.6	91.9		
17	PGMN-LTRCA-W212	SAC	13.4	-10.0	-68.7	14.0	9.98	1.0	92.6	6.58	-	13.4	23.2		
18	PGMN-LTRCA-W173	BR	15.6	-9.9	-68.6	17.2	38.8	1.0	122	9.60	-	12.9	89.1		
19	PGMN-LTRCA-W121	BR	3.8	-9.7	-69.0	17.6	176	10.4	142	12.9	-	47.1	421		
20	Port Perry OW05-3-shallow	ORAC	5.6	-9.7	-71.3	51.0	14.5	41.0	162	16.4	571	21.0	4.2	N-4	Ca- HCO_3
South (S) of Oak Ridges Moraine divide															
21	Richmond Hill MW 4 Ozark	TAC	90.5	-13.4	-96.7	< 0.8	52.9	3.04	69.0	11.6	656	2.16	14.7		
22	Stouffville MW 12d	TAC	129.5	-12.3	-75.9	23.4	14.0	1.02	91.9	18.7	259	67.3	28.4		
23	Nobleton MW 3d	TAC	86.4	-12.2	-82.4	< 0.8	4.7	1.96	242	0.86	897	70.0	16.3		
24	2/94-2	TAC	61.9	-11.9	-76.6	< 0.8	24.2	1.15	24.7	13.3	213	2.90	0.75		Na-Ca-Cl- HCO_3
25	644 Warden-s	TAC	10.7	-11.6	-81.3	51.0	390	2.7	246	31.3	458	45.3	834	S-3	
26	Stouffville MW 8d	TAC	106.1	-11.4	-76.3	< 0.8	14.6	0.9	30.5	11.0	182	<1	2.5	S-2	Ca- HCO_3
27	Stouffville MW9	ORAC	32.3	-10.9	-72.1	17.7	60.1	3.2	68.0	64.0	260	33	250		
28	294-4	ORAC	7.5	-10.6	-72.5	< 0.8	4.87	1.0	58.0	23.0	255	354	2.8		
29	PGMN-CVC-W165s-Heart Lake	ORAC	3.1	-10.5	-76.1	26.4	681	2.7	245	17.7	487	40	1270	S-4	Na-Ca-Cl- HCO_3

Table 6 - Select stable Isotope ($\delta^2\text{H}$, $\delta^{18}\text{O}$) and tritium (^3H) values from analyses of ORMGP isotope dataset (Waterloo study). Groundwater samples organized according to $\delta^{18}\text{O}$ value from more depleted (i.e., older water) to less depleted. *The map at the end of the table shows the location of the numbered samples. Select samples N-1 to N-5 (north of Oak Ridges Moraine divide) and S-1 to S-5 (south of Oak Ridges Moraine divide) represent select samples representing the range of water types, illustrated on Piper plots in Figure 79 and Figure 80.

ID#	Name	HS Unit	Depth (mbgs)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	^3H (TU)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	select	water types
30	PGMN-GRCA-W114 Jungle Cat N	ORAC	10.8	-10.3	-69.7	38.0	67.9	1.5	100	18.9	330	21	121		
31	194-3	HT	8.8	-10.2	-68.3	116.6	9.36	1.5	119	20.9	662	48	8.7	S-5	Ca- HCO_3
32	PGMN-GRCA-W114s	ORAC	5.9	-10.2	-70.7	32.1	58.4	1.5	103	20.7	334	25	116		
33	PGMN-CVC-W165i-Heart Lake	ORAC	30.5	-9.9	-76.9	24.0	701	1.0	250	17.4	493	50.7	1310		
34	PGMN-CVC-W165d-Heart Lake	SAC	168.0	-9.9	-75.3	< 0.8	88.1	4.9	31.3	16.2	194	5.15	135	S-1	Na- HCO_3 -Cl
35	PGMN-TRCA-W327s-Bolton	HT	13.1	-8.7	-63.7	7.4	42.9	2.0	34.6	68.7	496	33.1	44.9		
36	UofT-Meriano-MW02-07	GL	0.8	-8.5	-62.8	183.5	45.7	0.8	248	46.4	493	53.6	267		
37	Inglewood EW 3-2s	ORAC	9.1	-8.3	-61.1	23.2	12.1	0.68	81.5	15.4	291	4.64	26.5		

* Location map for Table 6



Tritium measured in the 2008 to 2017 ORM groundwater samples ranged from non-detect levels (<0.8 TU) to 183.50 TU at Station 36 (Table 6) near Frenchman's Bay close to the Pickering Power Plant on Lake Ontario which is the Meriano University of Toronto study well MW02-07. Tritiated groundwater was found primarily in the shallow, more surficial ORM deposits, and in some deeper Thorncliffe and Scarborough aquifer complex wells. A greater range (non-detect to 183.50 TU) of tritium values was found in the shallow aquifers as compared to a more restricted range of values (non-detect to 35.70 TU) found in the deeper aquifers. In cases where tritium was not detected in the shallow flow system, it is assumed that water older than approximately 60 years exists due to relatively little disturbance from pumping and usage, and/or a lack of recent recharge to that area of the aquifer.

The anthropogenic input of tritium to the atmosphere from nuclear power generation allows for levels of tritium in precipitation and shallow groundwater to be higher than natural levels (King-Sharp & Frape, 2020). The effect of nuclear power generation on tritium levels in precipitation varies geographically, with tritium levels decreasing with distance from the nuclear power plants. Gerber and others (2009) reported that monitoring stations up to 12 km from the Pickering Nuclear Generating Station show elevated levels of tritium. Lake Ontario levels of tritium are also elevated, with a maximum (267 TU) occurring in a sample that was taken closest to the station (Dove et al., 2021; King, 1997). A map of tritium levels in the shallow groundwater (Figure 75) that includes data from Gerber and others (2009) reveals elevated tritium levels throughout the study area due to the proximity to nuclear power generation at the Darlington, Pickering, and the Bruce Peninsula power plants. These localized sources are expected to impact shallow groundwater across the study area and will most likely provide a reliable tritium tracer source that will reflect recent recharge. Over time, this recharge will also affect water in deeper aquifers.

Elevated levels of tritium in the shallow system (>25 TU) might suggest additional tritium inputs above those only from precipitation influenced by inputs from nuclear power generation. In some cases—for example, in the Stouffville Gravel Pit (MW#4; in the central part of study area along the Oak Ridges Moraine)—evaporation of surface water, as indicated by the stable isotopes (^{18}O and ^2H), has led to evaporative enrichment and concentration of tritium (50.9 TU) in the shallow groundwater at this location. As groundwater samples in the Stouffville area also show elevated levels of tritium, there is likely also a component of anthropogenic tritium in the gravel pit surface water sample, typical of many lakes along the Oak Ridges Moraine (White, 2004). The occurrence of high head and high recharge support the presence of significant tritium levels in both shallow and deep wells at this location (Figure 75, Figure 76). Figure 76 shows locations and concentrations of tritium in the intermediate and deep aquifers. In general, tritiated water is found only in the Scarborough and bedrock aquifers where these units subcrop and/or

there is thin overburden—for example, along the Niagara Escarpment and south of the ORM (Priebe et al., 2021). There are some exceptions to this generalization where low tritium concentrations (0.8 to 5 TU) are encountered within Lower Sediments. In these cases, one must consider the possibility that the well casings may be leaking.

In the last 50 years, the application of road salt or de-icing chemicals to southern Ontario roadways has become standard practice during winter. Approximately 4.9 million tons of road salt are applied annually to Canadian roadways, accounting for about 3.0 million tons of chloride (Environment Canada and Health Canada, 2001). Within the study area, the median application rate of road salt is approximately 11.5 ton/km (Figure 69). The highest groundwater chloride concentrations (800 to 1,400 mg/L) are found south of the moraine, at shallow depths (Figure 77 and Figure 78) and carry the localized isotopic signature ($\delta^{37}\text{Cl}$) for road salt (Rosen, 1999). However, elevated concentrations (>200 mg/L) are also found in both older water (e.g., Port Perry deep well) and recently recharged water (tritiated) up to 170 m in depth (e.g., 2-Year Deep Sentry well; Figure 77 and Figure 78), some of which appear to carry the road salt signature. This suggests high chloride concentrations are not limited to shallow depths where anthropogenic input is high but also occur at greater depths where contributions from both natural—shale bedrock—and anthropogenic sources are present. Findings suggest that both natural and anthropogenic chloride sources need to be considered in the monitoring of chloride in the groundwater of the ORM flow system.

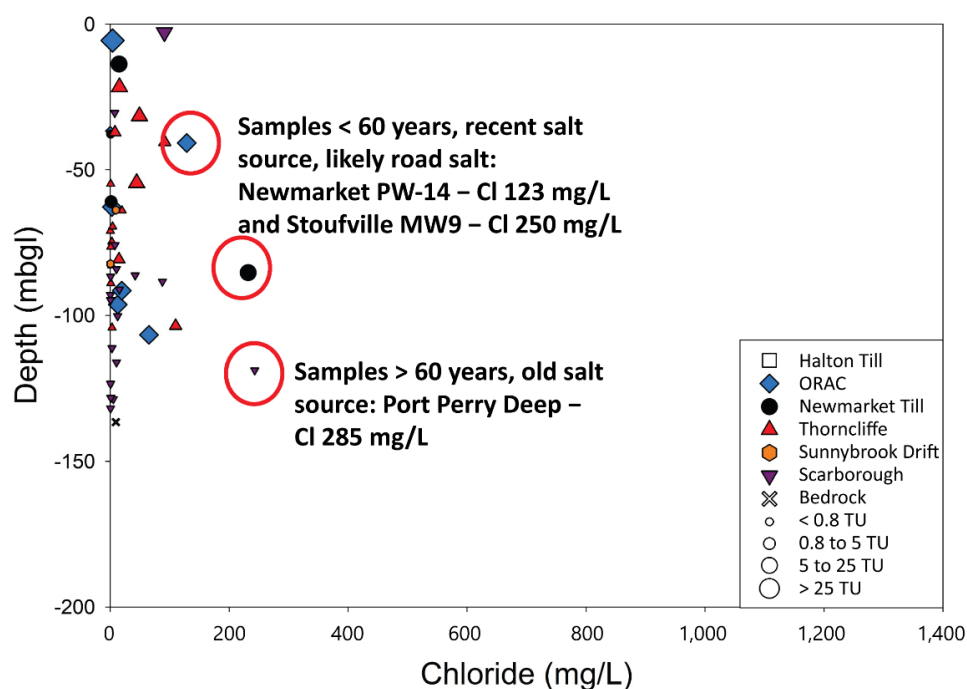


Figure 77 - Chloride concentration versus depth for the ORM northern flow system coded for tritium and hydrostratigraphic unit. Three samples are labeled: one sample older than 60 years—i.e. no tritium—with an elevated salt signature, indicating an older salt source, and two samples with elevated salinity and tritium indicative of more recent recharge. The size of the symbol reflects the tritium content of the sample with the highest tritium contents represented by the largest symbols, the legend shows ^3H values, mbgl=meters below ground level.

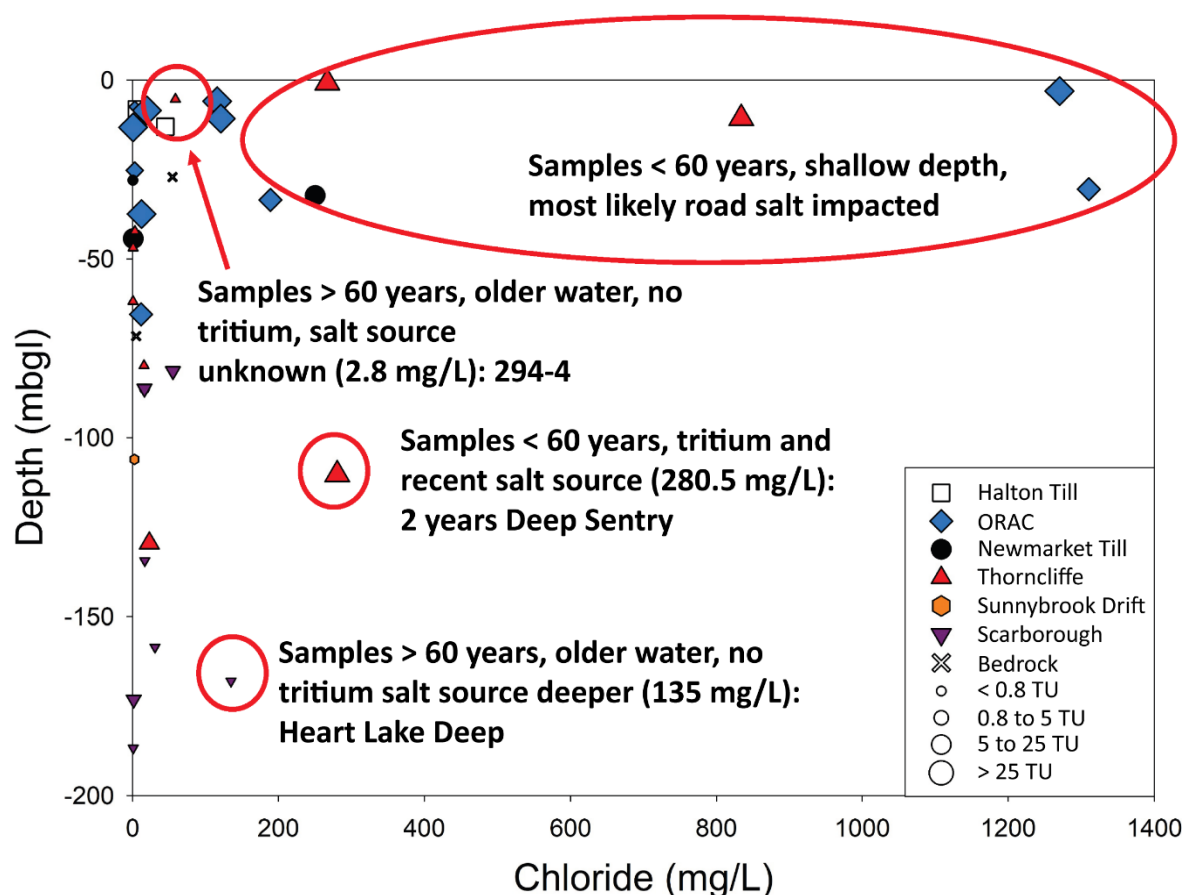


Figure 78 - Chloride concentration versus depth for the ORM southern flow system coded for tritium and hydrostratigraphic unit. The figure is annotated to show samples that have been recently recharged and that are most likely impacted by road salt. Also, four samples are labeled, and based on tritium results, two are interpreted as being older than 60 years and two younger than 60 years. The size of the symbol reflects the tritium content of the sample, with the highest tritium contents represented by the largest symbols.

The geochemical results from the study are presented in Piper plots (Figure 79; north of the ORM; Figure 80; south of the ORM). In both figures, the samples are coded for tritium—a larger symbol means more tritium and younger water—and relative depth using the hydrostratigraphic units as defined earlier. Water classification or water type is determined using groundwater geochemistry as shown on the Piper diagrams; the major water type is CaHCO_3 water—typical of groundwater controlled by carbonate reactions. Other water types include the following.

- Na-Cl waters typical of marine and old highly saline bedrock formation fluids, or groundwater impacted by road deicer salts (halite- NaCl ; Hem, 1985), which are usually shallow, more recently recharged water. In particular, three samples in the southern flow system show greater than 60 percent chloride (Figure 80).
- Ca-Cl water typical of groundwater in contact with the mineral gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or oxidation of sulfides, often abundant in some of the sedimentary units present within the study area (e.g., till).

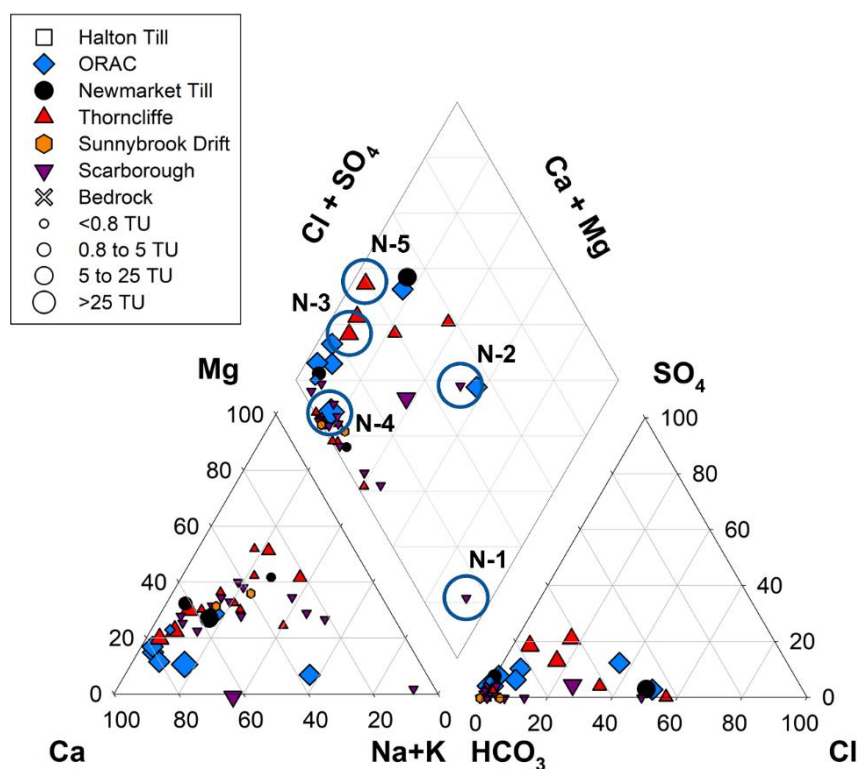


Figure 79 - Piper plot diagram indicating relative percentages of groundwater geochemical composition of water sampled from the northern ORM flow system coded for tritium and hydrostratigraphic unit. Five samples from Table 6 are labeled. The size of the symbol reflects the tritium content of the sample with the highest tritium contents represented by the largest symbols.

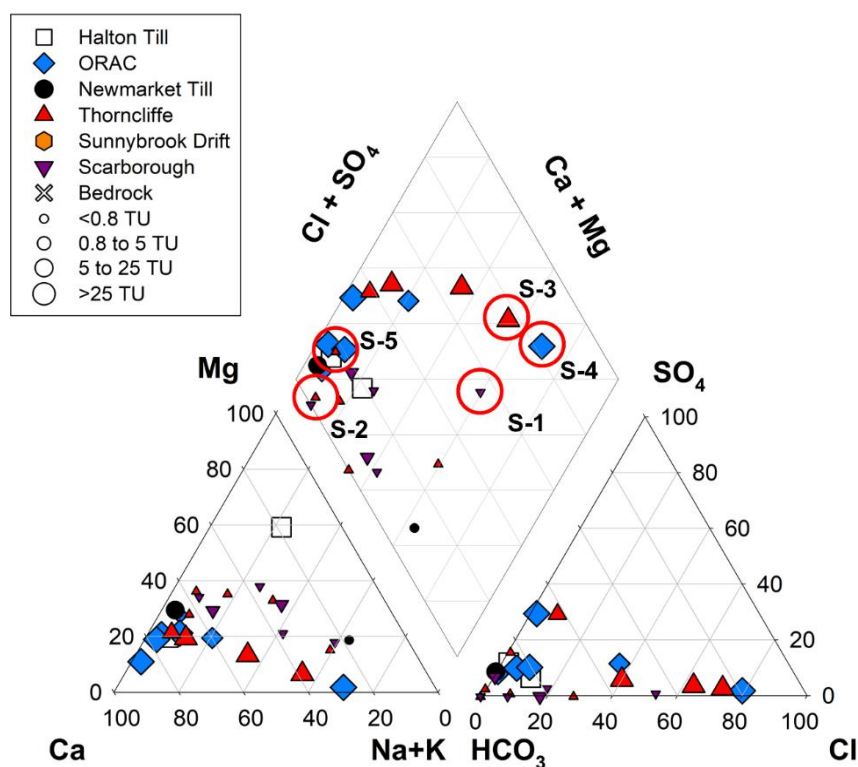


Figure 80 - Piper plot diagram indicating relative percentages of groundwater geochemical composition of water sampled from the southern ORM flow system coded for tritium and hydrostratigraphic unit. Five samples from Table 6 are labeled. The size of the symbol reflects the tritium content of the sample, with the highest tritium contents represented by the largest symbols.

When considering the ORM northern flow system (Figure 79), it is evident that elevated tritium levels are present mostly in samples taken from the upper ORAC unit, as well as some of the deeper Thorncliffe water. These samples also appear to have increased Cl concentrations. This similar geochemical signature between some of the shallow and deep groundwater may be due to the connection between the upper and lower parts of the flow system through tunnel channels and other conduits, as discussed in Section 5. Overall, regardless of the well depth and screened geological unit, the north system (Figure 79) has fewer samples containing elevated Cl concentrations than the southern flow system (Figure 80), likely attributed to the greater urbanization south of the moraine ([Exercise 11](#)). Increased Mg and Na concentrations are evident in the deeper units, which also have low to undetectable tritium, generally indicating older water that can be classified as mixed Ca-Mg-HCO₃. The likely source of NaCl in deeper units, where there is no detectable tritium—water more than 60 years in age—is upward migration of salts from highly saline sedimentary bedrock formations. The age of this groundwater is generally older than the onset of routine and intense NaCl road salt applications, which generally began in the 1970s.

