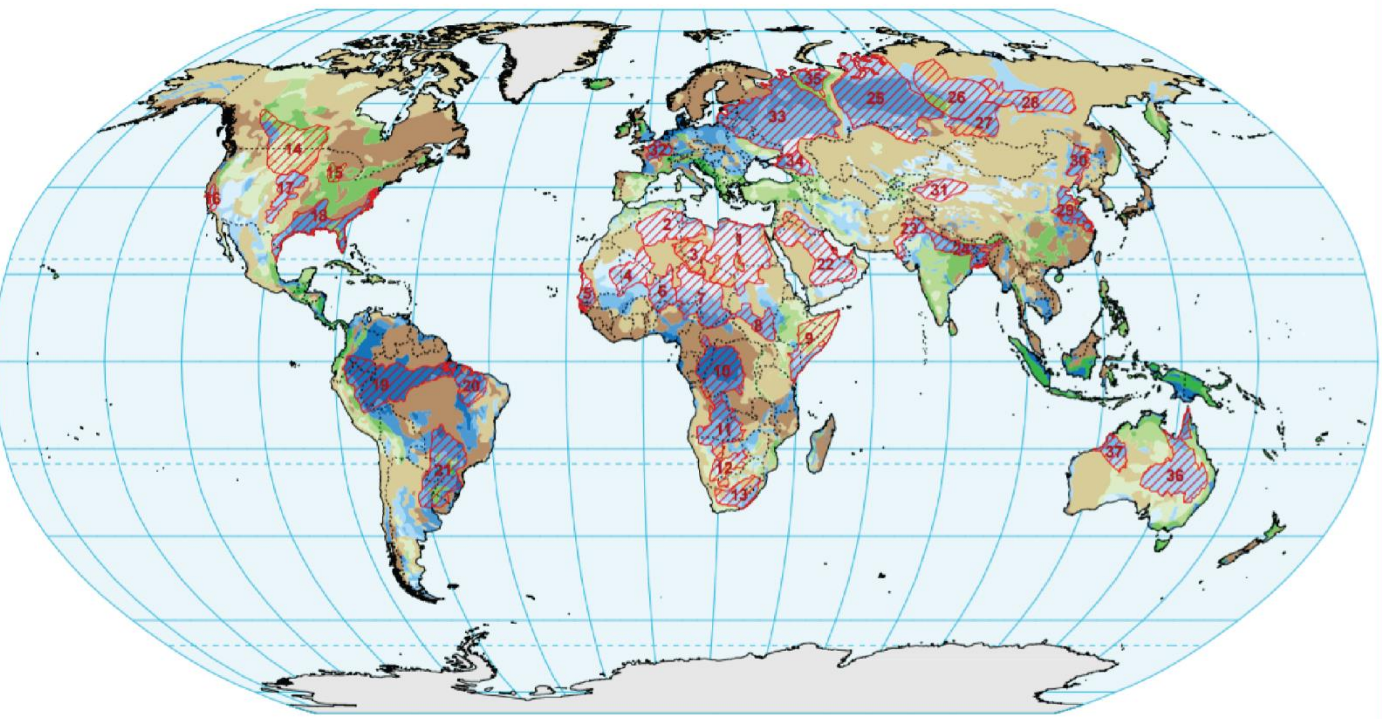

Large Aquifer Systems Around the World

Jac van der Gun

THE GROUNDWATER PROJECT

Large Aquifer Systems Around the World

The Groundwater Project

Jac van der Gun
International Groundwater Resources Consultant
Van der Gun Hydro-consulting
Schalkhaar, The Netherlands

Large Aquifer Systems Around the World

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THE GROUNDWATER PROJECT

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The Groundwater Project Foreword

The Year 2022 marks an important year for groundwater because the United Nations Water Members and Partners have chosen the theme of this year's March 22 World Water Day to be: "Groundwater: making the invisible visible". The goal of the Groundwater Project (GW-Project) is in sync with this theme.

The GW-Project, a registered charity in Canada, is committed to contributing to advancement in groundwater education and brings a unique approach to the creation and dissemination of knowledge for understanding and problem-solving. The GW-Project operates the website https://gw-project.org/↗ as a global platform for the democratization of groundwater knowledge, founded on the principle that:

"Knowledge should be free and the best knowledge should be free knowledge." Anonymous

The mission of the GW-Project is to promote groundwater learning. This is accomplished by providing accessible, engaging, high-quality, educational materials, free-of-charge online in many languages, to all who want to learn about groundwater. In short, providing essential knowledge tools for developing groundwater sustainably for humanity and ecosystems.

This is a new type of global educational endeavor in that it is based on the volunteerism of professionals from different disciplines and includes academics, consultants and retirees. The GW-Project involves many hundreds of volunteers associated with more than 200 hundred organizations from 27 countries and six continents, with growing participation.

The GW-Project is an ongoing endeavor and will continue with hundreds of books being published online over the coming years, first in English and then in other languages, for downloading wherever the Internet is available. An important tenet of the GW-Project books is a strong emphasis on visualization via clear illustrations that stimulate spatial and critical thinking to facilitate the absorption of information.

The GW-Project publications also include supporting materials such as videos, lectures, laboratory demonstrations, and learning tools in addition to providing, or linking to, public domain software for various groundwater applications supporting the educational process.

The GW-Project is a living entity, so subsequent editions of the books will be published from time to time. Users are invited to propose revisions.

We thank you for being part of the GW-Project Community. We hope to hear from you about your experience with using the books and related material. We welcome ideas and volunteers!

The GW-Project Steering Committee

June 2022

Foreword

Groundwater pumped from aquifers provides half of the world's population with drinking water and supports global food production by serving 38% of the world's irrigated lands. Of all groundwater withdrawn around the globe, 70 percent is used for agricultural production of food, fibers, livestock and industrial crops. Humanity depends on this important natural resource now and increasingly so as the global population rises from 8 to 10 billion people over the next few decades. To be informed citizens of the global community at this point in human history, *when the global population is still ballooning and continents are drying as aquifers are depleted while drought is expanding*, we need to be more aware of the role of groundwater and its importance to our well-being.

There are aquifers nearly everywhere in the world. They range in size from those with an area less than a soccer field and thinner than a two-story building to mega aquifers, which are more than a thousand kilometers across and hundreds of meters thick. Some are buried deep below low permeable strata that are not water-bearing (aquitards) while others are shallow, just below the ground surface. This book presents an overview of the world's 37 mega aquifer systems and discusses their state and relevance. These 37 aquifers represent more than half of the world's groundwater reserves, account for approximately 40% of the total volume of global groundwater withdrawal, and cover areas in 57 countries of the world on six continents.

This book presents key information about mega aquifers to provide a perspective on each related to its hydrologic circumstances. Appropriate background reading for this book includes the following Groundwater Project books: Groundwater in Our Water Cycle↗, Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow↗, and Groundwater Resources Development↗.

This book was authored by Jac van der Gun, a Dutch groundwater hydrologist and water resources specialist who is one of the few people qualified to address this topic. He has been engaged in this subject matter for over half a century with hands-on experience in many countries on four continents.

John Cherry, The Groundwater Project Leader

Guelph, Ontario, Canada, June 2022

Preface

Groundwater ranks among the world's most important natural resources. Apart from being a major source to meet human water demands for domestic, agricultural and industrial purposes, it provides a range of other services, such as supporting groundwater-dependent ecosystems, regulating (often buffering) a variety of natural processes and carrying geothermal energy. Making optimal use of these services and pursuing their sustainability requires sound hydrogeological knowledge: not only generic knowledge (necessary to understand the scientific rules governing groundwater-related processes) but also area-specific knowledge on the occurrence and properties of the invisible groundwater resources and their physical environment.