Shallow water from the southern flow system is mostly classified as Ca-HCO₃; however, many of the samples are strongly influenced by Na-Cl, and occasionally by SO₄. Many samples are also characterized by increased tritium levels indicating a significant component of more recently recharged anthropogenically impacted water. This is evident in both the shallow units of the ORAC and the deeper Thorncliffe unit. There is also evidence of Na-Cl influence in the deeper units with non-detect levels of tritium, most likely from deeper highly saline sedimentary formation fluids noted in other studies concerned with bedrock fluid geochemistry (Dollar et al., 1991; McNutt et al., 1987; Skuce et al., 2015; Weaver et al., 1995).

Stable isotopic characterization (¹⁸O, ²H)

The $\delta^{18}\text{O}$ isotopic signature of modern, recently recharged groundwater from the study area was identified by Fritz and others (1987) to be between -9‰ and -12‰ based on the geographic location of samples taken in the late 1970s and 1980s. Similarly, groundwater samples taken during the 2008 to 2017 Waterloo study that reflect meteoric recharge, had $\delta^{18}\text{O}$ ranging from -8.26‰ to -15.5‰. In general, the more depleted samples <-12‰ had little or no tritium. The range representing modern meteoric water (-9‰ and -12‰) contain measurable tritium agrees well with Fritz and others (1987; Figure 81). Figure 81 presents the ¹⁸O-²H values for all samples from the Waterloo study labeled for hydrostratigraphic units and coded for tritium values.

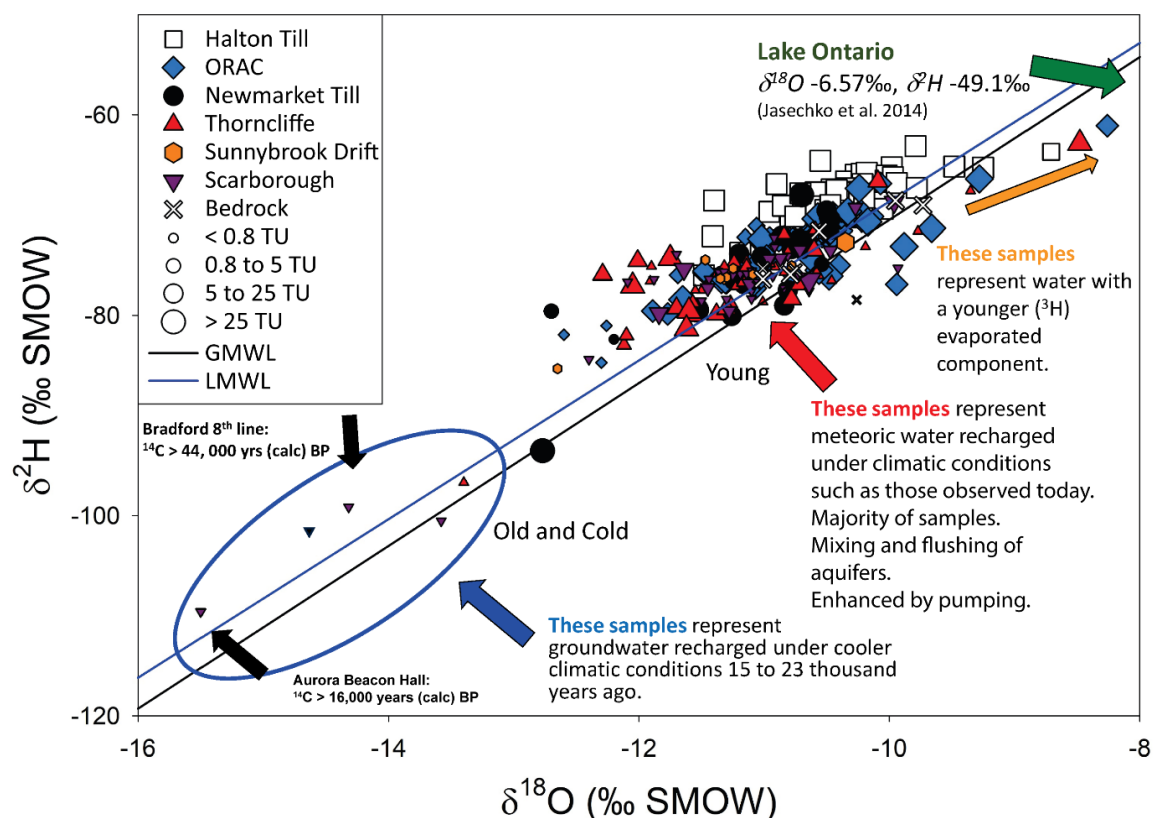


Figure 81 - Stable isotopes for all Waterloo study samples coded for tritium content and hydrostratigraphic unit. The figure is annotated to show processes represented along the global meteoric water line. Two samples are labeled indicating their relative carbon-14 age date. The size of the symbol reflects the tritium content of the sample with the highest tritium contents represented by the largest symbols.

Considering all the samples, including those with nondetectable tritium, the $\delta^{18}\text{O}$ values range from -8.26‰ to -15.50‰ and $\delta^2\text{H}$ from -61.1‰ to -109.6‰ . Isotopic data from the study area plot along a line falling above and parallel to the global meteoric water line (Craig, 1961) as well as above the local meteoric water line (LMWL). Fritz and others (1987) established the local meteoric water line ("LMWL" that is shown in Figure 81 and throughout this book). The LMWL is the local relationship of deuterium ^2H and ^{18}O isotopes in groundwater of the study area. The equation for the LMWL was developed using data from the Simcoe station situated west of the study area, and relates the two isotopes as shown as Equation (4) (Fritz et al., 1987; Simcoe International Atomic Energy Agency (IAEA) station).

$$\delta^2\text{H} = (7.92 \delta^{18}\text{O}) + 10.53 \quad (4)$$

The Waterloo study groundwater samples are consistent with the LMWL, demonstrating that most sampled groundwater reflects meteoric precipitation that has not been significantly affected by evaporation before recharging the groundwater (Clark & Fritz, 1997; Rozanski et al., 1993). The study area water is interpreted to be meteoric because of this relationship. If processes such as evaporation were to affect the precipitation, and ultimately the groundwater, this would show as a deviation from the slope of the LMWL.

A line indicating evaporation would fall to the right of the meteoric waterline with its specific position depending on the humidity of the atmosphere of the region (Clark & Fritz, 1997). The greater the humidity, such as found in the Great Lakes basin and the study area, the closer the evaporation line will be to the LMWL due to the impacts of vapor exchange.

Many of the samples, particularly in the shallow units, show a strong deuterium enrichment from impacts associated with Great Lakes humidity and vapor exchange (Gat et al., 1994; Jasechko, 2019; Jasechko et al., 2017), which is consistent with historical data from Gerber and others (2009). Evaporation of water from the Great Lakes contributes water vapor to the air masses and eventually the precipitation that falls across the study area. This water vapor, in turn, affects the isotopic signature of the precipitation that recharges the groundwater. Gat and others (1994) describe this lake effect on a regional scale and explain how mixing the Great Lakes water evaporated within an air mass causes an increase in the deuterium excess (d-excess) in the combined air mass. This increase occurs because the d-excess is greater in the evaporated water vapor than the original air mass, causing enrichment in the light isotopes of ^{18}O and deuterium. D-excess at the Ottawa IAEA station for data from the years 2000 to 2006 ranges from -9 to 44‰ with yearly averages between 8 and 15‰. The range of d-excess found in the study area (3 to 22‰) is less when compared to the Ottawa IAEA precipitation data and is most likely preserving some seasonal or climatic control affecting the water isotopic signature of precipitation in southern Ontario. ^{18}O values of approximately -8 to -9‰ are observed in groundwater near the Lake Ontario shoreline, whereas to the north, near Lake Simcoe, values around -12‰ are recorded. This range of ^{18}O values agrees with the groundwater map described by Fritz and others (1987). The relationship between ^{18}O and location within the study area relative to Lake Ontario is a generalization. Given seasonal recharge variation and/or flow path mixing due to groundwater withdrawal, some locations may deviate from the generalized d-excess model. Deuterium excess is not apparent in the deeper units; however, some Thorncliffe samples with higher tritium levels are influenced by d-excess. In the northern system, evaporation has affected one ORAC sample.

Figure 82 and Figure 83 display the stable isotopic data from the host geologic unit comparing the northern flow system (Figure 82) and the southern flow system (Figure 83) to differentiate the isotopic ranges in groundwater found in the hydrostratigraphic units in both systems and the potential evaporative secondary processes that can affect isotopic signatures. Several northern flow system water samples are significantly depleted in ^{18}O compared to most of the data, specifically samples taken from the deepest Scarborough aquifer complex (i.e., the Thorncliffe silty sand). Based on non-detect levels of tritium, and measured radiocarbon age dates (^{14}C) of between 4,500 and 44,000 years before present (Bradford 8th Line and Aurora Beacon Hall samples; Henkemans, 2010) this water is interpreted to be much older. The more depleted samples (with $\delta^{18}\text{O}$ values ranging from

-13‰ to -15.5‰) most likely represent much older cold-climate recharge under glacial conditions. When associated with high levels of Cl, then the samples are interpreted to also be influenced by upward migration of salts from the underlying saline bedrock units (e.g., the Port Perry OW05-1 sample from a screen in the Scarborough, with $\delta^{18}\text{O}$ of -13.6‰, non-detect tritium, and 243 mg/L of Cl). Several samples (34) from the ORAC, Thorncliffe and Scarborough have $\delta^{18}\text{O}$ values between -11‰ and -13‰ with little to no tritium and are also considered to be much older recharged water.

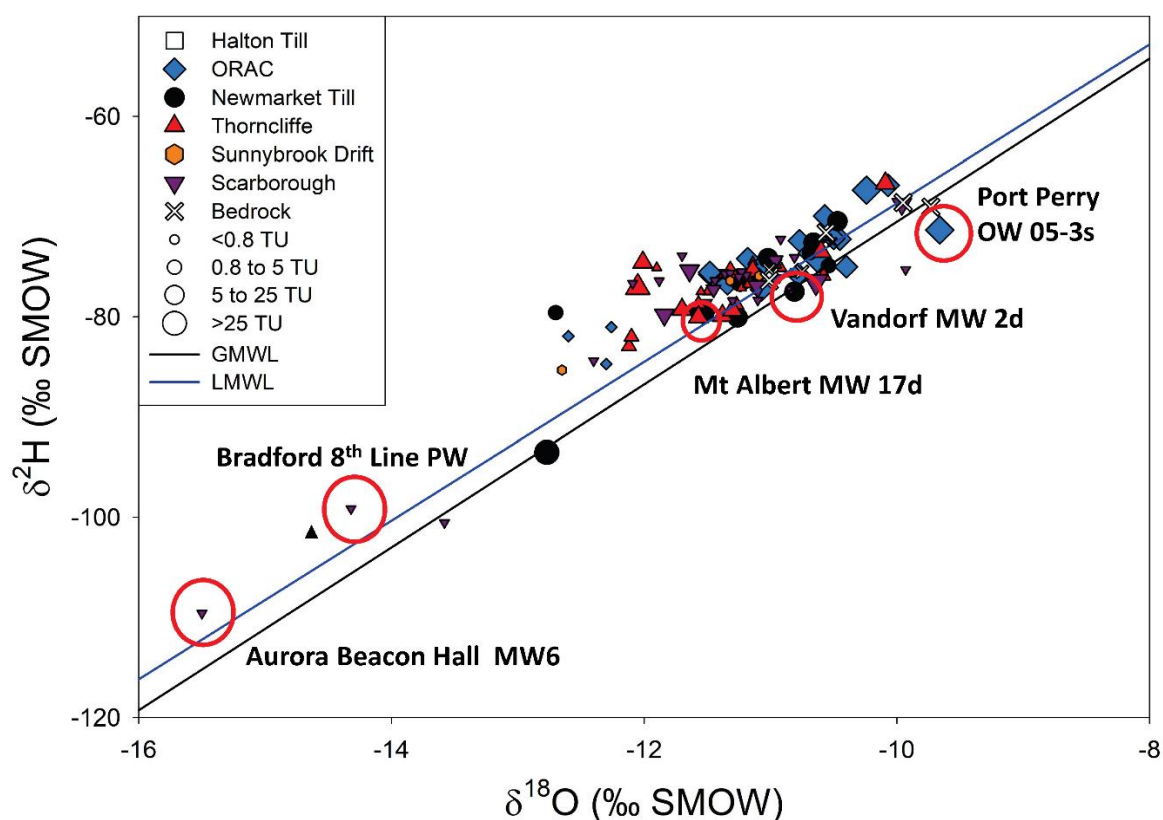


Figure 82 - Stable isotope plot for the northern flow system samples coded for tritium content and hydrostratigraphic unit. Several samples from Table 6 are labeled. The size of the symbol reflects the tritium content of the sample with the highest tritium contents represented by the largest symbols.

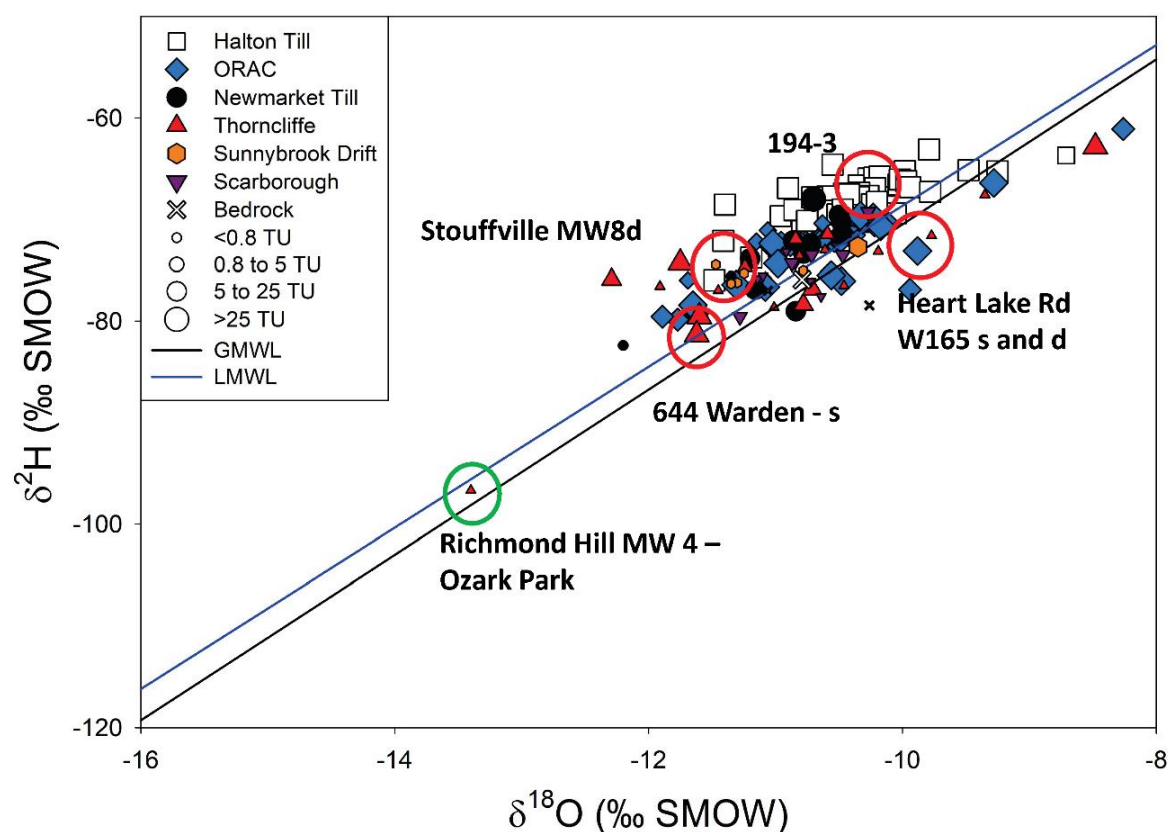


Figure 83 - Stable isotope plot for the southern flow system samples coded for tritium content and hydrostratigraphic unit. Several samples from Table 6 are labeled. The size of the symbol reflects the tritium content of the sample, with the highest tritium content represented by the largest symbols.

The stable isotopic values for ^{18}O and ^2H from samples taken in the southern flow system (Figure 83) differ significantly from the northern flow system. There is more evidence of d-excess in the shallow water for the Halton Till, the ORAC, and numerous Thorncliffe aquifer complex samples that have levels of tritium greater than 25 TU, indicating recently recharged water. Several less-depleted samples from Halton Till, ORAC, and Thorncliffe show evaporation effects as indicated by plotting below and to the right of the LMWL. One Thorncliffe sample ($\delta^{18}\text{O} = -3.4\text{‰}$; Richmond Hill MW4) with nondetectable tritium is depleted and potentially associated with cold climates or glacial recharge.

The presence of extreme d-excess in deeper, un-tritiated water in the Scarborough and Thorncliffe aquifer complexes may indicate the penetration of older shallow water to depth. At these depths, any record of seasonal variations in d-excess should be attenuated. D-excess at the upper or lower end of seasonal variation and the presence of tritium are generally characteristic of shallow groundwater. Their presence in a deep well may indicate the well is leaking or a fast flow path to depth exists at the site.

Summary and geochemical conceptual model

The ORM can conceptually be divided into two groundwater regimes, one flowing north toward Lake Simcoe and the other flowing south toward Lake Ontario (Figure 84). A key result of the water quality analyses is that groundwater quality can vary considerably over short distances. The observed variability in the concentrations of several key parameters (e.g., chloride, tritium) makes it possible to only broadly characterize the groundwater across the area.

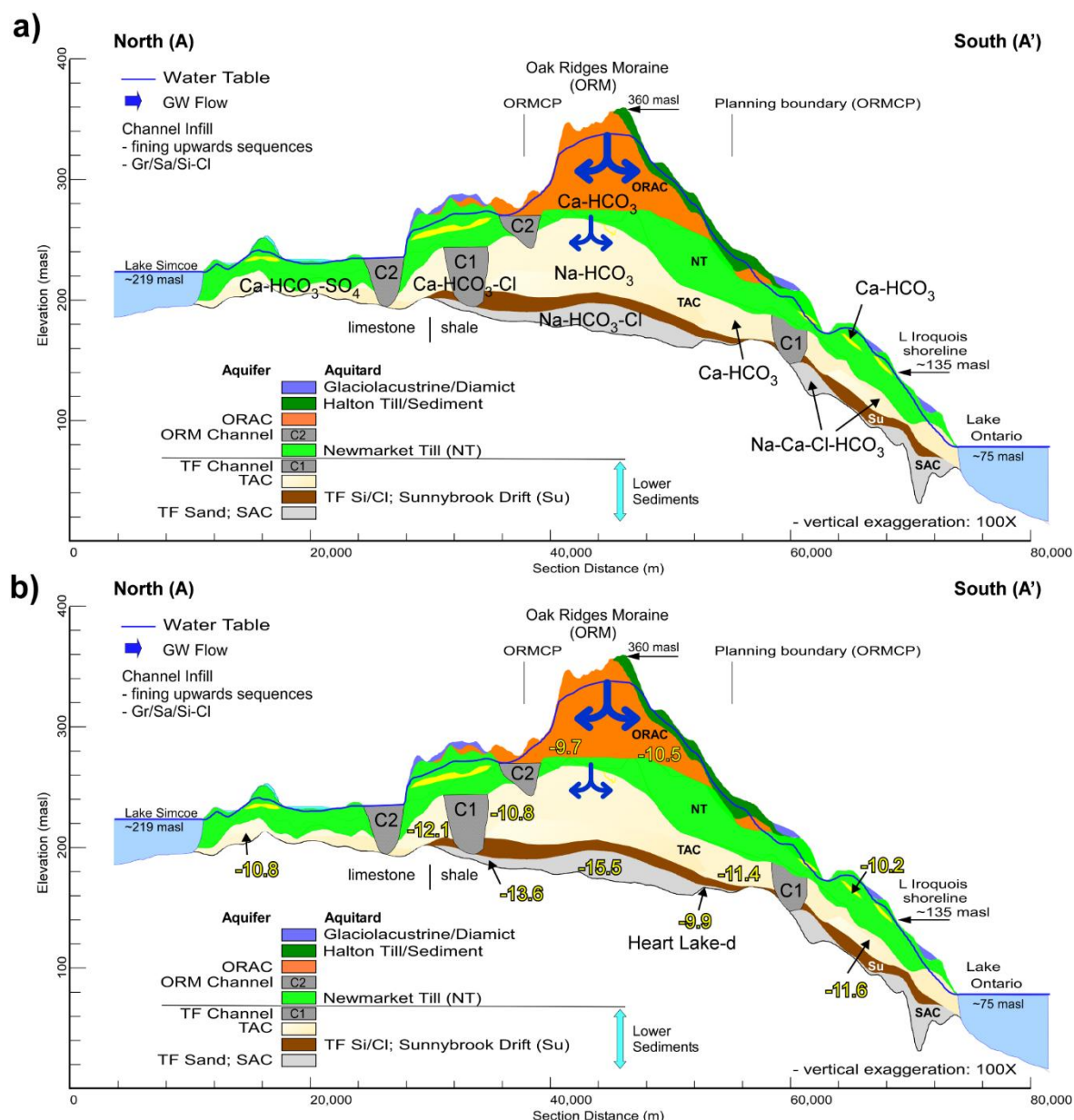


Figure 84 - Conceptual model and details regarding geochemistry and isotopes showing a) water types based on major ion concentrations and b) $\delta^{18}\text{O}$ values within the flow system showing $\delta^{18}\text{O}$ depleted groundwater at depth beneath and immediately north of ORM. Major reactions include cation exchange of Na for Ca and Mg and an increase in chloride concentrations from either road salt or interaction with shale bedrock.

In general, shallower groundwater across the north and south parts of the study area can be characterized as typical of recently recharged precipitation, being Ca-Mg-HCO₃ dominated water, with stable isotopic values reflecting precipitation differences, transport distances, and isotopic fractionation away from Lake Ontario. Often, the shallow water contains elevated tritium values, especially near nuclear power facilities. However, some shallow samples—and it is difficult to point to any particular location—exhibit elevated chloride and sodium levels, attributed to road salting impacts, whereas other shallow samples show elevated nitrate concentrations, resulting from septic system discharge or agricultural fertilizer applications. This variability can be generally attributed to slower groundwater travel times, which result in longer times for diffusion, dilution and/or mixing to act and homogenize the groundwater.

Similarly, water in deeper aquifers such as the Thorncliffe and Scarborough aquifer complexes exhibits a geochemical signature of older recharged water that has undergone cation exchange, and have minimal or no tritium. However, reflecting the variability seen in the shallow water, in some isolated locations, samples in the northern flow system show isotopically depleted groundwater (-13 to -15.5‰) indicative of cold climate, possibly glacial recharge. This water is significantly older as confirmed by radiocarbon dating indicating 3,000 to 10,000 years before present. At other locations, the sampled deep groundwater exhibits elevated tritium, sodium, and/or chloride, either attributed to quickly infiltrating road salt affected groundwater, or due to interactions with deeper high salinity bedrock water.

6.7 Water Use

Several different of sources are used to obtain a water supply in the province of Ontario, Canada, including lakes, streams, rivers, ponds, and groundwater. By law, any takings greater than 50,000 L/d must obtain a permit from the Province ([Permit to Take Water program](#)[↗], Ontario Ministry of Environment, Conservation and Parks). Ontario manages water takings through the [Ontario Water Resources Act](#)[↗] and the [Water Taking and Transfer Regulation](#)[↗]. Estimates of 2019 water use, attributed to various sectors in Ontario, are summarized in Figure 85a, whereas estimates for 2017, from a different source, are presented in Figure 85b, indicating discrepancies in water-use estimates by sector. These estimates are approximate due to a number of factors, including a lack of accurate records of water use, fragmentation of management, and fragmentation of data necessary to acquire a more accurate picture. Obtaining accurate data on water use in Canada is difficult due to the lack of coordination regarding water-resource management at both the national and provincial levels (Council of Canadian Academies, 2009; de Loë, 2009; Global Water Futures, 2019; Rivera, 2014). A recent initiative of the province was a refinement of the water taking system to require permit holders to annually report their water use. The province has also committed to the public release of the water-use data. To date however,

the data are poorly reported and the province is slow in releasing water use data. The premise that needs to be followed is that accurate data and estimates of water use are necessary as part of the knowledge base needed for management of the resource.

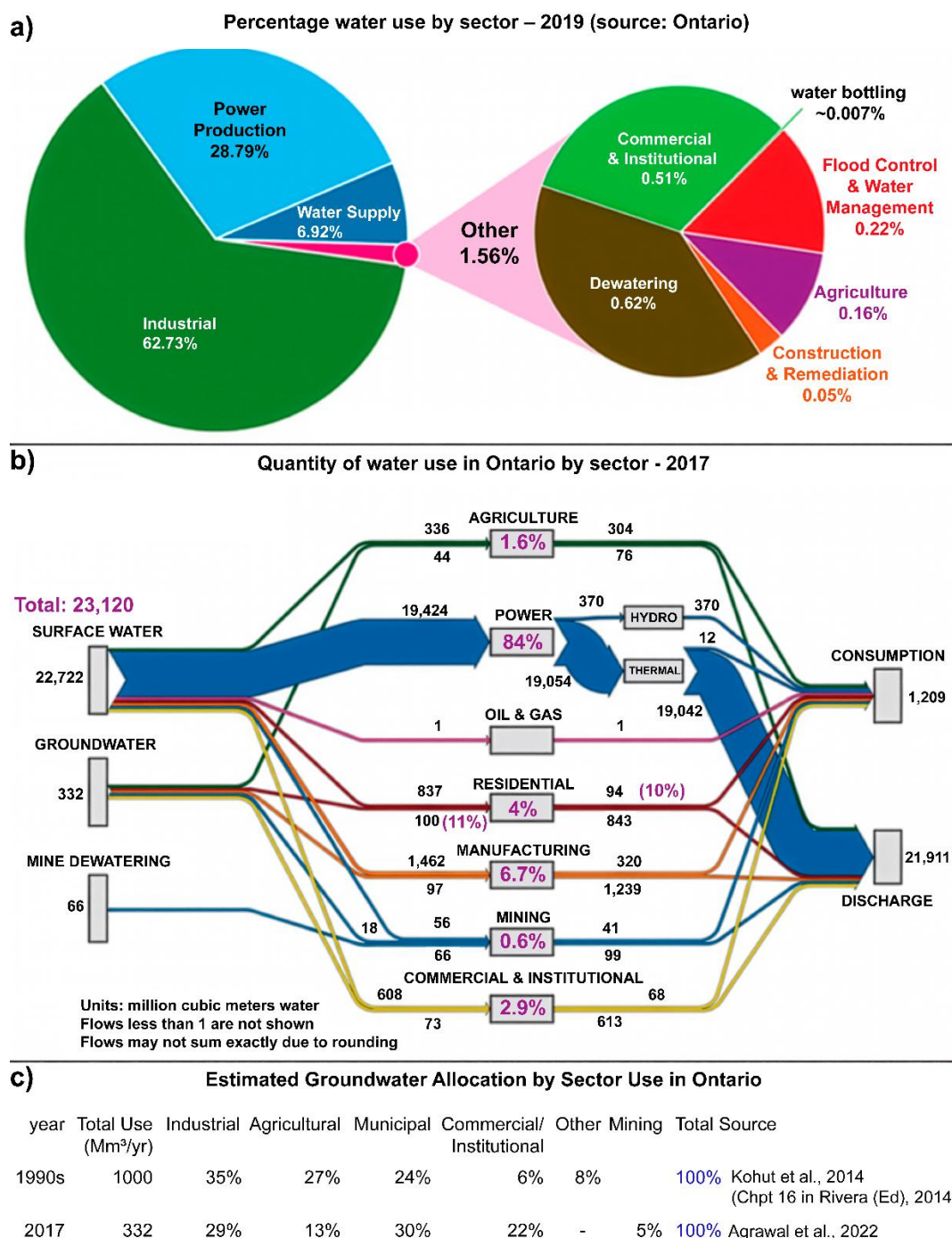


Figure 85 - Estimated freshwater and groundwater use in Ontario. a) Figure from the Province of Ontario's water-quantity management program ([Ontario.ca/page/ontarios-water-quantity-management-program](https://ontario.ca/page/ontarios-water-quantity-management-program)). b) Quantity of water use in Ontario by sector (Agrawal et al., 2022). There is a discrepancy in estimates of water use by sector between (a) and (b) because the data are provided by different sources and accounting for water use and availability in Ontario is inadequate. The Province of Ontario plans to make actual water use associated with water-taking permits available soon as part of its updated water-management strategy. c) The drop in total groundwater use between the 1990s and 2017 could reflect inaccurate estimates or the fact that water efficiency in various sectors has increased. For

example, residential water use in Canadian households serviced by municipal water supplies declined from 342 L/person/day in 1991 to 251 L/person/day in 2011 ([Government of Canada](#)↗).

It is estimated that approximately 30 percent of the Ontario population obtains a water supply from groundwater (Section 16 of Rivera, 2014). Residential use of groundwater is estimated to be 11 percent of the total freshwater use for this sector (Agrawal et al., 2022; Figure 85b). It is interesting that most freshwater for residential use is treated to drinking-water standards but only about 10 percent of that water is consumed, with approximately 90 percent discharged as wastewater (Figure 85b). Largely out of necessity, water reuse and recycling in Canada happens only on a limited basis, and more frequently in arid parts of the country—e.g., agricultural use in British Columbia and the Prairie provinces (Van Rossum, 2020). Water reuse is currently practiced on a limited scale in Ontario (e.g., aggregate washing) but many local governments offer incentives and programs to increase water-use efficiency (e.g., the Regional Municipality of York).

Figure 86 compares quantities of various water reservoirs and uses within the study area of approximately 30,000 km². The average precipitation rate of 900 mm/year is an annual average water volume of approximately 74,000 million liters per day (M L/d). In a closed system, the amount of precipitation that does not evapotranspire will either infiltrate as groundwater recharge or flow as surface runoff, both ultimately contributing to total streamflow, which approximates 30,000 M L/d. The total annual flows for various large rivers within the study area are shown in Figure 86. The Niagara River provides the major input to Lake Ontario and represents a collection of water from the entire upstream part of the Great Lakes watershed extending well beyond the study area. Large municipal water takings from Lake Ontario (Peel Region and the City of Toronto) are a fraction (<0.2 percent) of the 1,640 km³ reservoir (lake) volume on an annual basis (Government of Canada and United States Environmental Protection Agency, 1995). The largest groundwater use within the study area is the York Region -YSA consisting of Aurora, Newmarket, Holland Landing, and Queensville. The region taps the Yonge Street Aquifer (YSA) taking a maximum of 42 M L/d. This can be compared with the Region of Waterloo and the City of Guelph, two large municipal groundwater users situated to the west outside of the study area, who use approximately 100 and 46 M L/d, respectively.

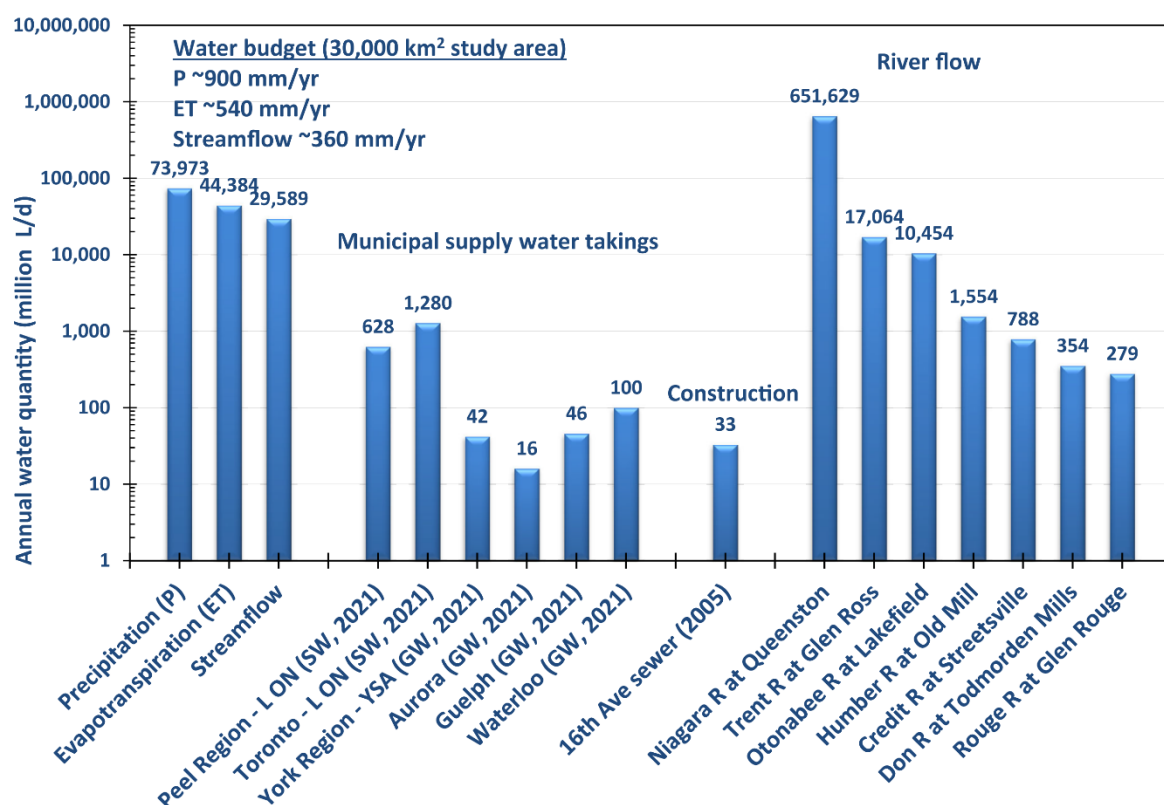


Figure 86 - Annual water quantity comparison for the study area showing approximate water budget quantities. The volume of precipitation on the study area is shown first, followed by the volume of evapotranspiration and streamflow leaving the area. Then, from left to right, large municipal supply takings from either surface water (SW) or groundwater (GW) are shown. This is followed by an example water taken by a large sewer construction project and the average annual flows of large rivers in or near the study area. The Niagara River is outside of the study area, and the average annual total streamflow is provided for comparison with large rivers in the study area. The Niagara River represents flow from the entire Great Lakes watershed and flows into Lake Ontario (L ON). YSA=Yonge Street Aquifer, which is a Thorncliffe channel aquifer situated beneath the communities of Aurora, Newmarket, Holland Landing, and Queensville. Aurora municipal groundwater use is shown as an indication of a large user of groundwater from the YSA. Guelph and Waterloo, situated to the west of the study area, are two of the largest communities in Canada with municipal water supplies either partially or entirely from groundwater.

6.8 Hydrogeologic Summary

The geologic interpretation for the ORMGP program has been built upon literature (Barnett, 1992; Barnett et al., 1998; Boyce & Eyles, 2000; Eyles, 1997; Karrow, 1967; Pugin et al., 1999; Russell, Arnott, & Sharpe, 2004; Sharpe et al., 2002, 2023) as well as borehole geologic descriptions and to a lesser extent groundwater levels within piezometers. While a plethora of geologic research and understanding exists for the study area, the literature contains ongoing debates on the Quaternary stratigraphy, including the origin of key landforms such as the ORM (Sharpe & Russell, 2020; Sookhan et al., 2018; Sharpe & Smart, 2025).

The geological setting of the study area is an eroded Paleozoic carbonate sedimentary basin that onlaps Precambrian rock of the Canadian Shield. The sedimentary rock dips gently westward as part of the Michigan Basin (Armstrong, 1999; Johnson et al., 1992), including the Niagara Escarpment promontory. Friable shale below carbonate cap

rock was eroded preferentially to form the escarpment and a large bedrock depression, the Laurentian valley or trough (Figure 13b). The study area straddles the Laurentian trough that extends from Georgian Bay to Lake Ontario and eastward along the St. Lawrence River valley (Figure 87). Preglacial processes eroded the landscape over time, with further modification occurring during glaciation(s). In addition to glacial erosion, glacial ice at times blocked eastward drainage, resulting in thick sequences of Quaternary glacial and interglacial lake and river sediments being deposited across the study area.

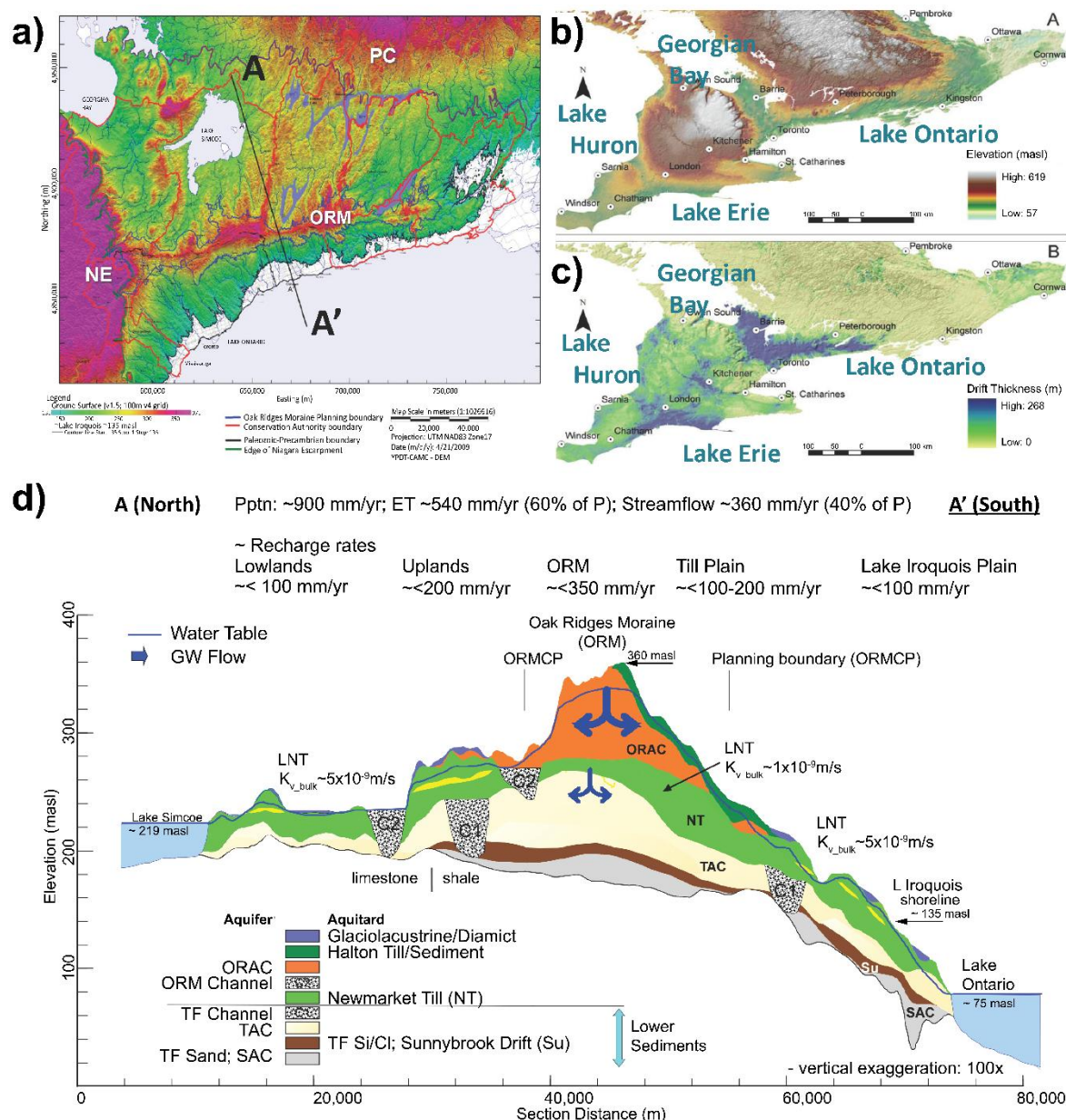


Figure 87 - Conceptual model of the flow system. a) Ground surface topography illustrating uplands (red-purple shade) of the Niagara Escarpment (NE), Oak Ridges Moraine (ORM), and the Precambrian Shield (PC). b) Interpreted bedrock topography showing Laurentian bedrock trough between the Niagara Escarpment and the Precambrian Shield (PC) (from Gao et al., 2006). c) Quaternary sediment thickness with blue indicating the greatest thickness of Quaternary sediments within bedrock troughs and beneath the ORM (from Gao et al., 2006). d) North-south cross section of the conceptual model.

The sparse oldest deposits, resting on carbonate bedrock—York Till—relate to the second-to-last glacial period—Illinoisan. Rare interglacial stream and lake sands of the Don Formation are locally preserved at Toronto. The predominantly glacial, glacio-fluvial, and glacio-lacustrine sediments of the Scarborough, Sunnybrook, and Thorncliffe Formations (Figure 87) were widely deposited between approximately 60 to 20 ka. These thick, regional, heterogeneous sediments accumulated in deep lakes during times when ice blocked eastward drainage of the St. Lawrence. The Wisconsin glacial maximum—approximately 20 ka—is marked by deposition of the dense regional carbonate-rich Newmarket Till, which forms a significant aquitard. Ice-sheet melt and release of meltwater deposited 80 km³ of permeable sediment in the rolling hills of the ORM. Reworked muds of the Halton Till drape western ORM sediment. Postglacial Lake Iroquois and deeply incised valleys record the area's last glacial influence.

The Oak Ridges Moraine (ORM) forms an east–west trending height of land stretching 160 km across south-central Ontario that overlies meltwater-dissected till plains to the north and south. Deposited approximately 13,000 to 14,000 years ago, moraine sediments consist of a series of four overlapping subaqueous fans with predominant east-to-west–fining facies deposited during the waning stages of the Laurentide Ice Sheet. ORM sediments reflect upward-fining gravel, sand, silt, and clay sequences, and east-to-west flow during deposition. Hummocky terrain, with hundreds of both dry and ponded kettle holes, records widespread burial of ice that later melted similar to Icelandic-style meltwater floods and rapid subaqueous sedimentation. High-resolution field evidence suggests that catastrophic-flood-events initiated formation of the ORM, while some researchers support the classical interlobate origin. Glacial floods, beneath the ice, eroded channels through the full sediment stratigraphic package, including the regional Newmarket Till (aquitard), in places to bedrock (Figure 14, Figure 15; Russell, Arnott, & Sharpe, 2003; Sharpe et al., 2004). These subglacial (*tunnel*) channels filled rapidly with gravel, sand, and mud sequences (Figure 14) prior to being overlain by four ORM sediment wedges. These dramatic events and structures shaped the Oak Ridges Moraine landscape and now determine how water flows across, into, and through this immense elevated sequence of porous sediment.