Acquiring and enhancing area-specific knowledge on groundwater and its setting belong to the core tasks of hydrogeologists. In this context, the aquifer concept has proven to be a powerful tool for integrating individual pieces of information about groundwater into a comprehensive spatial conceptual model and for sharing the acquired knowledge. Countless aquifers – ranging from small to very large – are scattered around the globe, many of them clustered in aquifer systems. The more important aquifers and aquifer systems usually carry a name, for easy identification.

This book is an introduction to the world's large aquifer systems. It focuses on thirty-seven so-called mega aquifer systems and presents a macroscopic picture of their state and relevance based on attributes such as spatial dimensions, geology, groundwater reserves, groundwater renewal, mineral content, groundwater withdrawal and storage depletion. This information is of little use for practical purposes at the field level, given its aggregated nature and the lack of spatial detail. However, the book intends to serve other purposes and interests, linked to other spatial scales. It informs the reader about the existence and geographical distribution of a set of very large aquifers that – although limited in number – together represent more than half of the world's groundwater reserves and constitute the source of approximately 40 percent of the global groundwater withdrawal. It reveals the huge differences in opportunities and challenges among these aquifer systems, resulting from differences in natural conditions (climate, geology, topography, hydrology, – including those prevailing in the remote past) and in interactions with people (groundwater withdrawal, pollution, mining, water management). Acquired knowledge of these mega aquifer systems may also contribute to a better understanding of the role of groundwater in various global processes, and to putting local groundwater issues into a wider geographic perspective.

Most information in this book is presented in the form of simple indicators and succinct explanatory text. For learning more about individual mega aquifer systems, however, many publications are available, the fruit of meticulous efforts by numerous scientists.

Acknowledgments

I deeply appreciate the thorough and very useful reviews of this book by the following individuals:

- Leonard F. Konikow – Emeritus Scientist, U.S. Geological Survey, USA
- Jack Sharp – Dave P. Carlton Professor of Geology, University of Texas, Austin, USA
- Jim Butler – Senior Scientist and geohydrologist, Kansas Geological Survey, USA
- Roberto Kirchheim – Hydrogeology Researcher, National Geological Survey of Brazil
- Wolfgang Kinzelbach – Emeritus professor ETH, Zürich, Switzerland
- Everton De Oliveira – President of Hidroplan, Director of the Sustainable Water Institute, Brazil
- Garth van der Kamp – Research Associate, Global Institute for Water Security, University of Saskatchewan, Saskatoon, Saskatchewan, Canada (Formerly, Research Scientist, Environment Canada)
- Hugh Whiteley – Independent Civil Engineering Professional and Emeritus Adjunct Professor, University of Guelph, Kitchener, Canada
- Ineke Kalwij – President, Principal Hydrogeologist, Kalwij Water Dynamics Inc., Canada
- Matthys Dippenaar – Associate Professor, Engineering Geology and Hydrogeology, University of Pretoria, South Africa

The comments and suggestions provided by each of these reviewers on the first draft of the book were very helpful to me in my endeavors to improve it. They focused on numerous aspects: overall scope of the book and observed gaps; relevance of the topics covered from a didactic point of view; errors and flaws concerning content; usefulness and quality of the graphs; uncertainty and how it is reflected in the text and presented statistics; terminology; shared knowledge and references to additional useful literature; flaws in presentation and suggestions for improvement; linguistic errors and their correction; and more. Especially the first three reviewers of the list made exceptional efforts and delivered very detailed reviews. My sincere thanks go to all reviewers.

I am grateful to Amanda Sills, Juliana Apolonio, Danilo Amendola of the Groundwater Project for their oversight and copyediting of this book, to Daniel Noble for skillfully drafting the world map of large aquifers, and to Mohammad Shamsudduha for his excellent graphs of GRACE groundwater storage anomalies. I thank Eileen Poeter (Colorado School of Mines, Golden, Colorado, USA) for reviewing, editing, and producing this book.

1 Aquifers and Aquifer Systems

The physical setting of groundwater can be viewed at different spatial scales, ranging from microscopic to global. Each level has its own merits for studying specific types of groundwater features and processes, making use of concepts and parameters tailored to the corresponding spatial resolution. This section focuses on aquifers and aquifer systems. It outlines their position in the hierarchy of spatial scales that are of interest for groundwater science and assessment; reviews how they are defined and how they are classified according to their hydraulic conditions; depicts briefly their diversity in terms of lithological aquifer categories, geological and climatic setting, and aquifer productivity; and gives an impression of the enormous variation in the size of aquifers and aquifer systems. The section ends with the presentation of a map of seventy large and very large aquifer systems spread across the world.

1.1 The Continuum Approach

The solid matrix of the subsurface (rocks and other solid geological material) contains interstices or open spaces (pores or fissures) in which air, water or other fluids (such as hydrocarbons) are present. When water infiltrates, it moves through a network of interconnected pores or fissures downwards. A fraction of the infiltrating water remains in the unsaturated soil zone, attracted by soil matrix suction forces and available for subsequent evapotranspiration, while the remainder moves further down, reaches the fully saturated zone and joins in the local groundwater flow.

At the micro-scale, say at the scale of drops of water and grains of sand, it is extremely difficult (or even impossible) to observe and describe the presence and movement of groundwater inside the labyrinth of pores or fissures. In addition, it would not serve any practical purpose. Therefore, groundwater hydrodynamics and groundwater hydraulics have adopted the macroscopic *continuum approach* as common practice. In this approach, the very complex physical reality is replaced by simple homogeneous elementary volumes, characterized only by location, geometry and hydraulic parameters (e.g., effective porosity, hydraulic conductivity); these elementary volumes reproduce in a macroscopic modeling approach (e.g., using Darcy's equation) the overall behavior of the replaced physical system (e.g., aggregated flow rate). Although the porosity and other properties of very small neighboring volumetric units (containing no more than a few pores and grains of sand) can be very different, they tend to converge to a meaningful statistical average as the control volume is gradually increased in size (Figure 1). A certain minimum size of the elementary volume – the *Representative Elementary Volume* – is required to filter out the effect of micro-scale variations and to ensure that the adopted hydraulic parameters are meaningful and spatially continuous (Bear, 1972; Bear, 1979; Freeze and Cherry, 1979).

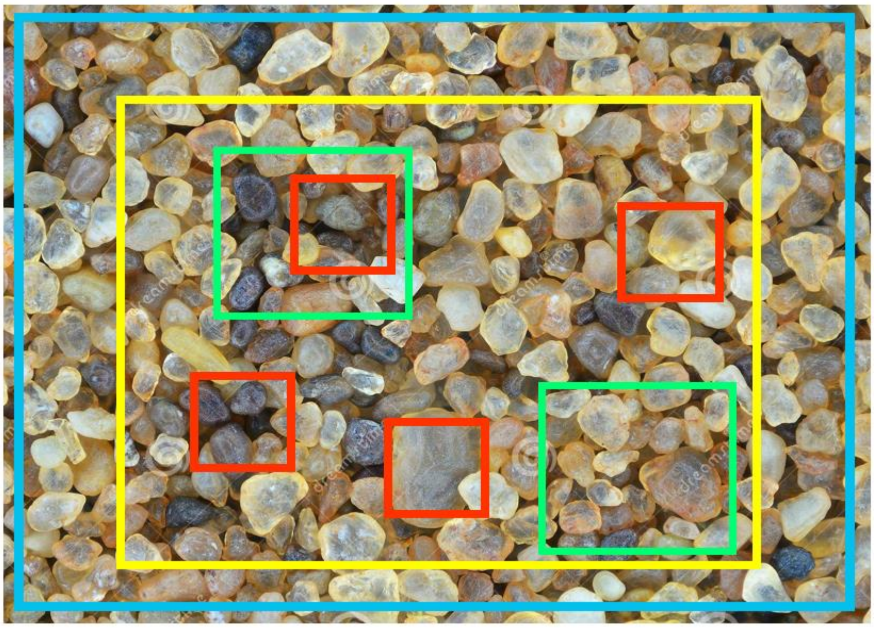

Figure 1 - Demonstration of the concept of *'Representative Elementary Volume (REV)'* of a porous medium (here shown in 2D projection). *Explanation:* With increasing size, the observed porosity (or void ratio) of a control volume changes from meaningless for macroscopic analysis (red boxes or smaller) to meaningful and representative (large blue box). Intermediate sizes may yield poorly (green boxes) to nearly representative porosity values (yellow box) for the medium considered.