Regional geologic features, ground surface topography, and climate serve as important drivers of the groundwater flow system. A key hydrostratigraphic unit is the Newmarket Till, which separates the shallow flow system from the deeper flow system. Ground surface topographic gradients are approximately 0.01, similar to horizontal hydraulic gradients within the shallow part of the groundwater flow system, whereas within the deep flow system horizontal hydraulic gradients are significantly lower—approximately 0.001. An increase in horizontal hydraulic gradients occurs along areas of steeper topographic slope and near stream reaches and valleys, which function as groundwater discharge areas. Like surface water divides, a groundwater flow divide occurs beneath the ORM and extends through the Quaternary sediment package and into

the shallow bedrock. Groundwater discharge is mainly to streams and wetlands, with a lower percentage of discharge—approximately <10 percent—occurring directly to large lakes such as Lake Simcoe and Lake Ontario. Approximately 60 to 75 percent of the total groundwater recharge is estimated to be discharged from the shallow part of the flow system—above the Newmarket Till—with the remainder replenishing deep aquifers within the Lower Sediment package. Travel times from recharge to discharge are estimated to encompass decades to centuries, depending on the recharge location. Recharge occurring closer to groundwater divides—watershed boundaries—has a greater likelihood of replenishing the deep part of the flow system, as does recharge in areas with channel breaches in the regional Newmarket Till aquitard beneath the ORM. The humid climate leads to relatively shallow water table conditions with water table depth beneath the ORM on the order of 20 to 30 m and elsewhere generally within 10 m of ground surface (Figure 87d). Seasonal fluctuations of precipitation type and amount lead to seasonal fluctuations in lake levels, streamflow, and groundwater levels.

Given the terrain in the 30,000-km² study area and some approximately 75 percent of the total recharge discharging from the shallow system to rivers/streams and small kettle lakes, the ORM setting lends itself to the formation of local and intermediate flow systems as described by Tóth (1963) and Freeze and Witherspoon (1967). Local flow systems form in the shallow sediments above the Newmarket Till, and an intermediate flow system extends into the Lower Sediments beneath the Newmarket Till. This classification is similar to that of Novakovic and Farvolden (1974) for the Big Creek and Big Otter Creek watersheds west of the study area that drain into Lake Erie. Lower Sediments generally do not crop out in the study area except in discharge areas along deep river valleys near large lakes such as Georgian Bay, Lake Simcoe, and Lake Ontario. Here the deeper aquifer complexes likely contribute groundwater to the lower reaches of the streams that headwater on the moraine. Groundwater flow within bedrock is considered negligible except in localized karst areas along the Niagara Escarpment as well as to the north and northeast. While regional flow systems within bedrock are not considered to occur within the study area, there are examples of such systems immediately west of the Niagara Escarpment in the Michigan and Appalachian Basins (Carter, Fortner et al., 2021).

The study terrain contributes several significant features to the conceptual model. Large-scale geologic features including bedrock valleys, continental ice sheet tills, and large glaciolacustrine and glaciofluvial lakes create a setting that can be discussed as areas of similar geology and hydraulic behavior:

- Oak Ridges Moraine crest and flanks,
- till plains,
- channels, and
- bedrock valleys.

These features are the key components of the flow system conceptual model and can be used to guide groundwater management and monitoring decisions.

Although there is some seasonal variability in the groundwater level response, typically the highest groundwater levels occur in late March through April. This corresponds to the time of year when the snow melts, prior to the onset of the summer growing season when evapotranspiration is a key driver of the water budget. During this period surplus water infiltrates to recharge the groundwater system. Then water levels decline throughout the summer, reaching their lowest levels in late summer and early fall, before slowly recovering. Deeper wells tend to show a lag in this typical response. The magnitude of seasonal water level fluctuations varies depending on the local hydrogeological setting. A typical range of variability is about 1 to 2 m; however, in extreme years, water table and confined aquifer groundwater levels have been observed to vary up to 5 m.

Longer-term trends in groundwater levels have been muted, showing no regional upward or downward trends. Where longer-term, multiyear trends have been observed, they are generally associated with pumping from deeper municipal wells or larger infrastructure projects such as sewer construction and long-term climate trends of increasing or decreasing precipitation. In cases where pumping is the cause, water levels typically recover, often quickly, when pumping stops. The groundwater system across the study area is resilient in this regard.

In terms of groundwater chemistry, the most common water type is a Ca-Mg-HCO₃-dominated water, indicative of reasonably fresh meteoric water. Other water types where cation exchange has occurred and where bicarbonate is less dominant are rare; and are usually encountered at greater depths. The most widespread and pervasive contaminant issue is that of road-salt use leading to elevated levels of sodium and chloride in groundwater near salt storage facilities and along roadways across much of the study area. Given that the study area is characterized by extensive agricultural areas interspersed with urban centers, other possible contaminants include nutrients, pesticides, and emerging contaminants such as PFAS compounds. Data are currently being collated on a regional basis to determine whether there are any other widespread contamination issues within the study area.

7 Management and Governance

7.1 Introduction

As in many jurisdictions, in Ontario the complexity of managing groundwater is reflected in the large number of government agencies, at several levels, that contribute regulations, rules, guidelines, and general oversight to control the human activities that may affect the groundwater system. Three levels of government—federal, provincial, and local (i.e., municipal and conservation authority) have interest in water management in general, and groundwater in particular.

The federal government plays a limited role in water management in Ontario, as well as in other provinces, having provided provincial governments with legislative authority over natural resources, including most water-management responsibilities. The federal government has legislative powers over water on federal lands—for example, national parks and military bases—and has jurisdiction over interprovincial and international water (for example the International Joint Commission between the United States and Canada) and fisheries. Along with its provincial counterparts, the federal government can play a role in other water-management activities, including environmental assessments, setting water-quality standards, monitoring, planning, and research.

At the provincial level, the Ministry of the Environment, Conservation and Parks (MECP); the Ministry of Northern Development, Mines, Natural Resources and Forestry; and the Ministry of Municipal Affairs and Housing take on significant roles in groundwater management and protection by setting broad water-use and land-use directions. The Ministry of Health and the Ministry of Agriculture, Food and Rural Affairs also play water-management roles, albeit at a more limited scope. At the local level, largely through the many submitted applications to alter land use, additional oversight and implementation of several groundwater management activities is carried out by municipal governments and conservation authorities. Actions and decisions at this local level must be consistent with directions from provincial legislation; however, these local decisions often have the greatest consequences for Ontario's groundwater resources. In Ontario, therefore, effective groundwater management should involve all levels of government and all departments within organizations that are involved in decisions that influence land use, resource use, servicing, and infrastructure.

Local government bodies, working within the guidance and policy framework as set out by the province, make some of the decisions that most affect groundwater. For example, municipalities are responsible for providing drinking water and sewage services to their residents. Away from the Lake Ontario shoreline, the water source is frequently groundwater. Communities such as Uxbridge, Newmarket, Caledon East, and Georgetown all have high-capacity municipal supply wells to service their communities. Other types of

regular, day-to-day municipal activities, ranging from land use approvals to decisions related to road-salt applications, can also significantly affect the groundwater system.

Table 7 provides an overview of the roles that each government level has in ensuring sound management decisions with respect to Ontario's groundwater resources. Given that Ontario has the largest role, Table 7 is centered on Ontario's legislation in the middle column, with the main thrusts of each Act presented. To the right and left are the somewhat lesser roles that the federal and local governments play with respect to each Act.

Table 7 - Government responsibilities in the management of Ontario's water resources.		
Federal	Ontario	Municipal (Local) Conservation Authority
	Water Resources Act	
	Manages water takings and transfers Issues approvals for sewage and water works Prohibits discharge of pollutants into water	Compliance in management of sewage and water waste
	Environmental Protection Act	
Federal lands and interprovincial and international waters	Prohibits discharge of contaminants to environment Regulates waste disposal sites Regulates deep well disposal	Ensure compliance in management of waste disposal sites
	Environmental Assessment Act	
Federal lands and interprovincial waters	Primary environmental statute Public sector initiatives must be designated to be covered by act Proponents required to identify, evaluate, and mitigate ecological (and other) impacts	Ensure compliance when undertaking large road/sewer/water/other infrastructure projects
	Safe Drinking Water Act	
	Provides for the control and regulation of drinking-water systems including testing of water at accredited labs	Ensure compliance in operation of water works systems
	Clean Water Act	
	Requires communities, through Source Water Protection committees, to assess threats to drinking-water supplies and take steps to reduce or eliminate them	Carry out technical and planning work related to WHPAs; determine and reduce/eliminate threats to drinking-water supplies
	Nutrient Management Act	
	Requires farm operators to develop plans for nutrient management as part of overall source water	
	Other legislation	
Fisheries Act	Planning Act	
Environmental Assessment Act	Places to Grow Act	
Canada Water Act	Greenbelt Act	
	Municipal Act	
	Niagara Escarpment Act	
	Municipal Act	
	Conservation Authorities Act	
	Lakes and Rivers Improvement Act	
		Approval of land use change applications, ensuring compliance with provincial legislation

The most recent changes in Ontario legislation came about because of the May 2000 tragedy in Walkerton, Ontario, Canada, where seven people died after consuming *E. coli*-contaminated municipal groundwater (O'Connor, 2002). This led the Ontario government to embark on a long-running and continuing journey to ensure safe drinking water for Ontarians. The Source Water Protection (SWP) program, a pillar of this work, was brought forward under the 2006 Clean Water Act.

7.2 Groundwater and Decision-Making in Ontario

As in many parts of the world, societal decisions that affect groundwater resources in Ontario are often made without an awareness of their full potential impact on groundwater. This is largely owing to the out-of-sight-out-of-mind nature of groundwater, as well as a lack of understanding of how the groundwater system is connected beneath the landscape. In addition, long-term monitoring data in Ontario is sparse, especially with respect to data focused on understanding the short- and longer-term impacts of land use change on groundwater quantity and quality. Decisions have been made based on assumptions and without sufficient knowledge of the potential for longer-term detrimental impacts on the overall groundwater flow system. By providing access to groundwater data, knowledge, interpretations, and understanding, the ORMGP has set out to improve upon decision-making practices.

As outlined in Table 7, many pieces of legislation are aimed specifically at groundwater and its ongoing management. For example, under Ontario's Water Resources Act, the province issues Permits to Take Water (PTTW), and where the taking involves the pumping of large quantities of groundwater, a hydrogeological assessment is typically required for review prior to the province granting or denying a PTTW. However, the cumulative impact of many small land use changes over longer time periods is generally not addressed. For example, municipalities are responsible for keeping roads clear of snow during winter months, thus road-salting materials have been applied by municipalities over many years with little forethought to groundwater, and has impacted groundwater quality (Marchildon et al., 2022). It is only recently that an effort has been made to minimize salt loading to roads, especially in areas with more vulnerable groundwater conditions such as coarser soils with shallow water tables.

Municipalities also approve land use decisions that drive new development. The impacts of such land use changes on the groundwater system, either through the alteration of recharge, the increase in water demand, or the introduction of urban contaminants—e.g., miscellaneous spills and lawn nutrients—to the subsurface are not a key consideration in these types of decisions, especially in areas that do not rely upon groundwater as a drinking-water source.

In an Ontario planning context, decisions with respect to individual land use applications “shall be consistent” with the provincial policy statement (PPS), which was

updated in 2020. The PPS requires that vulnerable or sensitive groundwater features and their function be protected, improved, or restored. If no groundwater feature—e.g., recharge/discharge areas, water table, aquifer—is recognized or identified with respect to a development application, then no further consideration of groundwater is necessary. Nonetheless, in practice, hydrogeological studies undertaken to support development applications frequently provide recommendations that attempt to maintain predevelopment water budgets. At a local site scale, groundwater features might not be found or detected, although long-term monitoring data is lacking. Rather, it is likely that when taking a step back to consider the regional scale, an increase in impervious surfaces across the landscape due to urbanization would significantly affect the groundwater system, including features that might be more distant from urbanizing development areas.

At a broader level, the PPS also mentions that the long-term ecological function and diversity of the natural heritage system should be maintained, restored, or, where possible, improved. However, the natural heritage system incorporates only select stream valleys and wetlands, and the groundwater contribution or linkage of any single land use change to the broader, perhaps somewhat distal, natural heritage system is difficult to quantify. The PPS fails to address the groundwater system as a whole and that is where improvements could be made.

7.2.1 ORMGP – Thinking Differently

Two significant, comprehensive publications on groundwater in Canada (Council of Canadian Academies, 2009; Rivera, 2014) have outlined several needs with respect to improving Canada's groundwater understanding and management. In both reports, the collection, maintenance, management, and accessibility of groundwater data has been emphasized, as has the analysis of these data to better understand groundwater flow systems and aquifer characteristics. Beginning in 2001, well before these reports were prepared, the ORMGP had positioned itself to fill these and additional needs within a large southern Ontario study region. With an initial focus on data collection and management, over time the ORMGP came to actively manage and make accessible some 100 gigabytes of water-related data and information. The term *actively* is meant to convey that the database is routinely updated with data and information—e.g., new wells, water levels, and water-quality samples—and fixed or corrected as errors are detected. A standardized database schema with robust protocols allows for a wide variety of water-related data—e.g., precipitation, water levels, chemistry, and stream flows—to be readily housed in the ORMGP database. With connections to regional government agencies, provincial ministries, conservation authorities, the federal government, and consulting companies, the ORMGP fosters cross-pollination of ideas between staff from many different agencies and serves as a foundation for the management of Ontario's water resources.

A prime requirement for managing any resource is a sound, reliable set of data from which managers can perform tasks such as monitoring water use, detecting

quality/quantity trends, and establishing benchmarks. This allows for data-driven, scientifically sound decision-making. However, Ontario, as do other parts of Canada and the world, lacks legislation that focuses on broad-based, long-term data collection and management. Recent water data acts (e.g., New Mexico, <https://newmexicowaterdata.org/> and California, <https://water.ca.gov/ab1755>) envision a data-management schema similar to the one that has been in place under the ORMGP since 2001. The pyramid diagram discussed in Section 1 (Figure 2) provides an overview of the basic structure of the ORMGP (www.oakridgeswater.ca) with data as the foundational pillar upon which understanding of the flow system, and ultimately decision-making, is built.

Since its inception in 2001, the ORMGP has recognized several issues and trends that have guided the program. Those that resonate the most include the following:

- there is fragmentation and lack of ready access to water-related data and interpretations (i.e., knowledge) that have been collected for projects commissioned for government agencies at all levels;
- regardless of the scale of a decision to be made (i.e., ranging from Great Lakes Basin-wide to aquifer-focused to site-specific to stormwater pond) the data from any individual water body/aquifer can be used, either solely or as part of an amalgamated dataset, as an input to decision-making;
- ongoing retirement of experienced water managers and technicians results in loss of considerable knowledge of Ontario's groundwater and surface-water resources that is not documented;
- there is discontinuity and fragmentation of long-term, local technical knowledge among professional staff, especially at the provincial level, due to an absence of technically focused career path opportunities; and
- larger societal changes will require effective longer-term data management to elucidate trends and enable effective decision-making to address emerging problems such as climate change, ongoing degradation of water quality from road salt and other contaminants, and recharge reduction due to urbanization.

Such trends have resulted in the ORMGP focusing on knowledge management and the transfer/dissemination of that knowledge not only to today's practicing technicians and decision-makers at public-sector agencies and consulting firms, but also to new and future technical practitioners as well as the community. This direction of focus makes the ORMGP unique as a local government-led program in Canada.

Areas encompassed under the ORMGP benefit from the program in that water-resource-related data, including geological, hydrogeological, and hydrological data, have been assembled and are managed (e.g., routinely reviewed, analyzed, and corrected) in a comprehensive, centralized database. With the ORMGP connected to a wide range of program partners, data within the database:

- can be contributed by any partner agency, including federal, provincial, and local government agencies, academia, and consulting firms;
- can range from current to historical;
- can be related to water quality or quantity;
- is linked to its source, including wells, streams, and aquifers; and
- is readily accessible for use by the agency's staff and the public via the ORMGP website (www.oakridgeswater.ca↗).

Because of application programming interfaces and other newer technology that allows for remote database connectivity via the internet, it is becoming less of a priority for data to be imported and directly incorporated into the ORMGP database, because data can be readily accessed from partner databases. Any external database must be properly managed to be accessed and effectively used alongside ORMGP data. Rigor in data management is becoming more common in Ontario and elsewhere as technological advancements continue to lead to more ways of effectively gaining insight from data.

7.3 ORMGP - Groundwater Management Through Knowledge Transfer: An Innovation Hub

In the past 10 to 20 years, both public-sector agencies and private corporations have come to recognize the importance of the need to manage information more effectively. In the case of a resource that is as disparately managed as groundwater, decision-making would benefit from a system that captures and organizes the collective memory of the many individuals and organizations, both public and private, that play a role in the management of Ontario's water resources. Water-resource knowledge can be found in sources such as corporate and individual databases, filing cabinets, reports, and staff knowledge and experience at all three levels of government—federal, provincial, and local, both municipal and conservation authority—as well as within the private sector. Indeed, the development of a comprehensive Environmental Knowledge Management strategy was a key recommendation arising from a 2001 Ontario-focused report, *On Managing the Environment* (Gibbons, 2001).

There is great economic value in the subsurface information that can be extracted from historical works. Consider the expense of drilling new wells, or the expense of flawed construction projects, for example, because of unexpected groundwater conditions. It has been estimated that the value accumulated within the ORMGP amounts to nearly \$1 billion CAD (Box 2↗), which documents only the costs of acquiring groundwater information and not its value related to groundwater decision-making—e.g., construction, infrastructure, and health and environmental protection. Thus, giving out-of-sight groundwater-based knowledge management higher societal priority is warranted.

With the increasing attention on water resources in Ontario since the Walkerton tragedy, and as demand for water increases due to population growth simultaneously with

climate change uncertainty, it is critical that groundwater practitioners in Ontario collate knowledge about our water resources. It can be difficult to determine which government level/agency or private-sector agency is best positioned to maintain groundwater-based knowledge, as illustrated by considering the following questions.

- How should it be remembered that there are significant localized artesian flowing conditions in High Park in Toronto, along Major Mackenzie Drive in Richmond Hill, or along Horseshoe Valley Road near Barrie?
- Who should remember that the Thorncliffe Formation contains a productive coarse-grained gravel channel at the location of the recently excavated sewer dewatering shaft along 16th Avenue in Markham?
- Who should make note of the locations of springs and former streams in the City of Toronto and other urbanized areas that may significantly affect current construction costs?
- How effectively are the locations of known trout spawning beds—groundwater discharge areas—incorporated into land use and stormwater-management decision-making?

Might decisions be improved and, perhaps equally important, might money be saved over the long term if these and other elements of the groundwater flow system were readily known by all? Remaining unaware of what is collectively known leads to duplication, re-invention, and waste (Australian Local Government Association, 2004). The ORMGP is tackling this issue head on. Concrete examples of this are presented as knowledge transfer described in the following subsections.

7.3.1 Knowledge Transfer 1 – Groundwater Knowledge/Insight Stories

One creative way to ensure ORMGP knowledge transfer is by collecting groundwater knowledge/insight stories that are mapped across the program area (Figure 88). Upon selecting a location on the map, users are provided with a short synopsis of a groundwater story that has been collected from hydrogeologists who have long been in practice in Ontario's groundwater community. By collecting and presenting these stories over time, a cumulative knowledge of unique hydrogeological settings emerges.

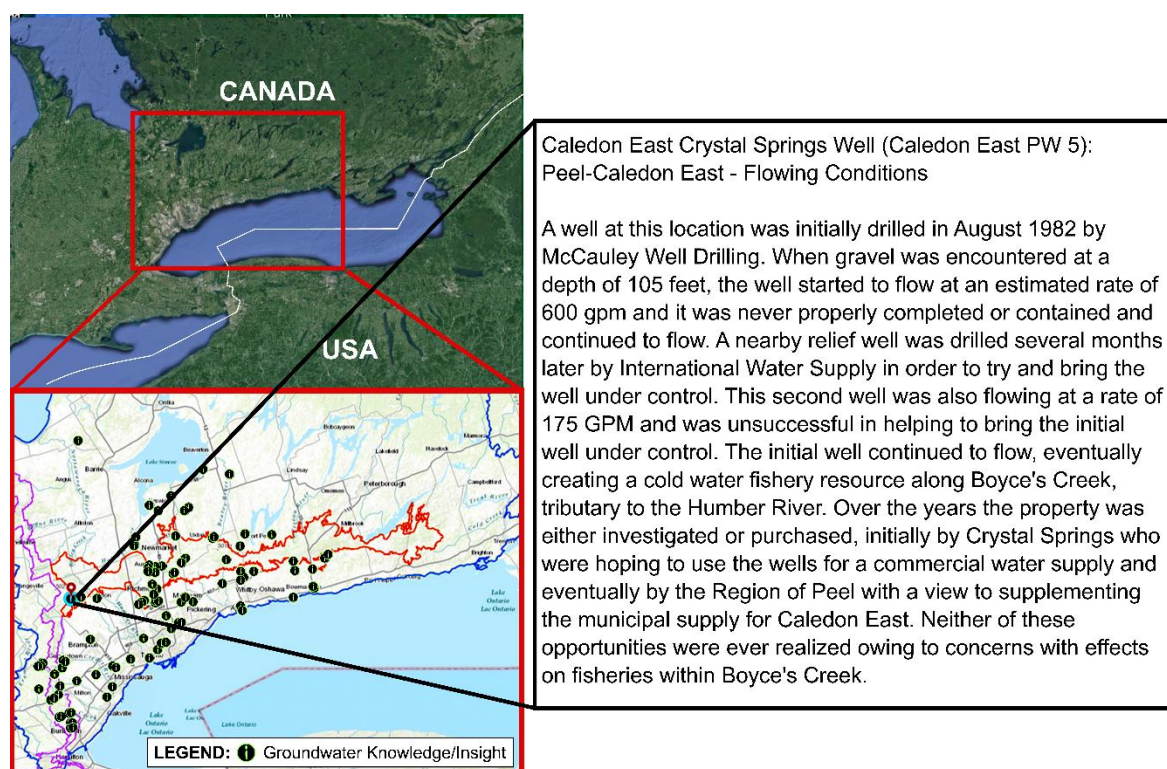


Figure 88 - ORMGP Groundwater knowledge locations. These locations are sites of collective experience of subsurface conditions of note collated by the ORMGP that are intended to inform future activities. Locations can be further explored at www.oakridgeswater.ca/—at Maps under the Locations map theme—or at [ORMGP-Maps-Locations theme](#).