1.2 Hydraulic Schematization of the Subsurface

If initial conditions, boundary conditions and stresses are specified, a three-dimensional description of the subsurface (in terms of hydraulic parameters) is adequate for simulating the behavior of groundwater variables such as pressures, water levels and flow rates. Nevertheless, hydrogeologists and other groundwater practitioners prefer, for various reasons, an additional step in conceptualization: *hydraulic schematization*. This is based on observed or assumed contrasts in the capacities of adjoining subsurface layers or other volumetric domains to store and transmit groundwater. The schematization subdivides the subsurface into volumetric bodies, classified in principle into the following categories:

- *unsaturated zone*: upper part of the subsurface in which the pores or fissures contain air as well as water;
- *aquifers*: domains with a high capacity to store and transmit groundwater;
- *aquitards*: domains with low capacity to transmit groundwater (storage capacity may vary); and,
- *impervious beds or rock masses:* domains unable to transmit groundwater (barriers to groundwater flow).

There are no absolute criteria to distinguish between 'high' and 'low' storage and transmission capacities; while lateral or vertical contrasts in these properties are in many cases not along sharp and undisputed divides. Furthermore, the frequently used term 'confining bed' refers in some cases to an aquitard, in other cases to a virtually impervious lithological unit. Therefore, the hydraulic schematization of the subsurface in any particular area is not only approximative but usually also somewhat subjective. Figure 2 shows a hypothetical cross-section of the subsurface in which the mentioned categories of hydraulic units are shown. Note that the aquifer covered by an aquitard (semi-pervious confining bed) is called a *'leaky confined aquifer'*.

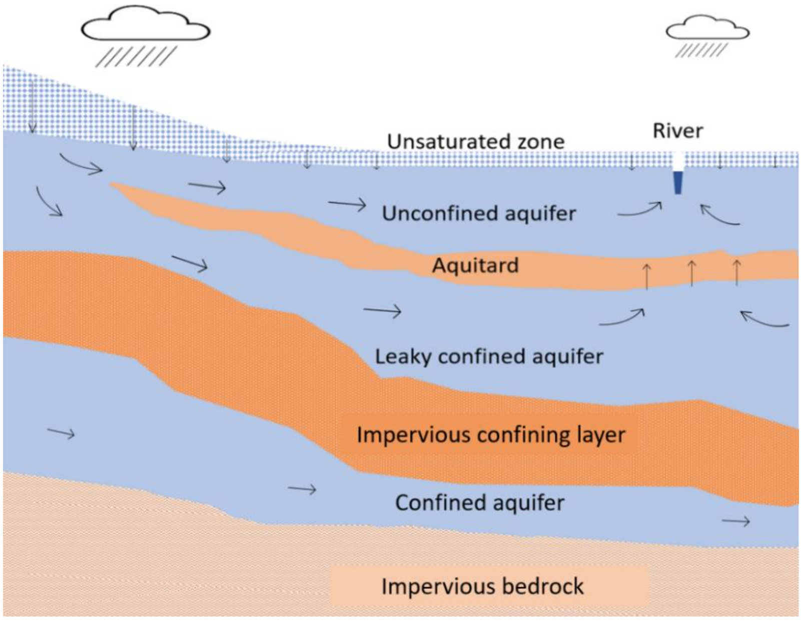

Figure 2 - Hypothetical vertical cross-section through the subsurface, showing the different categories of hydraulic units (vertical scale exaggerated).

The unsaturated zone may be absent at some locations (e.g., below a lake or river) and elsewhere be tens to hundreds of meters thick. The groundwater table forms its lower limit. Due to matrix forces, the water pressure in the unsaturated zone is less than atmospheric pressure. For this reason, water in the unsaturated zone is not included in the term 'groundwater'; it is called 'vadose water' or (if the unsaturated zone is shallow) 'soil moisture'.

Aquifers are both accessible reservoirs of groundwater and 'highways' for local or regional groundwater flow. Unconfined aquifers have a water table, while an aquifer bounded at its top and bottom by confining beds is called *'confined'*, or *'leaky confined'* (semi-confined) in the case where at least one of these boundary layers is an aquitard. The potentiometric water level of confined and semi-confined aquifers is located above the aquifer's top; if it is above the land surface, and thus allows free outflow of groundwater from wells, then the term *'artesian aquifer'* is used.

Like aquifers, aquitards may also contain very significant volumes of groundwater, but their low hydraulic conductivity does not allow substantial quantities of groundwater to be abstracted using conventional wells. Aquitards may provide shortcuts for groundwater flow from one aquifer to another (in a vertically stacked position); those of large areal extent may transmit considerable quantities of water to or from the aquifers they cover, markedly influencing regional groundwater flow.

1.3 A Closer Look at Aquifers and Aquifer Systems

1.3.1 Definitions and Interpretations

According to Theis (1983), the English noun 'aquifer' has been derived from the French adjective 'aquifère', introduced by Arago (1835), among others, in terms such as 'couche aquifère' (water-bearing layer). The term is based on the Latin words 'aqua' (water) and 'ferre' (to bear). Synonyms in English include water-bearing formation, water-bearing stratum, water-bearing layer and groundwater reservoir. A diversity of aquifer definitions can be found in hydrogeological textbooks and related publications (a selection is presented in Table 1).

Table 1 - Selected Aquifer Definitions

Definition	Source
An aquifer is a rock formation or stratum that will yield water in sufficient quantity to be of consequence as a source of supply.	Meinzer, 1923
Aquifers are permeable geologic formations having structures that permit appreciable water to move through them under ordinary field conditions.	Todd, 1959
An aquifer is a saturated bed, formation, or group of formations which yields water in sufficient quantity to be of consequence as a source of supply.	Walton, 1970
An aquifer is a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.	Lohman et al., 1972
An aquifer is a geologic formation or group of formations, which (i) contains water and (ii) permits significant amounts of water to move through it under ordinary field conditions.	Bear, 1979
An aquifer is a saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients.	Freeze and Cherry, 1979
An aquifer is a body of rock that is sufficiently permeable to conduct groundwater and to yield economically significant quantities of water to wells and springs.	Bates and Jackson, 1980
An aquifer is a permeable geologic unit that can transmit and store significant quantities of groundwater.	Smith and Wheatcraft, 1992
An aquifer is defined as a single geologic formation or a group of geologic formations that transmits and yields a significant amount of water.	Batu, 1998
'Aquifer' means a permeable water-bearing geological formation underlain by a less permeable layer and the water contained in the saturated part of the formation.	International Law Commission, 2008
An aquifer is a hydraulically continuous body of relatively permeable unconsolidated porous sediments or porous or fissured rocks containing groundwater. It is capable of yielding exploitable quantities of groundwater.	Margat and Van der Gun, 2013
An aquifer is a consolidated or unconsolidated (saturated) geologic unit (material, stratum or formation) or set of connected units that yields water of suitable quality to wells or springs in economically usable amounts.	Sharp, 2017

The definitions presented in Table 1 have much in common, but they also reflect differences in views or interpretation among groundwater professionals. As a key characteristic of aquifers, all definitions highlight permeability, or the capacity of aquifers to transmit and yield significant quantities of water. The storage function of aquifers receives less emphasis. Surprisingly, only one of the definitions (Smith and Wheatcraft, 1992) explicitly mentions the capacity of aquifers to store significant quantities of water, and only one (Sharp, 2007) includes water quality as a criterion.

Although the term aquifer has been in use for more than a century, among groundwater professionals there are still important differences in interpretation on several aspects:

- *Does the term 'aquifer' refer to the lithological matrix ('container') only, or does it include also the body of groundwater that fills its interstices ('content')?*
  There is no consensus on this aspect. Some of the definitions in Table 1 suggest the former (Meinzer, 1923; Todd, 1959; Lohman et al., 1972; Bates and Jackson, 1980; Smith and Wheatcraft, 1992; Batu, 1998) or avoid the issue, while other ones state the opposite (International Law Commission, 2008) or at least demand the presence of groundwater (Walton, 1970; Freeze and Cherry, 1979; Margat and Van der Gun, 2013). Commonly used terms such as unconfined aquifer, confined aquifer, artesian aquifer and fossil aquifer make sense only if the matrix and groundwater are considered together. When talking about a Paleozoic or Mesozoic aquifer, however, or about a sandstone or limestone aquifer, the adjectives refer to the lithological matrix and not to the groundwater in the interstices. In conclusion, there is no generally accepted strict definition of the term 'aquifer' and the perception of what it represents depends to some extent on the context in which the term is used.
- *The relation between geological formations (stratigraphic units) and aquifers.*
  Some groundwater professionals make a strict link between an aquifer and a single geological formation, assuming them to have the same boundaries, even if part of the formation is poorly permeable, or if permeable zones of that formation are in full hydraulic contact with the permeable zone of an adjacent formation. The more common approach among hydrogeologists, however, is to take a hydraulic perspective and consider aquifers as continuous permeable lithological bodies, whose boundaries are defined by contrasts in permeability rather than by stratigraphy, and thus may extend across formation boundaries. Hence, the aquifer may consist of either a single formation or only part of it, or a group of formations or hydraulically continuous parts of them (Lohman et al., 1972: Margat and Van der Gun, 2013).
- *Does the water table form the upper boundary of an 'unconfined aquifer' or does this type of aquifer extend above the water table and include also the unsaturated zone?*

Authors of reports and other publications on aquifers rarely specify their view on this aspect, but views likely diverge. Among the aquifer definitions in Table 1, only those of Walton (1970) and Freeze and Cherry (1979) link aquifers explicitly to the saturated zone, while the other definitions avoid addressing the issue. If an aquifer is viewed as a container, then it is not illogical to include the unsaturated zone (as long as it is permeable) since it represents the available space to store additional quantities of water and thus potentially may become part of the saturated zone. From a hydraulic point of view, it is convenient to consider a vertically movable water table as the upper boundary of an unconfined aquifer, because the water table marks the divide between substantially different hydraulic regimes.

The intention of presenting these ambiguities is not to make a choice between alternative interpretations or views or to express preferences. The purpose is simply to show the readers that 'aquifer' is not an unambiguously defined term, and to make them aware that hydrogeological reports and other groundwater literature may use different interpretations of the aquifer concept, usually without defining it with precision.

Aquifers rarely are completely homogeneous: significant variations can be highlighted by subdividing the aquifer into *zones* or *segments*. This can be done either in a vertical sense, for example, by differentiating between layers of different lithological characteristics (analogously to the members of a geological formation), or laterally, for example, based on lateral changes in lithological facies.

Depending on area-specific conditions and on the scale of investigation or mapping, two or more stacked aquifers with intercalated and overlying aquitards may together be called an *'aquifer system'*, as long as they can be considered as interconnected components of one hydraulically continuous system. Table 2 provides a few definitions of aquifer systems. The third definition does not necessarily require the presence of vertically stacked aquifer units, but includes also the option of aquifer systems formed by horizontally connected units. In practice, the distinction between aquifers and aquifer systems is somewhat arbitrary, because distinguishing between aquitards and low-permeability lenses, as well as between permeable and poorly permeable rocks, is subjective. With increasing complexity and size, the term 'aquifer system' tends to be preferred.

Table 2 - Selected aquifer system definitions.

Definition	Source
An aquifer system is a heterogeneous body of intercalated permeable and poorly permeable material that functions regionally as a water-yielding hydraulic unit; it comprises two or more permeable beds separated at least locally by aquitards that impede groundwater movement but do not greatly affect the regional hydraulic continuity of the system.	Poland et al., 1972
An aquifer system is a heterogeneous body of intercalated permeable and poorly permeable material that functions regionally as a water-yielding hydraulic unit; it comprises two or more aquifers separated at least locally by confining units that impede groundwater movement but do not greatly affect the regional hydraulic continuity of the system.	Laney & Davidson, 1986 (modification of Poland's definition)
'Aquifer system' means a series of two or more aquifers that are hydraulically connected.	International Law Commission, 2008

Although the majority of what groundwater professionals call an aquifer or aquifer system corresponds to the conceptual description presented above (a hydraulically continuous permeable unit or complex with significant storage capacity), a few somewhat differing variants may be encountered in practice. The first variant consists of assigning a single aquifer name to all occurrences of a single permeable geological formation (or group of formations), although consisting of spatially non-connected parts; these parts show similar hydrodynamic behavior but together they do not form one continuous hydraulic system. An example is the Basin and Range Aquifer System in the US. The second variant assumes that all permeable subsurface rocks present within the boundaries of a river basin form together one single aquifer system. Often such a system – usually named after the corresponding river – is defined without significant information on or knowledge of the permeable rocks included, except for the alluvial sediments directly associated with the river system. An example is the Amazon Basin Aquifer System.

1.3.2 Lithological Aquifer Categories and Aquifer System Settings

Aquifers occur in many different geologic, geographic and climatic settings, which explains the wide diversity of aquifer types and characteristics observed around the globe. Most notable are variations in lithology and geometry (in particular thickness and lateral extent), mainly defined by geological factors. Geography and climate have a major impact on the dynamics of the groundwater bodies inside the aquifers.

Most sedimentary rocks and some igneous and metamorphic rocks are stratified to some degree, whereas most igneous rocks form massive bodies that were intruded or extruded through the stratified rocks (Walton, 1970). Folding and faulting may lead to deformation of originally horizontal or sub-horizontal layers, in exceptional cases (recumbent folds, overthrust faults) even causing older formations to be located on top of younger ones. A distinction can be made between unconsolidated-rock (mainly gravel, sand, silt and clay) and consolidated-rock aquifers. Both classes include rock types that are permeable enough to be aquifers and other rock types that tend to obstruct groundwater flow.

1.3.3 Main Lithological Aquifer Types

Taking lithology as a criterion for classification, the following main categories of aquifers can be distinguished: (1) sand and gravel aquifers; (2) sandstone and conglomerate aquifers; (3) carbonate-rock aquifers (in particular karst aquifers); (4) volcanic rock aquifers; and (5) weathered crystalline and metamorphic bedrock aquifers. A brief description of each of these main categories follows, based on texts such as Todd (1959), Walton (1970), Norum (1973), Freeze and Cherry (1979), Fetter (2001) and Margat and Van der Gun (2013).

Sand and gravel aquifers are widespread and form the most widely exploited aquifers on earth. Most abundant in this category are sands and gravels of fluvial origin (also called alluvial sediments) that can be found in stream valleys, tectonic and intermontane valleys, and on river plains; in downstream zones they usually make way for clays and silts that can form aquitards. Other continental sand-and-gravel aquifers are formed by Pleistocene fluvio-glacial sediments (outwash, glacial fans and lake deltas, eskers, kames, buried valleys) that have been deposited in particular in a significant part of the Northern Hemisphere, together with less permeable glacial tills and fluviolacustrine clays and silts. Dune sands and other sands of aeolian origin consist of rounded grains of uniform size and may form good aquifers, while wind-blown silts (loess) are poorly permeable. Sand formations of marine origin may contain connate saline water (seawater entrapped in the interstices during the formation's deposition) unless this has been expelled after deposition and replaced by fresh water.