This mapping tool allows for knowledge of sites where unusual groundwater conditions were encountered, many of which have proven costly to address (e.g., artesian flowing conditions or unusual groundwater quality), to be transferred to the present day in a simple, effective, straightforward manner. This enables those undertaking subsurface works in areas adjacent to any of these mapped stories to quickly gain access to actionable advice from the past. In making decisions regarding groundwater, which is “out of sight, out of mind” unless up-and-coming water managers have ready access to knowledge gained in the past, they are largely condemned to unnecessarily inefficient progress and to repeating costly mistakes. These locations and their stories are also used to evaluate interpretive products, such as aquifer mapping, or water table and potentiometric surface maps, which of course must accurately portray the hydrogeological conditions that were encountered at these locations.

7.3.2 Knowledge Transfer 2 – Groundwater Documents

A key ORMGP knowledge-management plank is to make available searchable reports and papers that are relevant to the groundwater resources of the study area. Key reports have been scanned, converted to recognizable characters, and catalogued into a digital library with assigned coordinates so that they can be located quickly on a map (Figure 89). The reports are searchable within the database on any number of key fields, such as author, author agency, client, title, year, and keywords, along with text searching—

using optical character recognition, or OCR—capability. The digital report library is proving to be significant in capturing and organizing groundwater knowledge so that it can be readily brought to bear on current groundwater concerns.

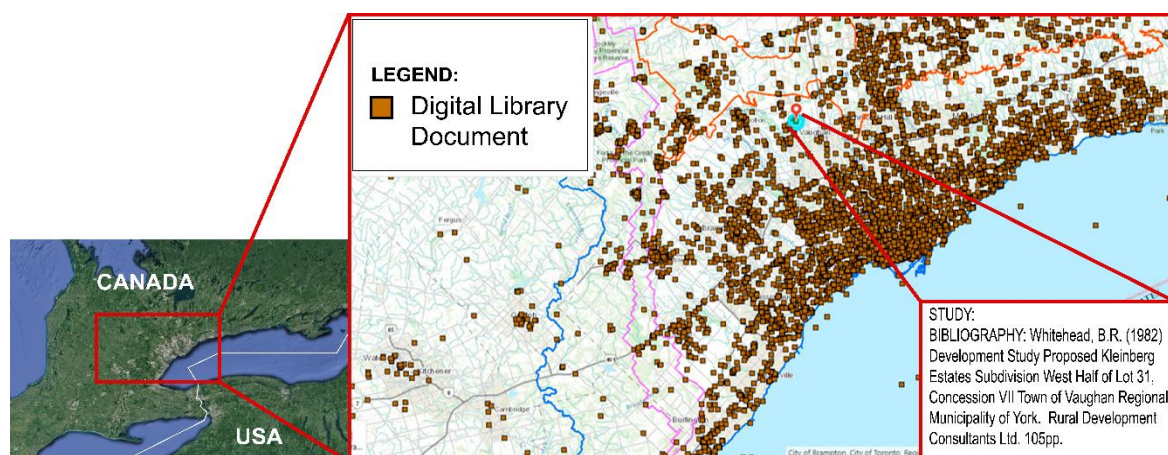


Figure 89 - ORMGP digital library locations.

7.3.3 Knowledge Transfer 3 – Raw Data Plus Interpretation

In a broader approach to knowledge transfer, the ORMGP is providing access to not only raw data but also to interpretations of the data. Database users can download raw water levels and other data from the ORMGP database and undertake their own analyses to determine subsurface attributes such as groundwater flow directions and depths to the water table. However, ORMGP recognized that this takes time, and that the same types of analyses could very well be repeatedly undertaken by different professionals, perhaps using different methodologies, to arrive at similar results—a hallmark of inefficiency. Availability of benchmark authoritative interpretations/maps that are periodically updated through the ORMGP, provides a broad-based benefit. Professionals outside of the ORMGP are welcome to provide input on materials such as interpreted maps and graphs as well as newly collected data so that updated renditions are improved for all.

One example of such an interpretive map is the water table surface (Figure 90). Using only wells where the screen is less than 20 m below ground, the static water levels have been interpolated to derive a water table surface. The resultant surface compares favorably with results obtained from numerical models. When the user zooms in to a specific area of interest, the contours automatically adjust so that the elevation of the water table is apparent, the data points to generate the surface are shown, and the direction of groundwater flow—perpendicular to contour lines—is also evident. Such mapping, while considered a regional map constructed from a regional data set, is effectively a regional scale map that is also locally accurate and functions as a compilation of local water table information based on the data available for the area.

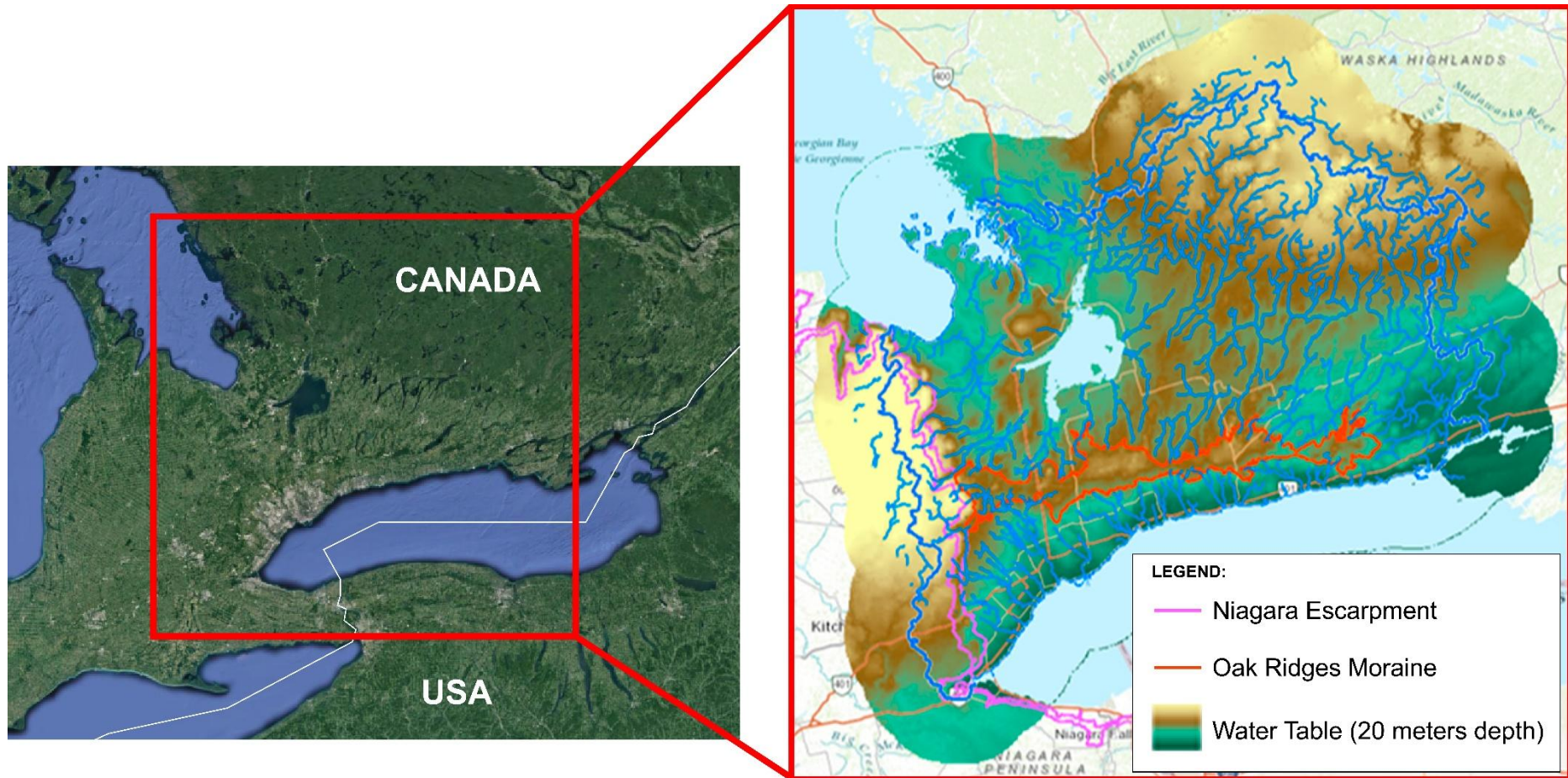


Figure 90 - ORMGP-interpreted water table elevation, rendered from groundwater-level information for wells screened within 20 m of ground surface. Interpreted water table elevation, and the interpreted depth to the water table, mapping can be further explored at [ORMGP-Maps-water table theme](#).

By subtracting the water table surface from the ground surface, the depth to water table map is also readily prepared. This map can be used, for example, to determine whether subsurface construction activities might anticipate the need for dewatering. Providing access to a regional water table map that has been constructed using a documented and reproducible process has benefited the local groundwater community.

7.3.4 Knowledge Transfer 4 – Numerical Modeling

Across Ontario, in response to the previously mentioned Walkerton tragedy of May 2000, the provincial government embarked on a Source Water Protection strategy that involved numerical modeling to delineate wellhead protection areas for municipal drinking-water supply wells. It is estimated that on the order of \$50 million (CAD) was spent to retain consulting firms to build numerical models across different parts of the province. The resultant models had a wide range in their geographic scales and in the complexity built into the conceptualization of the geology. Groundwater modeling can create unique opportunities to gain insight into groundwater flow systems. The modeling process requires that a wide range of data and understanding be synthesized and built into a robust modeling framework. When done thoroughly, considerable insights and knowledge are contained in the numerous model-related files and the accompanying documentation. For this reason, the ORMGP made a significant effort to establish a numerical model custodianship program. This program has ORMGP staff obtaining model documentation and all files needed to run the models, adding them to the numerical model library, and subsequently making models available to other practitioners for future use through standardized model-sharing agreements (Marchildon et al., 2017).

The ORMGP numerical modeling program manages numerical models as living entities with the vision that numerical models will be updated and improved as new data are collected and new insights or knowledge are gained. This pathway reflects the central tenet of the ORMGP—capturing and building upon previous knowledge. This overall model management direction, and in particular the concept that select models will be improved over time by different consultants or agencies through a versioning archival system, is uncommon. More typically, groundwater models are prepared to address only a particular issue and are then set aside and essentially abandoned once the goal is accomplished.

Figure 91 shows the extent of the numerical models held in the program. Models are made available by contacting ORMGP staff; however, the initial reports related to the construction of any numerical model are available for download on the ORMGP website.

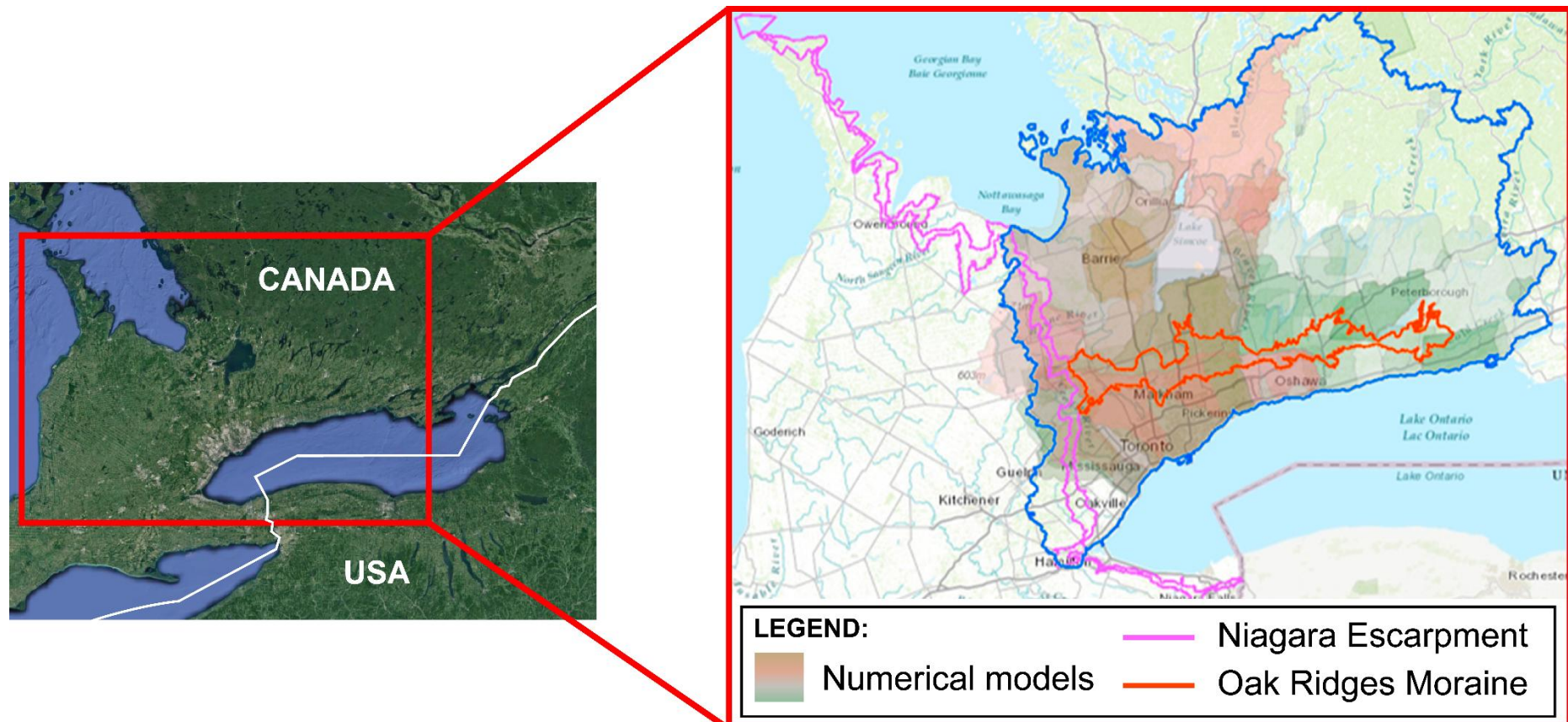
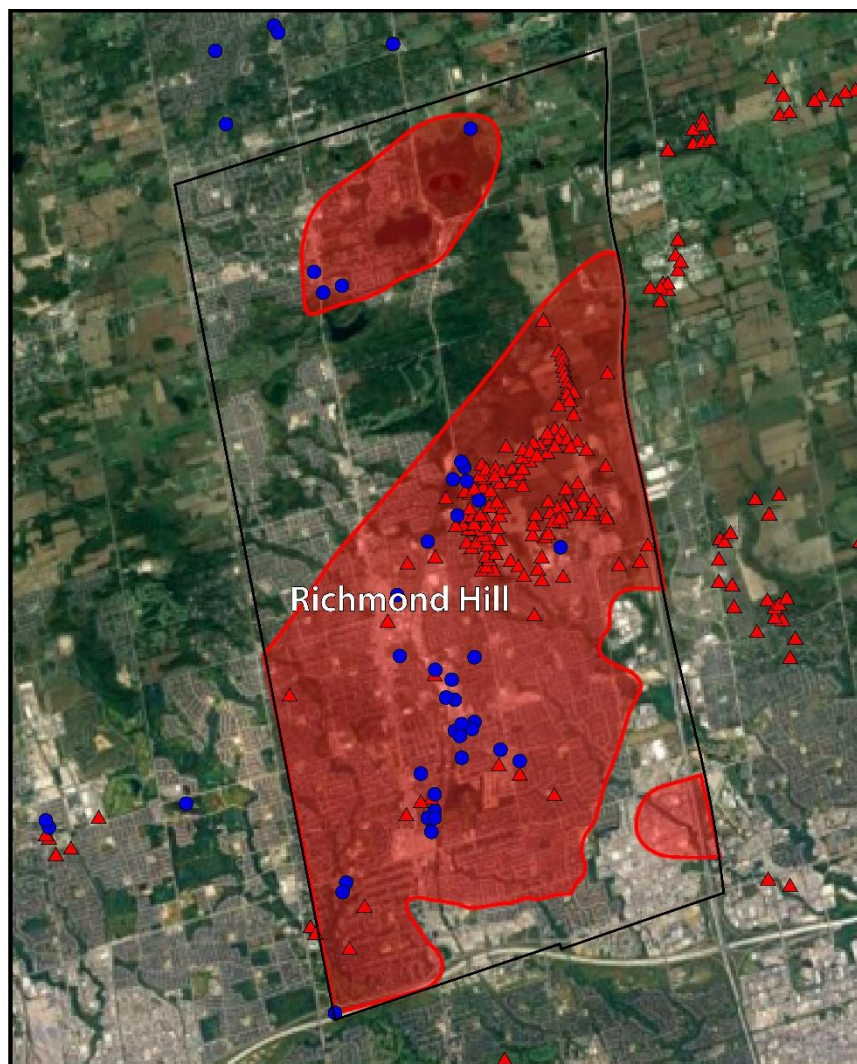


Figure 91 - ORMGP numerical model archive. More than 90 models in the archive have been constructed since 2002. Numerical models in the ORMGP numerical model archive can be further explored at [ORMGP-Maps-numerical models theme](#)⁷. Information on the ORMGP numerical model custodianship program is available at [ORMGP - numerical models](#)⁷.

7.3.5 Knowledge Transfer 5 – Groundwater Areas of Concern: Pulling it all Together

ORMGP staff have recognized that the amount of groundwater-related information available through the ORMGP is immense. To facilitate and improve the incorporation of this information into the decision-making process, ORMGP and partner staff have begun an initiative to synthesize the available data into actionable maps. Working with partnered agencies, which often have the greatest local groundwater knowledge, ORMGP staff have initiated a series of technical memos and maps known as groundwater Areas of Concern mapping. By analyzing and synthesizing information held in the ORMGP database (including: water levels, flowing wells, surficial geology, three-dimensional geologic interpretation, cross-section analysis, groundwater flow model results, streamflow and baseflow analyses) these maps highlight areas where potential groundwater problems—such as flowing conditions, upward hydraulic gradients, and shallow productive aquifers—are likely to be encountered in the subsurface. Such areas can result in additional cost, sometimes significantly higher than normal, for subsurface construction activities. The maps, of which Figure 92 is an example, are being used by municipalities and conservation authorities to increase landowner/developer awareness as to the groundwater conditions beneath their property. In these mapped areas, additional drilling and precautionary measures might be required by the municipality prior to construction activities being approved. In the example shown in Figure 92 for the City of Richmond Hill, groundwater areas of concern occur along the south flank of the ORM where the ORAC becomes confined by and pinches out beneath the overlying Halton Till. This leads to upward vertical hydraulic gradients, stream headwater formation, and flowing well conditions (Figure 93). Subsurface activities such as construction require extra care in these areas to avoid problems that could be avoided if the concern is known at the start of the project.



Legend:

- Knowledge – groundwater
 - ▲ Flowing wells
 - Richmond Hill
groundwater Areas of Concern
- August 30, 2018

Figure 92 - Example of a groundwater Area of Concern map for the City of Richmond Hill completed by the ORMGP and Regional Municipality of York staff. To date, six technical groundwater Areas of Concern memos have been prepared and are available at <https://www.oakridgeswater.ca/resources/?rc=areas-of-concern> under Publications & Reports/Areas of Concern. 'Knowledge-groundwater' locations are where historical problematic subsurface conditions have been encountered.

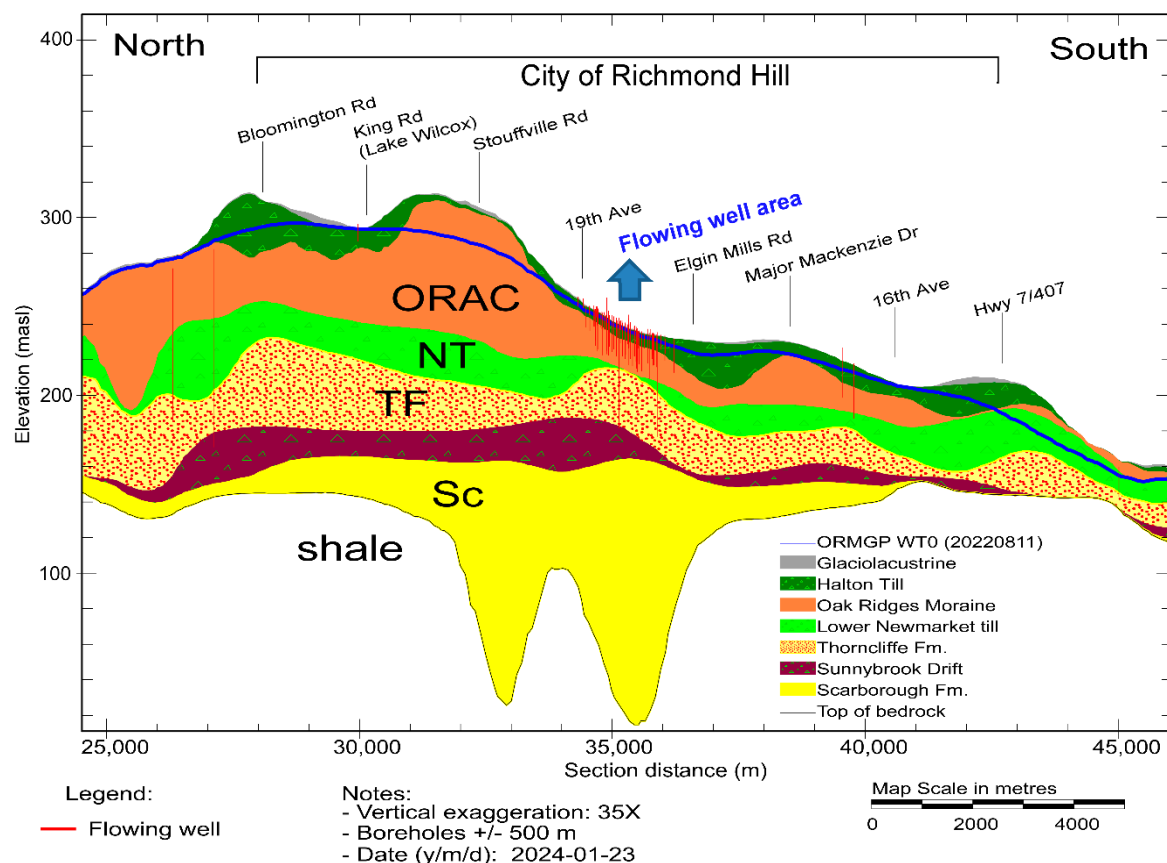


Figure 93 - North-south cross section through the center of the city of Richmond Hill (Figure 92) illustrating subsurface conditions leading to flagging groundwater areas of concern. The flanks of the Oak Ridges Moraine are characterized by steep topographic slopes. Along the north slope, the water table within the ORAC intersects the ground surface, leading to stream headwater and spring formation. Along the south slope (e.g., in the city of Richmond Hill), the ORAC becomes confined by, and pinches out beneath the surficial Halton Till, leading to stream headwater formation and flowing well conditions. Groundwater levels in wells along the south slope can locally approach up to 10 m above ground surface. In these flowing well areas, excavators must be cognizant of water ingress from the regional aquifer (ORAC) and basal heave (Canadian Geotechnical Society, 2006) conditions created by subsurface groundwater pressures. Groundwater areas of concern technical memos completed for the study area are available at <https://www.oakridgeswater.ca/resources/?rc=areas-of-concern> —Publications & Reports/Areas of Concern—(geologic interpretation from Earthfx Inc., 2014b).