Sandstone and conglomerate aquifers are the consolidated counterpart of sand and gravel aquifers. Their porosity and permeability are in general lower, because of compaction and cementation (part of the original pores has been filled with solid material that cements the grains together). Sandstones represent around 25 percent of all sedimentary rocks on earth (Freeze and Cherry, 1979). Pores facilitate the storage and flow of groundwater in soft, poorly cemented sandstone, while in hard, massive sandstone this role is played by fissures. Flow in many sandstone aquifers is governed by both pores and fissures combined (dual porosity/permeability). Intercalated shales usually function as aquitards. Interbedded layers of coal at shallow depths may behave as aquifers.

Carbonate-rock aquifers consist mainly of limestone and/or dolomite. Like sandstone, limestone occurs in versions ranging from rather soft and porous (chalk) to very hard and dense (massive limestone). The latter qualifies only as an aquifer rock if it has sufficient fissures, fractures and/or karst conduits. Since carbonates are soluble minerals, fissures can become wider over time, which improves the overall porosity and permeability of the formation. In an advanced stage of dissolution, the formation becomes a *karst aquifer*, characterized by sinkholes, caves and networks of large subsurface conduits that replace surface drainage systems and feed springs, some of them with very high flow rates. In such cases, triple porosity/permeability (pores, fissures, large subsurface conduits) may be present. Karst may also develop in deposits of gypsum or rock salt.

Most *volcanic rocks* are poorly permeable, but productive heterogeneous *volcanic rock aquifers* can be found in Cenozoic volcanic rock formations, especially in basalts of Quaternary age. These aquifers, which are scattered over the world's volcanic massifs, form extensive aquifers on lava plateaus and may occur interbedded in sedimentary basins. Dense lava rock is nearly impermeable, but the formations owe their favorable aquifer properties to blocky rock masses produced by cooling of individual lava flows and to associated gravel interbeds.

Intrusive and metamorphic rocks, outcropping in approximately 30 percent of the area of the continents, are often considered impermeable. Nevertheless, the shallow horizons of these rocks are weathered at numerous locations and thus have storage capacity, which – combined with the transmission capacity of fissures extending to greater depth – results in modestly productive local aquifers. This category of weathered *crystalline and metamorphic bedrock aquifers* is particularly important for low-cost domestic water supplies in areas where other shallow aquifers are missing.

1.3.4 Aquifer System Settings

Vertical sequences of several permeable sedimentary formations are common and form either heterogeneous aquifers or – if intercalating aquitards are present – multilayer aquifer systems.

The uniqueness of each aquifer or aquifer system arises not only from lithological diversity but also from variations in geographical and geological settings (Figure 3 and Figure 4).

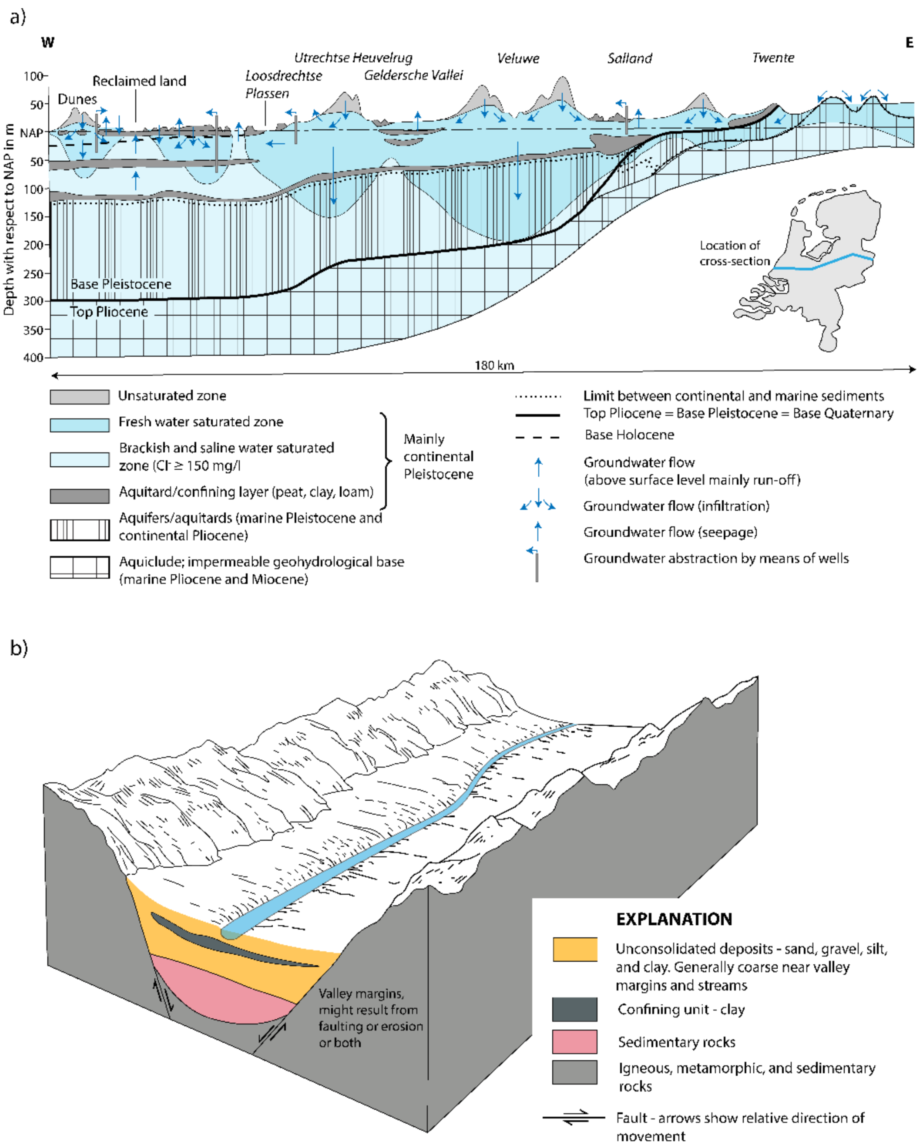

Figure 3 - Two examples of sand and gravel aquifers in different geological settings: a) a hydrogeological cross-section through The Netherlands showing a multi-layer aquifer system in a subsiding geological basin, bordered at its western margin by the North Sea (Dufour, 2000); and, b) a conceptualization of a basin-fill aquifer (USGS, 2000).