7.4 Summary

Today in Ontario, it could be asked whose responsibility it is, if indeed it is anyone's, to house groundwater-resource knowledge and make it more user-friendly, analyze it, and finally make it accessible to practitioners to improve overall decision-making. Should such a task be undertaken by the public sector, and if so at what level—i.e., federal, provincial, or local? Or is it better overseen by the private sector on a for-profit or even a not-for-profit basis? Too often, these questions go unanswered and there is no coordinated effort to consolidate groundwater knowledge.

For an extended period in Ontario's water-resource development history, the responsibility for collecting groundwater data and information as well as managing and understanding Ontario's water resources, including groundwater systems, was borne by the province. With changes in priorities, increasingly restricted budgets, and a decrease in staffing levels, water-resource-knowledge management in Ontario's public sector

splintered and declined. This left a gap in the management and understanding of Ontario's water-resource data.

In Ontario, considerable and costly groundwater-related work has been undertaken since the Walkerton crisis of May 2000 through the province's Source Water Protection directives. It is important that this significant provincial investment be effectively used and built upon. In areas outside of the ORMGP, the data, knowledge, and understanding gained through SWP are in danger of winding up on the shelves—and subsequently the recycle bin—if a concerted effort to harness and build upon the work is not undertaken. Locally led initiatives such as the ORMGP, whereby local-level (e.g., regional municipalities and conservation authorities) public-sector agencies have collectively pooled resources, have proven to be effective in assuming this groundwater-knowledge management responsibility. Groundwater-related data are being thoroughly and carefully collected, analyzed, and managed within the ORMGP. By extension, groundwater flow systems, including links to the surface, and the associated implications for planning and municipal servicing, are more accurately characterized and understood, leading to sounder water-management decisions and policy. Also, having the information, knowledge, and tools readily available has meant that groundwater is being considered in situations and issues; in the past, this was not always the case. The ORMGP provides the direction forward to address this gap in the management of Ontario's water resources. At its essence, the strength of the ORMGP program is that it provides a forum and template for interaction and ongoing discussion for many different agencies, thereby creating a more collaborative approach to various water-resource management endeavors and solutions and avoiding duplication of effort. This is important in a limited-funding environment.

8 Future Issues and Tasks

Southern Ontario will continue to urbanize, with ongoing pressures on the groundwater resource. These pressures will include:

- additional requirements for groundwater takings, especially in areas more distant from the Great Lakes;
- maintaining functioning aquatic ecosystems as increasing urbanization and its accompanying subsurface infrastructure continues to affect groundwater flow systems;
- diminishing interest in groundwater as communities intensify and switch from groundwater-based to Great Lakes-based drinking-water supplies;
- understanding the potential impacts of denser urban development (i.e., deeper construction that frequently leads to increased need for groundwater control via dewatering or depressurization often in perpetuity, to maintain dry conditions);
- continued compliance with Ontario's Clean Water Act and its requirements to manage threats to municipal drinking-water supplies;
- maintaining groundwater quality in light of studies that continue to indicate substantial groundwater—and surface water—quality degradation from road deicers, agricultural fertilizers and pesticides, and emerging contaminants (e.g., PFAS, pharmaceuticals, antibiotics; Pradhan et al., 2023);
- the need to educate both urban and rural residents on the role of groundwater in supplying drinking water and in maintaining Ontario's healthy natural environment; and
- the need to understand how climate change will affect Ontario's water resources.

Having established a solid underpinning based on data and data management, the ORMGP's foundation is one that can be built upon and capitalized upon to address Ontario's water-resource management. A central tenet of the ORMGP and of this book is that effective water-management decisions require ready access to data, knowledge, and information. To meet the challenges posed by the many intertwined issues presented herein, ORMGP staff continue to seek ways to synthesize, illustrate, and communicate groundwater-system knowledge. This involves finding new and improved ways of sharing knowledge via the ORMGP website.

In the short term, next steps are:

- increasing awareness of the overall ORMGP program, particularly within the community of upper-level managers, directors, and politicians who might not have the technical grounding to appreciate the magnitude of what the ORMGP offers in terms of subsurface and water-management support;
- finding ways of better presenting and exposing the insights gleaned from the numerical models;

- ongoing testing and refinement of the conceptual model as new data and information are received;
- finding additional ways for technical staff to compare flow-system understanding and hydrogeologic behavior in different locations across the area covered by the program;
- increasing the awareness of the ORMGP at universities and colleges with goals of using ORMGP materials to drive increased water-resource research and use of program resources in teaching courses so that graduating students are aware of the potential to harness ORMGP resources as they move into the marketplace; and
- undertaking more detailed interpretations of groundwater quality as a check on the current conceptual model of the groundwater flow system.

There is a wise saying; *the best time to plant a tree was 30 years ago, but the second-best time is now*. Borrowing from this saying, the best time to monitor groundwater was decades ago, however, the second-best time is now. At the program's onset in 2001, the ORMGP faced a seemingly daunting task of gathering, interpreting, and widely providing access to water-related information. However, and this is key, the tasks *were* started, without dwelling on the challenge ahead. Over time, many small actions and tasks added up to the robust, leading-edge ORMGP knowledge framework that supports decisions related to water-resource management. It is time to start replicating this initiative on a global basis.

9 Exercises

Exercise 1

Often water-resource-related policy and decision-making is hampered by a lack of readily available data and information. In other cases, a significant amount of information and data has been collected over time—for example, within the ORM area of southern Ontario. The ORMGP’s attempt to be transparent and make all information readily available (if legally possible) on a website along with interpretations and summaries (knowledge transfer) is an ongoing endeavor. Please provide a critique of the way that data, information, and knowledge transfer are presented on the ORMGP website (www.oakridgeswater.ca). The goal is to make the website as useful as possible and perhaps provide a global template for others who are interested in water-resources understanding and management.

[Solution to Exercise 1](#) ↓

[Return to where text linked to Exercise 1](#) ↑

Exercise 2

Describe the elements and importance of a conceptual model of a groundwater flow system. Start with an explanation of what a conceptual model is. Are conceptual models static?

[Solution to Exercise 2](#) ↓

[Return to where text linked to Exercise 2](#) ↑

Exercise 3

A three-dimensional geologic model is a valuable tool to have when evaluating groundwater flow systems. Describe the elements, tasks, and thought processes that go into rendering a three-dimensional geologic interpretation.

[Solution to Exercise 3](#) ↓

[Return to where text linked to Exercise 3](#) ↑

Exercise 4

How is the ORM different from other glacial moraines across Canada?

[Solution to Exercise 4](#) ↓

[Return to where text linked to Exercise 4](#) ↑

Exercise 5

Using the cross section of the conceptual model (Figure 10), identify the topographic and hydrostratigraphic settings in which flowing artesian wells are most likely to occur. Examine the locations of flowing artesian wells on the ORMGP website ([ORMGP-Maps-boreholes theme](#)[↗]).

[Solution to Exercise 5](#)[↴]

[Return to where text linked to Exercise 5](#)[↴]

Exercise 6

The heterogeneity associated with glacial sediments can result in complex, discontinuous layers of aquifers and aquitards. Mapping of geologic units is often completed utilizing a wide range in quality of data. For example, geologic descriptions from water-well records are considered to have relatively lower reliability compared to continuously cored boreholes logged by a professional geologist. Lithologic descriptions from water-well records drilled in Ontario, and particularly around the Oak Ridges Moraine, typically look like the image on the following page. Given a cluster of well records with lithologies such as this, how might you distinguish between aquifers and aquitards? Water-well records in Ontario can be accessed from the source (Province of Ontario) at <https://www.ontario.ca/page/map-well-records>[↗]. These same records can also be explored on various ORMGP mapping themes (Boreholes, MECP-WWIS Wells, Groundwater Levels and Water Table) at [ORMGP-Maps](#)[↗].



Ministry
of the
Environment
Ontario

WATER WELL RECORD

1. PRINT ONLY IN SPACES PROVIDED

2. CHECK ☒ CORRECT BOX WHERE APPLICABLE

11

6923544

69005

CON

107

COUNTY OR DISTRICT: [REDACTED] TOWNSHIP: [REDACTED] BOROUGH: [REDACTED] CITY: [REDACTED] VILLAGE: [REDACTED]
 LOT: 7 BLOCK: 15 SIDE RD. 7 DATE COMPLETED: 08-01-96

LOG OF OVERBURDEN AND BEDROCK MATERIALS (SEE INSTRUCTIONS)					
GENERAL COLOUR	MOST COMMON MATERIAL	OTHER MATERIALS	GENERAL DESCRIPTION	DEPTH METERS	
				FROM	TO
Yellow	Silt	Clay	Dense	0	7.5
Grey	Sand	Silt Very Fine	Soft	7.5	26
Grey	Clay	Sand Interbeds		26	40
Grey	Fine Sand			40	47.5
Grey	Med Sand	Coarse Sand & Gravel	Loose	47.5	59
	Clay			59	112
Grey	Fine Sand	Med. Sand		112	125
	Clay	Silt	Dense	125	155
Grey	Fine Sand	Silt & Clay Layers	Dense	155	168
Grey	Fine Sand	Shell Fragments & Wood	Loose	168	180
	Silty Sand	Silty Clay	Dense	180	188
	Med Sand	Coarse Sand	Loose	188	190
	LIMESTONE	Shale Interbeds		190	192.63

31 [REDACTED] 32 [REDACTED]

41 WATER RECORD				51 CASING & OPEN HOLE RECORD				61 PLUGGING & SEALING RECORD			
WATER FOUND AT: 10m, 47.5m, 112m, 188m KIND OF WATER: ☒ FRESH, ☒ SALTY, ☒ SULPHUR, ☒ MINERALS, ☒ GAS				INSIDE DIAM: 6", 5", 3", 2" MATERIAL: STEEL, GALVANIZED, CONCRETE, OPEN HOLE, PLASTIC WALL THICKNESS: 0.188", 0.188", SCH 40, 1/2"				SCREEN: #10, 3" DIAMETER, 10' LENGTH MATERIAL AND TYPE: PVC, 612			
PUMPING TEST METHOD: ☐ PUMP, ☐ BAKER WATER LEVEL END OF PUMPING: 19-21, 22-24, 25-28, 29-31, 32-35 PUMP INTAKE SET AT: 30-33 RECOMMENDED PUMP TYPE: ☐ SHALLOW, ☐ DEEP				DURATION OF PUMPING: 15-18, 19-21, 22-24, 25-28, 29-31, 32-35 WATER LEVELS DURING PUMPING: 19-21, 22-24, 25-28, 29-31, 32-35 WATER AT END OF TEST: 30-33 RECOMMENDED PUMP RATE: 30-33				DEPTH SET AT: 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200 MATERIAL AND TYPE: BENEFICIAL GROUT, CEMENT GROUT			

71 PUMPING TEST		FINAL STATUS OF WELL		WATER USE		METHOD OF CONSTRUCTION	
1 ☐ PUMP, 2 ☐ BAKER WATER LEVEL END OF PUMPING: 19-21, 22-24, 25-28, 29-31, 32-35 PUMP INTAKE SET AT: 30-33 RECOMMENDED PUMP TYPE: ☐ SHALLOW, ☐ DEEP	1 ☐ PUMP, 2 ☐ BAKER WATER LEVELS DURING PUMPING: 19-21, 22-24, 25-28, 29-31, 32-35 WATER AT END OF TEST: 30-33 RECOMMENDED PUMP RATE: 30-33	1 ☐ WATER SUPPLY, 2 ☐ OBSERVATION WELL, 3 ☐ TEST HOLE, 4 ☐ RECHARGE WELL 5 ☐ ABANDONED, INSUFFICIENT SUPPLY, 6 ☐ ABANDONED, POOR QUALITY, 7 ☐ UNFINISHED, 8 ☐ DEWATERING	1 ☐ DOMESTIC, 2 ☐ STOCK, 3 ☐ IRRIGATION, 4 ☐ INDUSTRIAL, 5 ☐ OTHER	1 ☐ CABLE TOOL, 2 ☐ ROTARY (CONVENTIONAL), 3 ☐ ROTARY (REVERSE), 4 ☐ ROTARY (AIR), 5 ☐ AIR PERCUSSION 6 ☐ BORING, 7 ☐ DIAMOND, 8 ☐ JETTING, 9 ☐ DRIVING, 10 ☐ DIGGING, 11 ☐ OTHER	LOCATION OF WELL IN DIAGRAM BELOW SHOW DISTANCES OF WELL FROM ROAD AND LOT LINE. INDICATE NORTH BY ARROW. CON 7, CON 8, 15 SIDE ROAD, #4785 DRIVEWAY, 40' FROM ROAD ON TOP OF HILL, 100' FROM TOP OF HILL		

CONTRACTOR		WELL CONTRACTOR'S LICENCE NUMBER		DATE RECEIVED	
NAME OF WELL CONTRACTOR: ALL-TERRAIN DRILLING LTD. ADDRESS: 3-661 COLBY DR. WATERLOO ONT N2L 1C2 NAME OF WELL TECHNICIAN: MIKE STECKO SIGNATURE OF TECHNICIAN/CONTRACTOR: [Signature] SUBMISSION DATE: 12-02-96		1129		1129 APR 17 1996	

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FORM NO. 0506 (11/86) FORM 9

[Solution to Exercise 6](#)

[Return to where text linked to Exercise 6](#)

Exercise 7

Glacial deposits are often characterized by heterogeneity, particularly till deposits. In the study area, till deposits, along with glaciolacustrine silts, are the aquitard units that control much of the groundwater flow system. These till deposits are often considered to be impermeable and therefore good hosts for waste facilities such as landfills. Is it a good idea to host landfills in till deposits?

[Solution to Exercise 7](#) ↓

[Return to where text linked to Exercise 7](#) ↑

Exercise 8

Glaciated settings are often characterized as being heterogeneous with large facies changes over short distances. In the study area, the highest yielding aquifer units are related to either gravel-filled bedrock valleys or channels within the overlying Quaternary sediment package, where erosive activity and subsequent infill has occurred within channel-esker-subaqueous fan settings. This channelization process often erodes regional till and silt-clay aquitard units. Describe the hydrogeological significance of channelization and subsequent sediment infill on the groundwater flow system. How would you go about exploring for these channel features? What types of information would you look at? Would your exploration program for bedrock valleys look similar to that for Quaternary sediment channel structures?

[Solution to Exercise 8](#) ↓

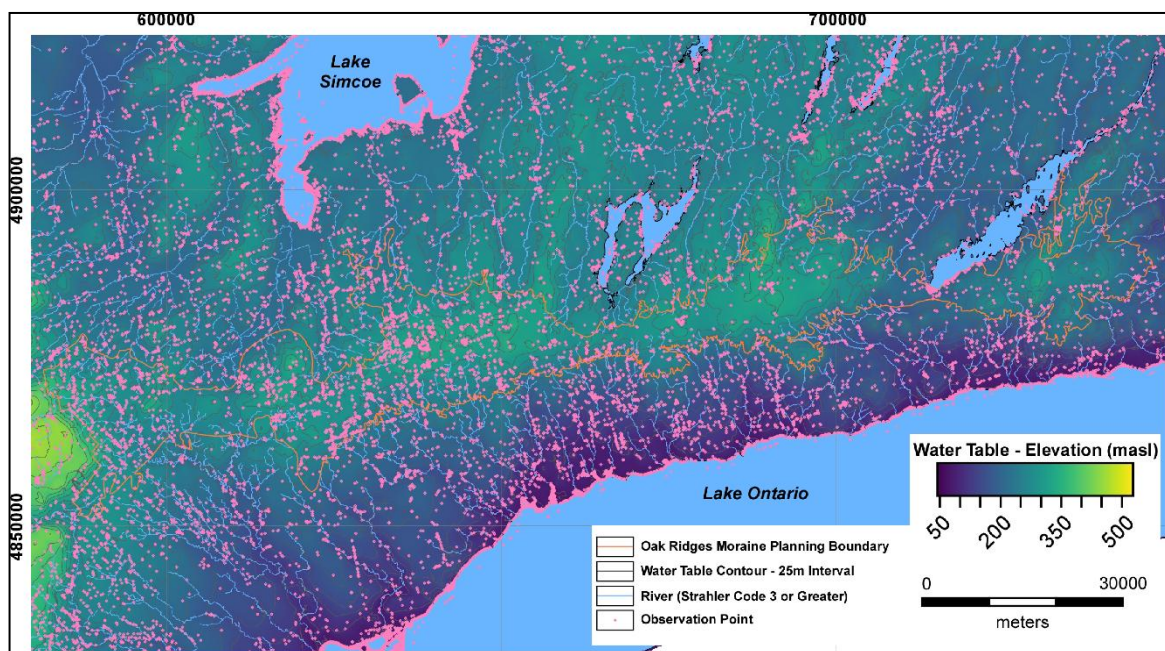
[Return to where text linked to Exercise 8](#) ↑

Exercise 9

Regional water table maps are drawn using water-level data from boreholes. The current version of the interpreted water table below gives a good indication of the shallow regional groundwater flow system. However, certain assumptions are associated with this water table map.

- List the many assumptions and limitations of this map
- In light of these assumptions and limitations, discuss how this regional water table map can still be useful.

Interaction with the current water table (and deeper potentiometric surface) can be found at [ORMGP-Maps-water table theme](#).



[Solution to Exercise 9](#) ↓

[Return to where text linked to Exercise 9](#) ↑

Exercise 10

Numerical flow models are powerful tools used to understand flow systems and to provide predictions of groundwater conditions for scenarios of interest. The ORMGP maintains a numerical model archive of dozens of models that have been prepared over the last decade for various objectives and purposes. What are some of the considerations involved in preparing numerical models and in using existing models to analyze for other purposes and objectives?

[Solution to Exercise 10](#) ↓

[Return to where text linked to Exercise 10](#) ↑

Exercise 11

The study area is experiencing increasing population growth and by extension urbanization. What are some of the impacts or changes that occur to flow systems in areas with increasing population and associated urbanization?

[Solution to Exercise 11](#) ↓

[Return to where text linked to Exercise 11](#) ↑

10References

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11 Boxes

Box 1 - Oak Ridges Moraine Groundwater Program

The Oak Ridges Moraine Groundwater Program (ORMGP) was initiated in 2001, driven by the encroachment of development onto the Oak Ridges Moraine and the recognition of the lack of high-quality environmental data and analyses, particularly with respect to groundwater. Since inception, the program has provided partner agencies with an actively managed water-related database and the regional geological and groundwater context for ongoing, day-to-day, water-resource-management activities such as development review, Permit to Take Water review, watershed management, and source water protection. The framework for the program is succinctly summarized in Figure Box 1-1, taken from the Council of Canadian Academies 2009 report *The Sustainable Management of Groundwater in Canada*.