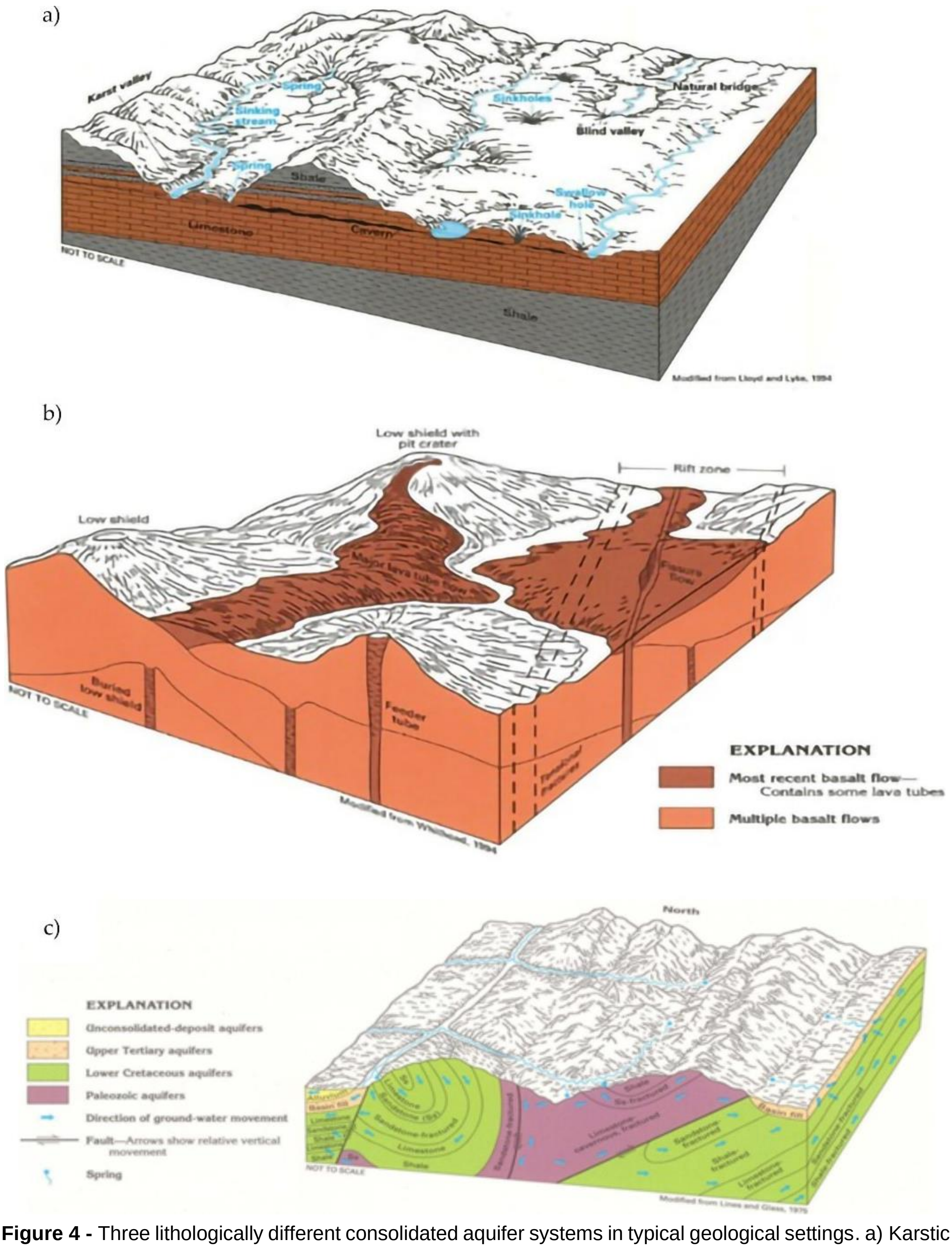

Figure 4 - Three lithologically different consolidated aquifer systems in typical geological settings. a) Karstic limestone aquifer with associated land-surface features such as springs, sinkholes, karst valleys and sinking streams (after USGS, 2000). b) A thick complex of overlapping flows of basaltic lava extruded from numerous overlapping shield volcanoes (Southern Idaho). Most flows issued from a central vent or fissure and some are associated with large rift zones in the Earth's crust (after USGS, 2000). c) Structurally affected groundwater system consisting of sandstones, shale and limestones (after Whitehead, 1996).

Aquifers may be situated along the coast or more inland; in sedimentary basins, in tectonic depressed zones (rift valleys), under plains flanking mountain ranges (piedmont plains), on elevated plateaus, or scattered across mountain areas, often folded or fragmented by faulting; some aquifers are shallow, others are located at great depth and isolated from the active water cycle. Current climatic conditions set their stamp on the dynamics of the groundwater bodies inside aquifers. One product of extreme climatic conditions forms permafrost, observed in polar regions of the Northern hemisphere; frozen soils there prevent groundwater in aquifers from being recharged and thus cause these resources to be non-renewable. Aridity, on the other hand, causes groundwater in other regions (in particular in the Middle East and Northern Africa) also to be non-renewable or only scarcely replenished. In such areas, groundwater development is more likely to become unsustainable than in humid areas or areas with a temperate climate.

Figure 3 and Figure 4 present highly-simplified examples of different types of aquifer systems and their geological setting.

1.3.5 Spatial Patterns of Aquifers and Aquifer Productivity

The spatial distribution of different types of aquifers is not random but follows to a large extent geological macro-structural patterns. This was highlighted by Meinzer (1923) when he divided the territory of the conterminous USA into 21 *Groundwater Provinces*. Each of these provinces is characterized by a broad uniformity of hydrogeological and geological conditions. The International Groundwater Assessment Centre (IGRAC) adopted this idea of groundwater provinces, applied it on a global scale (resulting in 217 groundwater provinces) and defined additional units at a more aggregated level: *Global Groundwater Regions* (Van der Gun et al., 2011; Margat and Van der Gun, 2013). The 36 global groundwater regions, each encompassing several groundwater provinces, are shown in Figure 5. Global groundwater regions are less uniform than groundwater provinces, but they still depict a macroscopic pattern of geological environments in which each region can be associated with a certain predominant type of aquifer setting, contrasting with neighboring regions. In this way, a hierarchical system has been created of spatial units related to groundwater systems, all of them identifiable by names and by delineated lateral boundaries. This hierarchy includes, from local to global scale, the following levels: aquifer zones, aquifer segments, aquifers, aquifer systems, groundwater provinces and global groundwater regions.

Hydrogeological maps produced according to the methodology of the United Nations Educational, Scientific and Cultural Organization (UNESCO), described by Struckmeier and Margat (1995), do not delineate discrete spatial groundwater system units but focus on hydrogeological characterization, notably by classifying the hydraulic properties of the subsurface in terms of groundwater productivity and type of interstices. Such maps have been prepared for many areas and countries of the world, as well as for the continents. A compilation in the form of a global map, at a scale of 1:25 million, has been produced and published by the international "World-wide Hydrogeological Mapping and Assessment Programme" or WHYMAP (BGR and UNESCO, 2008). BGR is the German Institute for Geosciences and Natural Resources. A simplified version of WHYMAP's main map is shown in Figure 6.