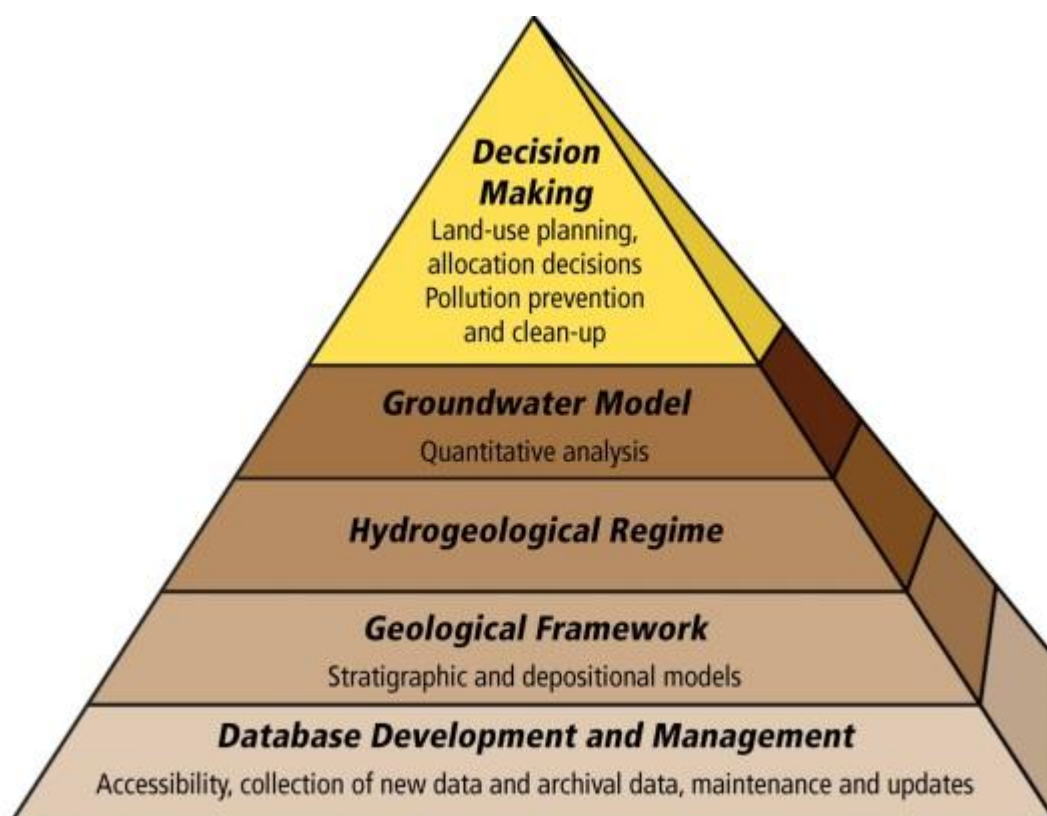


Figure Box 1-1 - Framework of the information and analysis system utilized by the ORMGP (Figure from Council of Canadian Academies, 2009 as modified from Earthfx Inc., 2006 and Sharpe, Hinton et al., 2002). Details on the ORMGP database can be found at ORMGP (2022).

Mandate

The mandate of the ORMGP partnership is to provide a multiagency, collaborative approach to collecting, analyzing, and disseminating water-resource data as a basis for effective stewardship of water resources. The ORMGP builds, maintains, and provides to partnered agencies, the regional geological and hydrogeological context for ongoing groundwater studies and management initiatives within the partnership area.

As such, the program will do the following.

- Build and maintain a master database of water-related information that is accessible to all partner agencies.
- Build and maintain a digital geological construction of the subsurface layers that is accessible to all partner agencies.
- Build and maintain a numerical groundwater flow model(s) that can be used to address any number of issues that arise at any of the partner agencies.
- Coordinate and lead investigations that will acquire new field data to strategically infill key data gaps.
- Provide technical support to source-water protection teams to ensure that interpretations used in source water are consistent with the regional understanding.
- Provide technical support to planning authorities to ensure that official plan policies are developed so they are consistent with up-to-date groundwater science as derived from the project.
- Provide technical support to all partnered agencies for addressing other provincial legislation.

The ORMGP study area includes approximately 30,000 km² situated within south-central Ontario (Figure Box 1-2). More information regarding the program is available at www.oakridgeswater.ca.

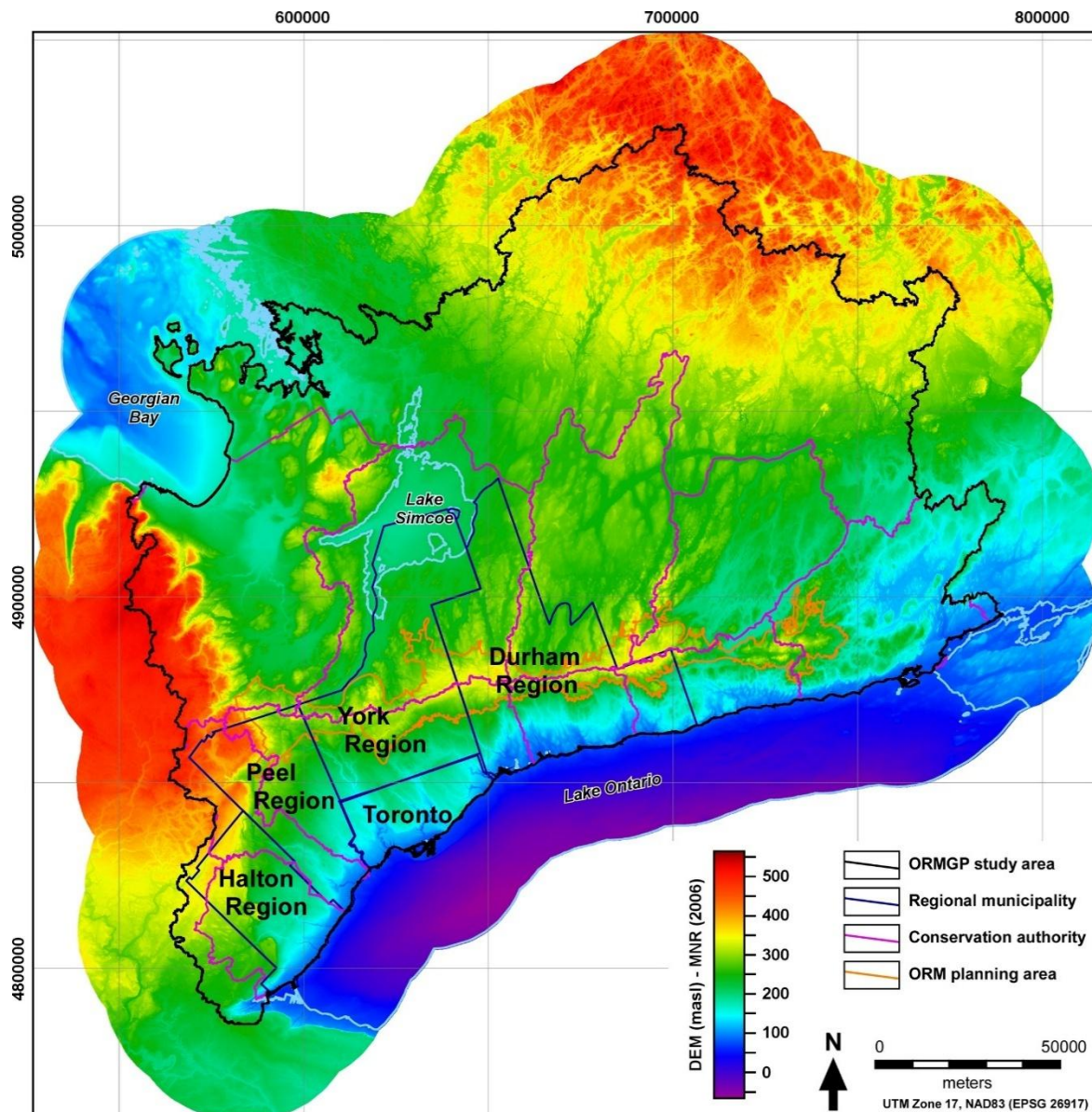


Figure Box 1-2 - The ORMGP study area (www.oakridgeswater.ca). For data-management purposes, the program area comprises the entirety of three source water protection (SWP) regions and a substantial portion of a fourth region (Figure Box 1-3). The regions are: Credit/Toronto/Central Lake Ontario (CTC); Southern Georgian Bay–Lake Simcoe (SGBLS); Trent Conservation Coalition (TCC); and a portion of the Halton Region and Conservation Halton portion of the Hamilton Halton SWP region (HH). SWP regions are shown in Figure Box 1-3. The focus of ORMGP work is directed to the GTA municipalities with boundaries (regional municipality) shown on the figure (York, Peel, Durham, Halton, and Toronto) and their associated conservation authorities.

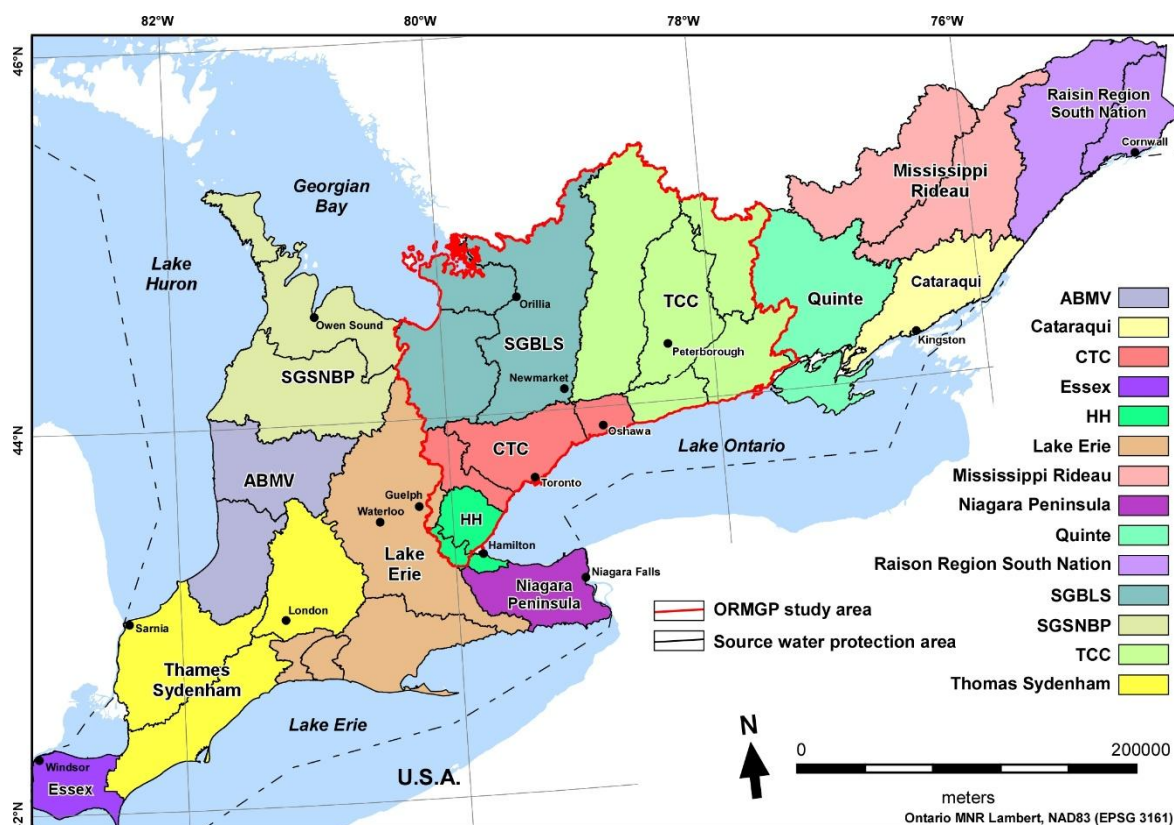


Figure Box 1-3 – Source Water Protection (SWP) regions (shaded) and areas in Ontario. Some SWP regions are subdivided into SWP areas generally following conservation authority jurisdiction boundaries. Further information on the SWP program can be found at [Ontario Source Water Protection](#)⁷. SWP regions and areas were established during the early 2000s to protect drinking water at the source areas following the Walkerton tragedy of May 2000 that resulted in seven deaths and over 2,000 illnesses due to contamination of the town's water supply (O'Connor, 2002). The ORMGP study area (outlined in red line) covers all or most of four SWP regions situated in south-central Ontario (Figure Box 1-2). Figure modified from the [Ontario Source Protection Information Atlas](#)⁷, downloaded January 17, 2024.

[Return to where text linked to Box 1](#)[↑]

Box 2 - ORMGP Housed Estimated Groundwater Infrastructure Value

The following table provides a high-level estimate of the value of hydrogeologic information that can be collected over time. It is anticipated that having ready access to such information will enhance and improve the decision-making process as it relates to water-resource management. It is also anticipated that information and data can be considered as vital infrastructure in that these resources provide the underlying foundation related to the activity of water-resource management.

Item	Million \$ (CAD)
Program cost (2001–2020)	\$ 14
Boreholes/wells (approximately 550,000 wells totaling 1.3 million m of well bore) Assume approximately \$130/m average drilling cost	\$169
Water quality Assume 116,000 samples at \$280/sample	\$ 32
Groundwater levels (>100,000,000) Assume hourly groundwater levels = 11,416 years-worth of data Assume 4 data downloads per year = 45,662 day-trips Assume each download visit = 8 hours x \$80/hour	\$ 29
Documents/reports (approximately 12,000 reports) Assume \$50,000/report	\$600
Numerical models (70 numerical models) Assume \$350K/model	\$ 25
Total	\$869

[Return to where text linked to Box 2](#) ↑

12 Exercise Solutions

Solution Exercise 1

There are no wrong or right answers here. We are simply seeking opinions and suggestions for ways to improve the availability and presentation of water-resource-related information. This will, at the very least, stimulate conversation and perhaps also provide a template for others situated anywhere on the globe.

[Return to Exercise 1](#) ↗

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Solution Exercise 2

A conceptual model of a flow system is a basic understanding of how the system functions including where water enters and exits the system and the general patterns of flow within the system. It is based on all data currently available, including climate, surface water, groundwater, geology, geophysics, and chemistry. A conceptual model should always be tested and refined as new information becomes available.

[Return to Exercise 2](#) ↗

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Solution Exercise 3

Datasets and input used in developing a three-dimensional geologic architecture for a region include the following.

- ground surface geologic maps and digital elevation models
- borehole and outcrop geologic descriptions including laboratory analysis for soil and rock properties (mineralogy, porosity, moisture content, etc.)
- surface (e.g., seismic) and borehole (e.g., gamma logs) geophysics
- understanding of geologic environment and depositional systems to guide interpretation of geologic unit extent and facies changes; this may also help in the interpretation of variable quality information
- *pushdown* information such as deep boreholes that do not encounter bedrock but may suggest bedrock valleys
- conceptual geological model
- hydraulic indicators such as gaining stream reaches and cold-water stream reaches
- ecosystem indicators such as vegetation and cold-water fish species
- groundwater-level fluctuations and vertical hydraulic gradients for an indication of geologic unit extent and relative permeability; for aquitards, the largest vertical hydraulic head difference will occur vertically across the lowest permeability facies

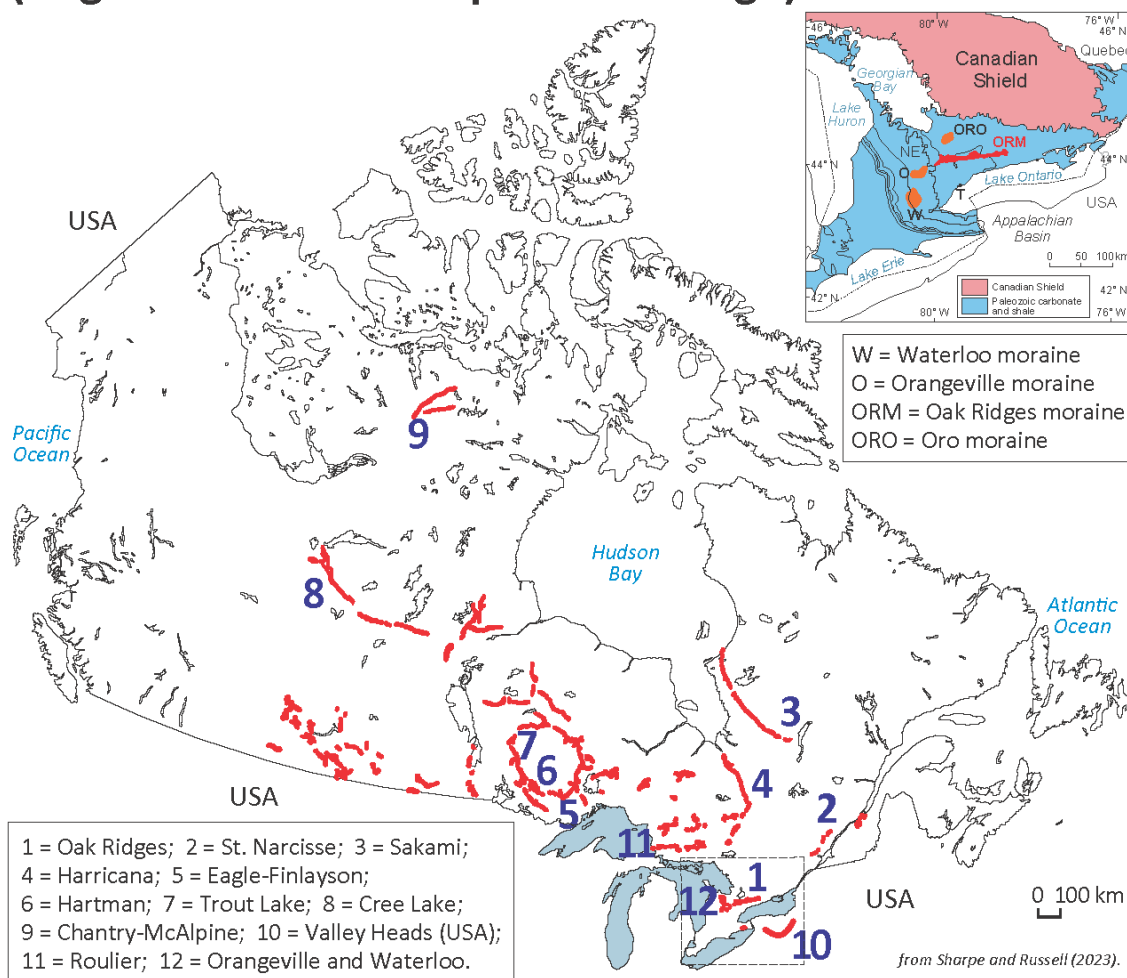
[Return to Exercise 3](#) ↗

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Solution Exercise 4

Periods of glaciation from the most-recent ice ages resulted in continental-scale glaciers that advanced and retreated many times in the past ~2 million years. Most moraines across glaciated North America are composed of glacial diamicton (till) (Fulton & Prest, 1987), particularly in the Great Lakes region. In contrast, the Oak Ridges Moraine is predominately composed of sand and gravel and is thus a 'stratified moraine'. Such sand and gravel stratified moraines are rare across Canada (the map below shows stratified moraines in Canada) and formed due to special conditions related to meltwater flow (floods) as opposed to the 'bulldozing' action of glaciers.

Major stratified (sand and gravel) moraines in Canada (large moraines with sparse coverage)



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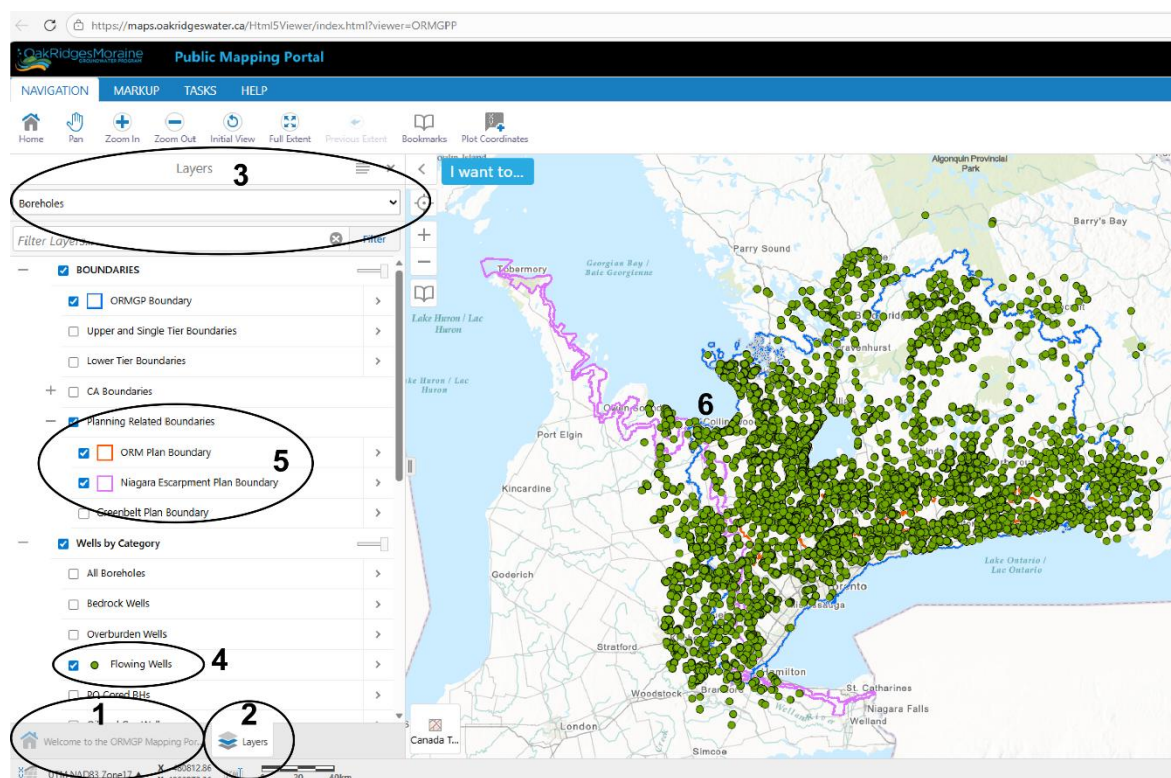
Solution Exercise 5

Flowing wells occur in areas of steep topographic slopes, which coincide with aquifer units being at shallower depth below ground surface and where aquifer units pinch out.

Flowing wells on the ORMGP web site can be accessed by selecting 'Open Access' at the top left of the web site home page (<https://www.oakridgeswater.ca/>). The 'Open Access' mapping portal can also be accessed using the following link.