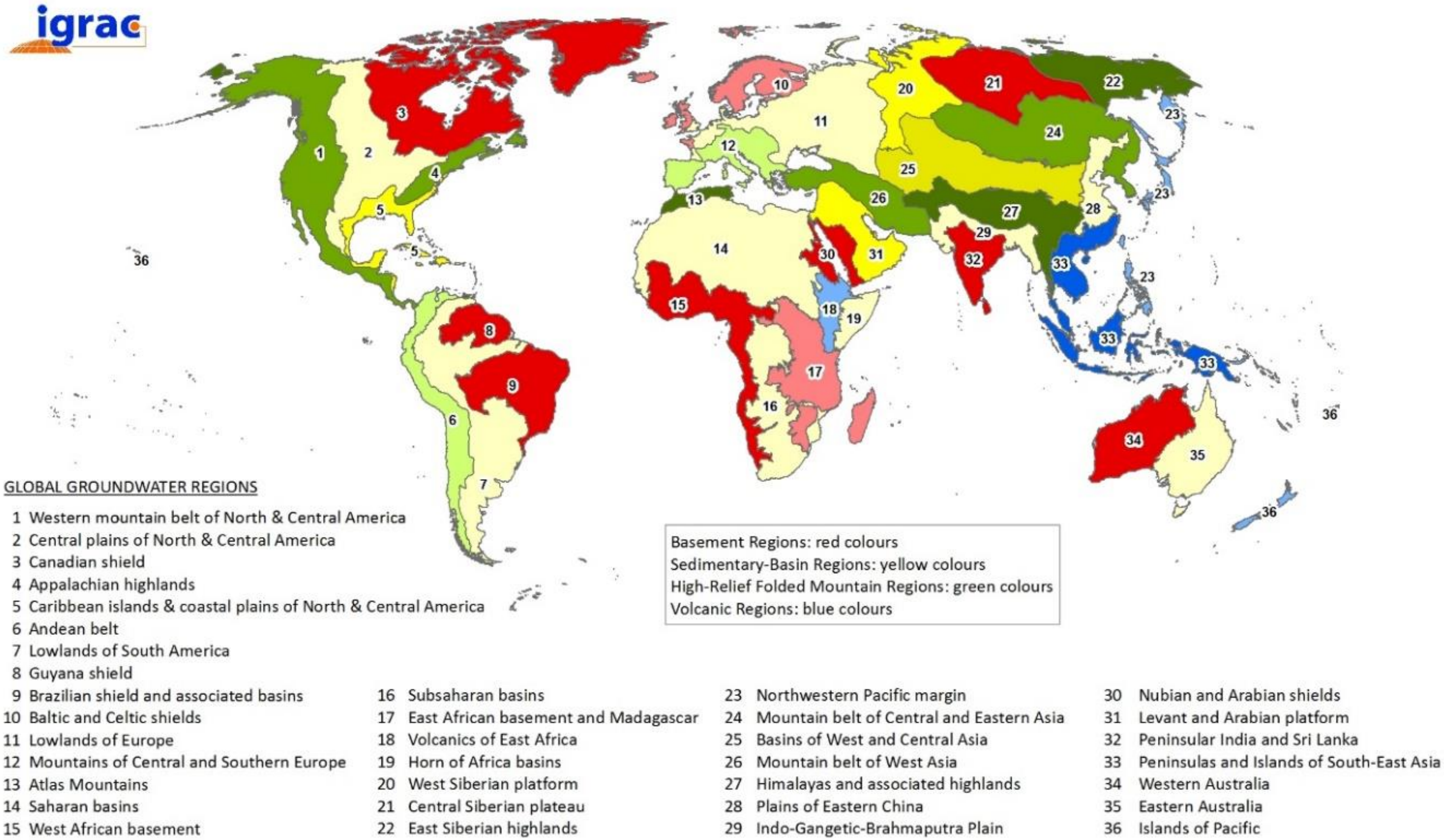

Figure 5 - The global groundwater regions as defined by IGRAC (Van der Gun et al., 2011; Margat and Van der Gun, 2013).

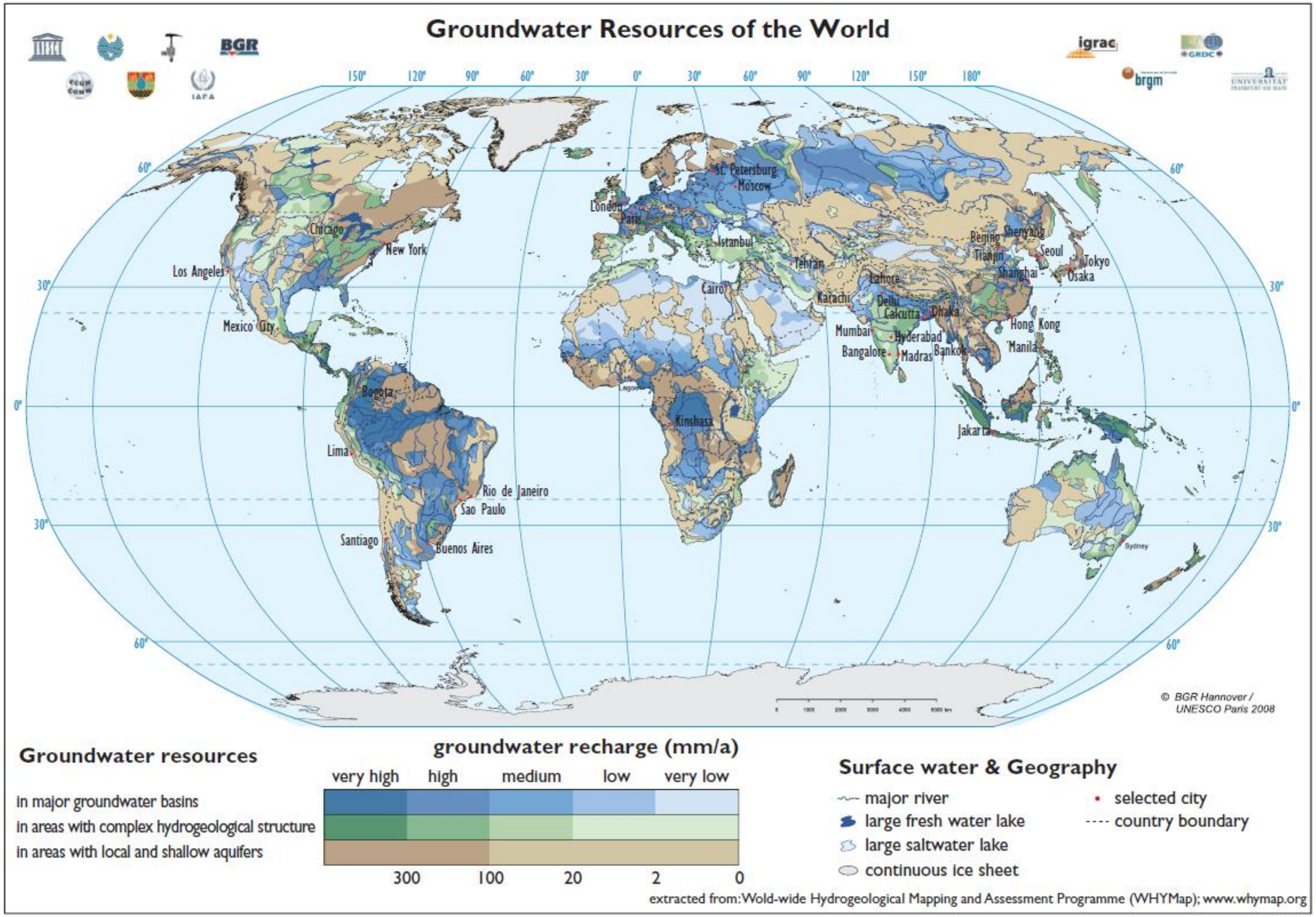

Figure 6 - Simplified version of WHYMAP's Hydrogeological World Map (BGR and UNESCO, 2008).

1.3.6 Renewable and Non-Renewable Groundwater Resources

Aquifer recharge corresponds to the inflow of water into an aquifer system[1]. The majority of the aquifers located within a few hundred meters of the land surface and containing fresh groundwater are actively recharged, in other words: they contain *renewable groundwater resources*. Most recharge water comes from natural sources (infiltration of rain, meltwater or surface water), but some regions also enjoy recharge from anthropogenic sources, such as infiltration of excess irrigation water, artificial recharge or pumping-induced recharge. Some aquifers, however, receive very little – if any – recharge due to climatic or geological factors; for that reason, their groundwater resources are called *non-renewable*. In practice, this qualification is not limited to absolutely zero recharge but is also used in cases of very low recharge. Among groundwater professionals, there is a lack of consensus on clear and numerically consistent criteria for distinguishing between renewable and non-renewable groundwater resources. Non-renewable groundwater may be linked to:

- the rate of contemporary mean annual recharge;
- groundwater age (Döll and Fiedler, 2008: fossil water);
- mean residence time (Margat et al., 2006: > 500 years; Bierkens and Wada, 2019: > 100 years);
- mean residence time combined with low mean annual recharge (Margat and Van der Gun, 2013: > 1000 years and < 5 mm/year, respectively); or,
- transition time required to re-establish hydraulic equilibrium after intensifying groundwater withdrawal (Ferguson et al., 2020: > 50-100 years).

Figure 7 shows the main regions around the globe where aquifers are not or are only weakly replenished due to climatic characteristics. Comparing Figure 7 with Figure 6 reveals that significant parts of the major groundwater basins in Northern Asia are located within a huge zone of continuous permafrost and therefore are not receiving any groundwater recharge. The major groundwater basins of Northern Africa, Southern Africa, the Arabian Peninsula and Australia are all located in arid and hyper-arid regions, which causes their groundwater resources to be non-renewable or weakly renewable. By contrast, aquifer systems containing only non-renewable groundwater resources are less abundant in the Americas, and they are much smaller. None of the very large groundwater basins in the Western Hemisphere belongs to the category of aquifer systems containing only non-renewable groundwater.