<https://maps.oakridgeswater.ca/Html5Viewer/index.html?viewer=ORMGPP>.

Once in the Public Mapping Portal you will see a description of the various mapping themes or layers on the bottom left 'Welcome to the ORMGP Mapping Portal' (1). Select the Layers tab in the lower left (2). This will activate the various themes or layers in the Layers dropdown menu (3). Select the 'Boreholes' layer. By default, the Flowing wells will be selected (4) along with the Planning Related Boundaries (5) relating to the Niagara Escarpment and the Oak Ridges Moraine, two main upland areas within the study area. The flowing wells and Planning Related Boundaries will be shown on the map (6). Select any location and information will pop up including a MECP (provincial) water well record if available.



[Return to Exercise 5](#)

[Return to where text linked to Exercise 5](#)

Solution Exercise 6

Look at all available data: lithologies, water levels, screen intervals. Water levels can give an indication of groundwater flow direction. A vertical gradient could be indicative of an aquitard. Screened intervals are typically installed in water-bearing units, or aquifers. This information can be tied back into the lithologic records. Looking at borehole logs on cross section can be useful to relate one (or more) lithologic unit at one location to a unit at another location.

For this particular area, application of the steps above would lead to the delineation of aquifers and aquitards as shown in the image below. The hydrostratigraphic unit acronyms, as per Figure 30, are as follows: HAC = Halton Aquitard Complex; ORAC = Oak Ridges Aquifer Complex; LNT = Lower Newmarket Till; TAC = Thorncliffe Aquifer Complex; Su = Sunnybrook Drift (aquitard); and SAC = Scarborough Aquifer Complex. Note that all interpretations are subject to refinement as more information becomes available. Review of water well records also leads to the realization of the variable quality of transcriptions in water well records, and in all datasets.



Ministry
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Ontario

WATER WELL RECORD

1. PRINT ONLY IN SPACES PROVIDED
2. CHECK ☒ CORRECT BOX WHERE APPLICABLE

11

6923544

MUNICIP.

69005

CON.

CON.

107

COUNTY OR DISTRICT: [REDACTED] TOWNSHIP: [REDACTED] BOROUGH, CITY, TOWN, VILLAGE: [REDACTED]
ADDRESS: 4785 15 Side Rd. LOT: 10
DATE COMPLETED: DAY 08 MO 01 YR 96

LOG OF OVERBURDEN AND BEDROCK MATERIALS (SEE INSTRUCTIONS)					
GENERAL COLOUR	MOST COMMON MATERIAL	OTHER MATERIALS	GENERAL DESCRIPTION	DEPTH METERS	
Yellow	Silt	Clay	Dense aquitard (HAC)	0	7.5
Grey	Sand	Silt Very Fine	Soft aquifer (ORAC)	7.5	26
Grey	Clay	Sand Interbeds	aquifer w clay & silt interbeds	26	40
Grey	Fine Sand		ORM Channel	40	47.5
Grey	Med Sand	Coarse Sand & Gravel	Loose aquitard (LNT)	47.5	59
	Clay		aquifer (TAC)	59	112
Grey	Fine Sand	Med. Sand	Dense aquitard (Su)	112	125
	Clay	Silt	transition	125	155
Grey	Fine Sand	Silt & Clay Layers	Dense	155	168
Grey	Fine Sand	Shell Fragments & Wood	Loose aquifer (SAC)	168	180
	Silty Sand	Silty Clay	Dense	180	188
	Med Sand	Coarse Sand	Loose	188	190
	LIMESTONE	Shale Interbeds	Bedrock	190	192.03

41 WATER RECORD
WATER FOUND AT - FEET: 10m, 47.5m, 112m, 188m
KIND OF WATER: FRESH, SALTY, SULPHUR, MINERALS, GAS

51 CASING & OPEN HOLE RECORD
INSIDE DIAM. INCHES: 6, 5, 3
MATERIAL: STEEL, GALVANIZED, CONCRETE, OPEN HOLE, PLASTIC
WALL THICKNESS INCHES: 0.188, 0.188, 40
DEPTH - FEET: 210, 200, 632

61 PLUGGING & SEALING RECORD
DEPTH SET AT - FEET: 10, 10, 10
MATERIAL AND TYPE: BENSEAL GROUT 3" CASING, CEMENT GROUT 6" CASING

71 PUMPING TEST
PUMPING METHOD: 1 PUMP, 2 RAILER
PUMPING RATE: 15-18 GPM
WATER LEVELS DURING: 19-21, 22-24, 25-27, 28-30, 31-33, 34-36, 37-39, 40-42, 43-45, 46-48, 49-51, 52-54, 55-57, 58-60, 61-63, 64-66, 67-69, 70-72, 73-75, 76-78, 79-81, 82-84, 85-87, 88-90, 91-93, 94-96, 97-99, 100-102, 103-105, 106-108, 109-111, 112-114, 115-117, 118-120, 121-123, 124-126, 127-129, 130-132, 133-135, 136-138, 139-141, 142-144, 145-147, 148-150, 151-153, 154-156, 157-159, 160-162, 163-165, 166-168, 169-171, 172-174, 175-177, 178-180, 181-183, 184-186, 187-189, 190-192, 193-195, 196-198, 199-201, 202-204, 205-207, 208-210, 211-213, 214-216, 217-219, 220-222, 223-225, 226-228, 229-231, 232-234, 235-237, 238-240, 241-243, 244-246, 247-249, 250-252, 253-255, 256-258, 259-261, 262-264, 265-267, 268-270, 271-273, 274-276, 277-279, 280-282, 283-285, 286-288, 289-291, 292-294, 295-297, 298-300, 301-303, 304-306, 307-309, 310-312, 313-315, 316-318, 319-321, 322-324, 325-327, 328-330, 331-333, 334-336, 337-339, 340-342, 343-345, 346-348, 349-351, 352-354, 355-357, 358-360, 361-363, 364-366, 367-369, 370-372, 373-375, 376-378, 379-381, 382-384, 385-387, 388-390, 391-393, 394-396, 397-399, 400-402, 403-405, 406-408, 409-411, 412-414, 415-417, 418-420, 421-423, 424-426, 427-429, 430-432, 433-435, 436-438, 439-441, 442-444, 445-447, 448-450, 451-453, 454-456, 457-459, 460-462, 463-465, 466-468, 469-471, 472-474, 475-477, 478-480, 481-483, 484-486, 487-489, 490-492, 493-495, 496-498, 499-501, 502-504, 505-507, 508-510, 511-513, 514-516, 517-519, 520-522, 523-525, 526-528, 529-531, 532-534, 535-537, 538-540, 541-543, 544-546, 547-549, 550-552, 553-555, 556-558, 559-561, 562-564, 565-567, 568-570, 571-573, 574-576, 577-579, 580-582, 583-585, 586-588, 589-591, 592-594, 595-597, 598-600, 601-603, 604-606, 607-609, 610-612, 613-615, 616-618, 619-621, 622-624, 625-627, 628-630, 631-633, 634-636, 637-639, 640-642, 643-645, 646-648, 649-651, 652-654, 655-657, 658-660, 661-663, 664-666, 667-669, 670-672, 673-675, 676-678, 679-681, 682-684, 685-687, 688-690, 691-693, 694-696, 697-699, 700-702, 703-705, 706-708, 709-711, 712-714, 715-717, 718-720, 721-723, 724-726, 727-729, 730-732, 733-735, 736-738, 739-741, 742-744, 745-747, 748-750, 751-753, 754-756, 757-759, 760-762, 763-765, 766-768, 769-771, 772-774, 775-777, 778-780, 781-783, 784-786, 787-789, 790-792, 793-795, 796-798, 799-801, 802-804, 805-807, 808-810, 811-813, 814-816, 817-819, 820-822, 823-825, 826-828, 829-831, 832-834, 835-837, 838-840, 841-843, 844-846, 847-849, 850-852, 853-855, 856-858, 859-861, 862-864, 865-867, 868-870, 871-873, 874-876, 877-879, 880-882, 883-885, 886-888, 889-891, 892-894, 895-897, 898-900, 901-903, 904-906, 907-909, 910-912, 913-915, 916-918, 919-921, 922-924, 925-927, 928-930, 931-933, 934-936, 937-939, 940-942, 943-945, 946-948, 949-951, 952-954, 955-957, 958-960, 961-963, 964-966, 967-969, 970-972, 973-975, 976-978, 979-981, 982-984, 985-987, 988-990, 991-993, 994-996, 997-999, 1000-1002, 1003-1005, 1006-1008, 1009-1011, 1012-1014, 1015-1017, 1018-1020, 1021-1023, 1024-1026, 1027-1029, 1030-1032, 1033-1035, 1036-1038, 1039-1041, 1042-1044, 1045-1047, 1048-1050, 1051-1053, 1054-1056, 1057-1059, 1060-1062, 1063-1065, 1066-1068, 1069-1071, 1072-1074, 1075-1077, 1078-1080, 1081-1083, 1084-1086, 1087-1089, 1090-1092, 1093-1095, 1096-1098, 1099-1101, 1102-1104, 1105-1107, 1108-1110, 1111-1113, 1114-1116, 1117-1119, 1120-1122, 1123-1125, 1126-1128, 1129-1131, 1132-1134, 1135-1137, 1138-1140, 1141-1143, 1144-1146, 1147-1149, 1150-1152, 1153-1155, 1156-1158, 1159-1161, 1162-1164, 1165-1167, 1168-1170, 1171-1173, 1174-1176, 1177-1179, 1180-1182, 1183-1185, 1186-1188, 1189-1191, 1192-1194, 1195-1197, 1198-1199

CONTRACTOR: ALL-TERRAIN DRILLING LTD. 1129
WELL CONTRACTOR'S LICENCE NUMBER: 1129
NAME OF WELL TECHNICIAN: MIKE STECKO
WELL TECHNICIAN'S LICENCE NUMBER: T-2458
SUBMISSION DATE: DAY 12 MO 02 YR 96

OFFICE USE ONLY: DATA SOURCE: 1129, DATE RECEIVED: APR 17 1996, DATE OF INSPECTION: [REDACTED], INSPECTOR: [REDACTED], REMARKS: [REDACTED]

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FORM NO. 0506 (11/86) FORM 9

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Solution Exercise 7

It depends. Clay-rich till deposits are often good hosts, with relatively homogeneous low K characteristics (e.g., Saskatchewan, Canada; Sarnia, Ontario, Canada). In other locations, such as the study area, this may not be a good idea due to various heterogeneities and secondary permeability features including fractures and sand bodies, which can affect contaminant transport. Also, it may be more difficult to monitor and/or remediate within aquitard units compared to aquifer units.

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Solution Exercise 8

The highest yielding aquifers within the study area occur within either bedrock valley systems or Quaternary sediment channel features. The remainder and majority of the study area is largely silty sand aquifer units, or aquitards. One key feature of these channel features is that they may have eroded through aquitard units, thereby leading to reduced vertical hydraulic gradients (depending on infill sediments) and perhaps leading to increased aquifer vulnerability in regard to contaminant transport, depending on the direction (upward or downward) of vertical hydraulic gradients. To explore for channel features, one could consider the following information types.

- ground surface DEM. Often channels appear as over-widened river valleys compared to current stream flow regimes. For bedrock valley features the ground surface DEM may not be a useful tool, as most of the bedrock valley features are buried under large thicknesses of Quaternary sediment. Perhaps one could use the ground surface DEM over the upland areas (Niagara Escarpment and Canadian Shield) as a starting point for valleys, but then extension of these features beneath thick Quaternary sediments would need to be explored using other datasets and methods
- seismic surveys and associated core from drilled boreholes to confirm seismic or other geophysical survey information
- groundwater level response within a strip aquifer to stresses such as pumping. These will have a directional component and drawdowns greater than would be expected and observed within a sheet aquifer
- vertical hydraulic gradient. It will decline if aquitard has been thinned or eroded

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Solution Exercise 9

a)

- Some boreholes have only a single water-level measurement, taken soon after the borehole is drilled. This may have occurred decades ago, and conditions may have changed as a result of land use or groundwater extraction, so the single water-level reading is likely not representative. Also, the water level may not have fully recovered by the time the measurement was taken.
- Using shallow water levels to interpret a water table could be misleading in the presence of a perched water table. If a perched system exists, the regional water table could be misinterpreted.
- Water tables fluctuate over time in response to changes in stress (climate, pumping). A single water table measurement in one location might be taken in the spring whereas at another location, the measurement might have been taken in the summer.

b)

- The distribution of groundwater-level data can be sparse. A regional water table map such as this can provide a good estimate of shallow groundwater flow directions over a large area.
- Understanding the depth to the water table can be valuable in projects that involve excavations (e.g., mining and land development). A water table map provides a good initial guess at the depth to the water table in the absence of other data or information.

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Solution Exercise 10

Numerical models are only as good as the input and calibration information. They do not provide *the* answer but can be used to provide possible outcomes for scenarios of interest. The key to good model construction is use of high-quality building blocks (e.g., three-dimensional geologic layer interpretation, water table and potentiometric surface maps, groundwater pumping data, hydraulic property estimates, and streamflow data) that are part of the flow-system conceptual model. Prior to reusing numerical models many factors need to be considered, particularly whether the conceptual model has been refined or changed since the model was constructed. It is important to identify the original purpose of the model and determine whether that led to a design appropriate for the new objective. Another consideration is whether the assumptions made to build the model are reasonable for the purpose of the new model. If the new model will include contaminant transport, is the original model gridding sufficient, the model discretization may need to be refined and additional hydraulic parameters incorporated. Was the original model calibrated to steady-state and now a transient calibration and analysis is needed? In moving a model from a steady state to a transient analysis, storativity parameters need to be included and the spatial discretization may need to be refined.

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Solution Exercise 11

Increasing population means greater capacity for water supply is necessary. Does this water come from surface-water bodies (i.e., large lakes)? Or, does this water come from groundwater? If from groundwater, one needs to consider potential impacts on down-gradient users, while also accounting for ecosystem needs. The sustainable use of groundwater is not limited by the amount of recharge that occurs but must also consider the changes that might ultimately occur to discharge zones, such as the impact of decreased baseflow on ecosystems along streams and rivers. Increased urbanization changes the water balance in that more impervious surfaces decrease recharge and increase evaporation. There are also groundwater-quality concerns, as urbanization tends to provide more, or perhaps different, contaminant sources. For example, within the study area, all water reservoirs including lakes, streams and groundwater are experiencing increasing Na and Cl concentrations with estimated steady-state concentrations not being reached for centuries.

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13 Notations

13.1 Mathematical Nomenclature

The following list of mathematical parameters provides units in green font with **M** as mass, **L** as length, and **T** as time.

- A = planimetric (map) area (L^2)
- AET = actual evapotranspiration (LT^{-1})
- ET = evapotranspiration, typically annual (LT^{-1})
- g = acceleration of gravity (LT^{-2})
- Δgw = change in saturated groundwater storage volume per unit area, controlled by changes in water table elevation; positive for water table rise (L)
- k = intrinsic permeability of the solid matrix (L^2)
- K = hydraulic conductivity (LT^{-1})
- μ = fluid (groundwater) dynamic viscosity ($ML^{-1}T^{-1}$)
- p = fluid (groundwater) mass density (ML^{-3})
- P = precipitation, typically annual (LT^{-1})
- PET = potential evapotranspiration (LT^{-1})
- Qs = Shallow groundwater discharge flow rate to surface water or the atmosphere (L^3T^{-1})
- RO = surface runoff per unit area, typically annual (LT^{-1})
- SC = Specific Capacity which is the discharge of a well divided by the drawdown in the well (L^2T^{-1})
- Δsm = change in soil moisture storage volume per unit area, controlled by changes in water content in the unsaturated zone; positive for increase (L)
- t = time duration being considered (T)
- T = Transmissivity which is the discharge through a unit width of the entire saturated thickness of an aquifer for a unit hydraulic gradient normal to the unit width (L^2T^{-1})
- U = deep aquifer flow rate (underflow) (L^3T^{-1})

13.2 Acronyms

AET	=	actual evapotranspiration
DEM	=	digital elevation model
GSC	=	Geological Survey of Canada
GTA	=	Greater Toronto Area
MECP	=	Ontario Ministry of Environment, Conservation and Parks
ORM	=	Oak Ridges Moraine
ORMCP	=	Oak Ridges Moraine Conservation Plan
ORMGP	=	Oak Ridges Moraine Groundwater Program
OWRC	=	Ontario Water Resources Commission
PET	=	potential evapotranspiration
PGMN	=	Provincial Groundwater Monitoring Network
PTTW	=	Permit to Take Water
QA/QC	=	Quality Assurance and Quality Control
SOLRIS	=	Southern Ontario Land Resource Information System

14 About the Authors



Richard Gerber is a senior hydrogeologist and co-manager of the Oak Ridges Moraine Groundwater Program, a now widely recognized leading-edge program in groundwater management focused on much of south-central Ontario. He obtained his undergraduate degree in earth sciences at the University of Waterloo and graduate degrees in hydrogeology at the University of Toronto. His expertise gained through teaching, research, and consulting activities focuses on groundwater flow and solute transport characteristics of relatively low-permeability porous media (aquitards), delineation and quantification of regional groundwater flow systems, groundwater recharge, and groundwater-surface-water interaction.

Present projects involve understanding and quantifying the flow system for watersheds situated in south-central Ontario on behalf of various levels of government including regional municipalities, conservation authorities, the City of Toronto, and the Province of Ontario. This regional flow-system understanding provides the foundation for water supply and water-resources planning, particularly as related to the requirements of the Oak Ridges Moraine Conservation Plan and the Ontario Clean Water Act.



David Sharpe is a research scientist at the Geological Survey of Canada in Ottawa specializing in the glacial geology of Canada as applied to mineral exploration and hydrogeology. He has worked in many areas of the country including Arctic Canada, the barren lands, the Prairies, and most parts of Ontario, including the Oak Ridges Moraine and the Ottawa regions. For over 30 years he has, along with others, developed a defensible geological model for the ORM region, which is used as a conceptual framework for ongoing groundwater analysis and modeling. He is the lead author on a chapter on the regional hydrogeology of southern Ontario in a book about Canada's groundwater resources.



Steve Holysh is passionate about helping Ontario improve water-related management decisions. For the past 22 years, Steve has overseen the Oak Ridges Moraine Groundwater Program. With a focus on careful, comprehensive, and active data management, the ORMGP makes data, along with interpretations, knowledge, and insights, available via its web portal. The goal is to build and maintain a long-standing and trusted geological and hydrological framework model, a legacy for Ontario. Steve has a BSc from the University of Toronto and an MSc degree from the University of Alberta. Steve has served as president of the Canadian Chapter of the International Association of Hydrogeologists and has contributed as a member of the technical committee for Ontario's Source Water Protection initiative and as a member/author on the Council of Canadian Academies' 2009 report on sustainable management of groundwater in Canada.



Mason Marchildon is a water-resource engineer whose primary focus is on hydrological processes at the regional scale. Through big data analytics and numerical modeling, Mason utilizes open-source graphical resources to reduce the hydrological cycle to a form that remains accessible to the layperson.



Mike Doughty worked at the University of Toronto before joining the Oak Ridges Moraine Groundwater Program in 2007. In 2014 he received his doctorate from McMaster University. Mike has also been a member of the Association of Professional Geoscientists of Ontario since 2002.



Shaun Frape received his BSc, MSc, and PhD in geology and geochemistry from Queen's University. Dr. Frape has been a professor of hydrogeochemistry and isotopes at the University of Waterloo since 1980. He specializes in groundwater flow systems using isotopic and geochemical tracers to delineate the transport of natural and contaminant parameters in groundwater flow systems, as well as regional groundwater-resource studies. He is the author of more than 350 publications, including over 100 refereed international journal articles and 70 other refereed articles. He is an active peer reviewer of radioactive waste programs in Canada, Finland, and the United States and has collaborated with SKB, Sweden; POSIVA and GTK, Finland; and AECL, NWMO, Canada, for over 40 years. Dr. Frape specializes in developing new isotopic tools for use in tracing natural and anthropogenic processes in hydrogeological and ecological environments. He is a Fellow of the International Association of Geochemistry, an elected Fellow of the Geological Society of America, and the GSA 2007 O. E. Meinzer award recipient.



Lori Labelle is a passionate PhD student at the University of Waterloo, specializing in groundwater research. With a MSc and a BSc from the University of Western Ontario, she focuses her doctoral research on using stable isotopes and geochemical tracers to better understand regional groundwater flow systems. As she nears the completion of her PhD, Lori has developed strong expertise in isotopic geochemistry and regional groundwater studies. Her dedication and commitment to the field drive her to contribute to sustainable groundwater management and deepen our understanding of regional groundwater systems.



Britt Smith is a Trent University and Niagara College graduate. The focus of her studies has been biology and environmental management and assessment. Britt has worked for the Oak Ridges Moraine Groundwater Program for the past six years as a groundwater management analyst.

Prior to her work with the ORMGP, Britt was a project manager during the early development of the National Disaster Mitigation Program and co-authored the program's pilot watershed assessment, *Central Lake Ontario Watershed Flood-Risk Assessment* (2017). She was a guest speaker at the 2017 Provincial Emergency Management

Conference and continues to promote safe and sustainable water and groundwater-management practices.



Steve Shikaze, PEng, MSc, completed his undergraduate degree in geological engineering in 1990 and his master's in science in hydrogeology in 1993, both from the University of Waterloo. Since graduation, he has worked in academia, research (Environment Canada), and consulting. His experience includes using quantitative tools to aid in the understanding of groundwater systems. He has worked on water resources, mining, and contaminant projects across Canada, the United States, and South America.

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