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[1] Aquifer recharge appears to be a simple variable, but is complicated in practice by its many potential components (sources) and the variations of omitting/including each particular type of source in the recharge estimate.

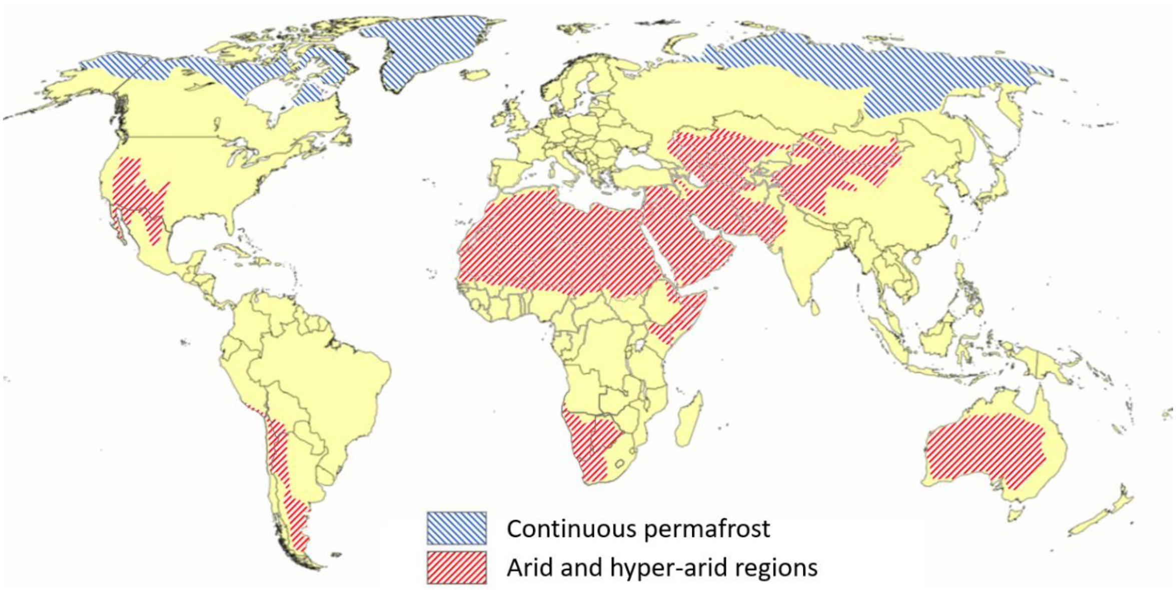

Figure 7 - Main regions with only non-renewable or weakly renewable groundwater resources due to climatic characteristics (based on Hanan et al., 2021, and Dolgikh, 2019).

It should be borne in mind that geology is another factor that may cause groundwater to be non-renewable. Many aquifers in deep groundwater basins are confined by impermeable layers and thus effectively disconnected from overlying aquifers and/or from the surface; therefore, they contain non-renewable groundwater. In principle, confining layers at or near the surface may also prevent shallow aquifers from being recharged.

1.4 Differences in Size: Small and Large Aquifers/Aquifer Systems

1.4.1 Criteria

How is the size of an aquifer defined? For those who see an aquifer as a container (the lithological matrix in which drainable groundwater is stored), it seems logical to define the size of an aquifer theoretically as its volumetric storage capacity, which equals the bulk volume of the aquifer rock times its mean specific yield. Specific yield is the fraction of the bulk aquifer volume occupied by water that can be drained by gravity. Estimating aquifer size according to this concept, however, is in practice possible for only very few aquifers in the world. In most cases, the data required for making such estimates with reasonable accuracy are not available because the aquifers are thick or deep, extend over large areas, and/or have been scarcely or only partially explored.

If an aquifer is perceived as a container (matrix) plus its content (groundwater), then one may resort to a more feasible, semi-quantitative approach for comparing or classifying the size of aquifers or aquifer systems. This approach is based on the following parameters: (i) horizontal area covered by the aquifer or aquifer system (in most cases reasonably known) and (ii) mean cumulative thickness of the hydraulically productive aquifer zones included in the vertical lithological sequence. In many cases, the size of an aquifer is only a rough estimate.

Tentatively, the following aquifer size classification is proposed:

- very small: less than 100 km^2 in horizontal extent;
- small: 100–500 km^2 in horizontal extent;
- medium: 500–5,000 km^2 in horizontal extent and with at least 20 m cumulative thickness of productive aquifer zones;
- large: 5,000–50,000 km^2 in horizontal extent and with at least 50 m cumulative thickness of productive aquifer zones; and,
- very large: more than 50,000 km^2 in horizontal extent and with at least 100 m cumulative thickness of productive aquifer zones.

If the thickness criterion is not met, then the aquifer is classified one class lower than the class corresponding to its area.

1.4.2 Small Aquifers

In principle, there is no lower limit to the size of an aquifer, but very small permeable bodies in the subsurface – say, 100 km^2 or less in lateral extent – are rarely identified as a separate aquifer (with a given aquifer name). Notable exceptions include a few small aquifers that span international boundaries:

- the Abbotsford-Sumas Aquifer, sand and gravel of 100 km^2 extent that provides water supply to 10,000 people in the USA and 100,000 in Canada;
- the Okanagan-Osoyoos Aquifer, multilayer unconsolidated sedimentary aquifer of 25 km^2 extent shared by Canada and the USA;
- the Grand Forks Aquifer, unconsolidated sediments 34 km^2 in extent shared by Canada and the USA; and,
- the Genovese Aquifer, Quaternary fluvio-glacial deposits that are 15-40 m thick of approximately 30 km^2 extent, from which 15-17 mm^3/year of groundwater is abstracted and shared by Switzerland and France. It is the first aquifer in the world with a formal international transboundary aquifer management agreement which has been in force since 1978.

These examples show that even very small aquifers can be important, which is highlighted by such aquifers being included in transboundary aquifer publications and/or agendas (Puri and Aureli, 2009; IGRAC, 2015). Also, myriad small aquifers – often unnamed – that are entirely located within one country (domestic aquifers) are important locally. Because they are numerous, usually shallow, and often closely linked to surface water (alluvial aquifers) thus favorably located to sources of recharge, small aquifers provide a significant share of the world's exploited groundwater. The smallest aquifers are predominantly tapped by self-suppliers, usually for domestic and agricultural purposes; many of them are vulnerable to seasonal depletion, especially in arid regions. Water utilities usually locate their wells in aquifers that are at least a few hundred square kilometers in extent and have sufficient capacity to buffer seasonal and interannual variations in recharge.

1.4.3 Large and Very Large Aquifers/Aquifer Systems

With increasing horizontal extent and thickness, aquifers tend to become more complex, interbedded with several aquitards, and often hydraulically connected to other aquifers that are usually located above or underneath. In such cases the term ‘aquifer systems’ is appropriate. Large aquifer systems play an important role in hydrogeology and as a source of water because together they cover a significant part of the continents and contain huge quantities of groundwater.

Figure 8 shows the approximate location of 70 large or very large aquifers/aquifer systems scattered over the globe. Table 3 lists their names corresponding to the numbers used to identify them in the figure. The selection consists of two distinct sets: a) 37 so-called mega aquifer systems; and, b) 33 other large aquifers or aquifer systems. The mega aquifer systems are considered to be our planet’s largest aquifer systems (these are discussed in Section 2). They contain a large share of all fresh groundwater reserves on earth. Part of the groundwater they store may be of considerable age (i.e., the time elapsed since water entered the aquifer system), up to the order of a million years. The selected ‘other large aquifers/aquifer systems’, although belonging to the category ‘large’ or ‘very large’, do not necessarily represent the next largest aquifer systems. Rather, aquifers have been selected that are large and also rank among the most well-known in their regions, either because of their importance or as an object of investigation. The selection thus is somewhat subjective.

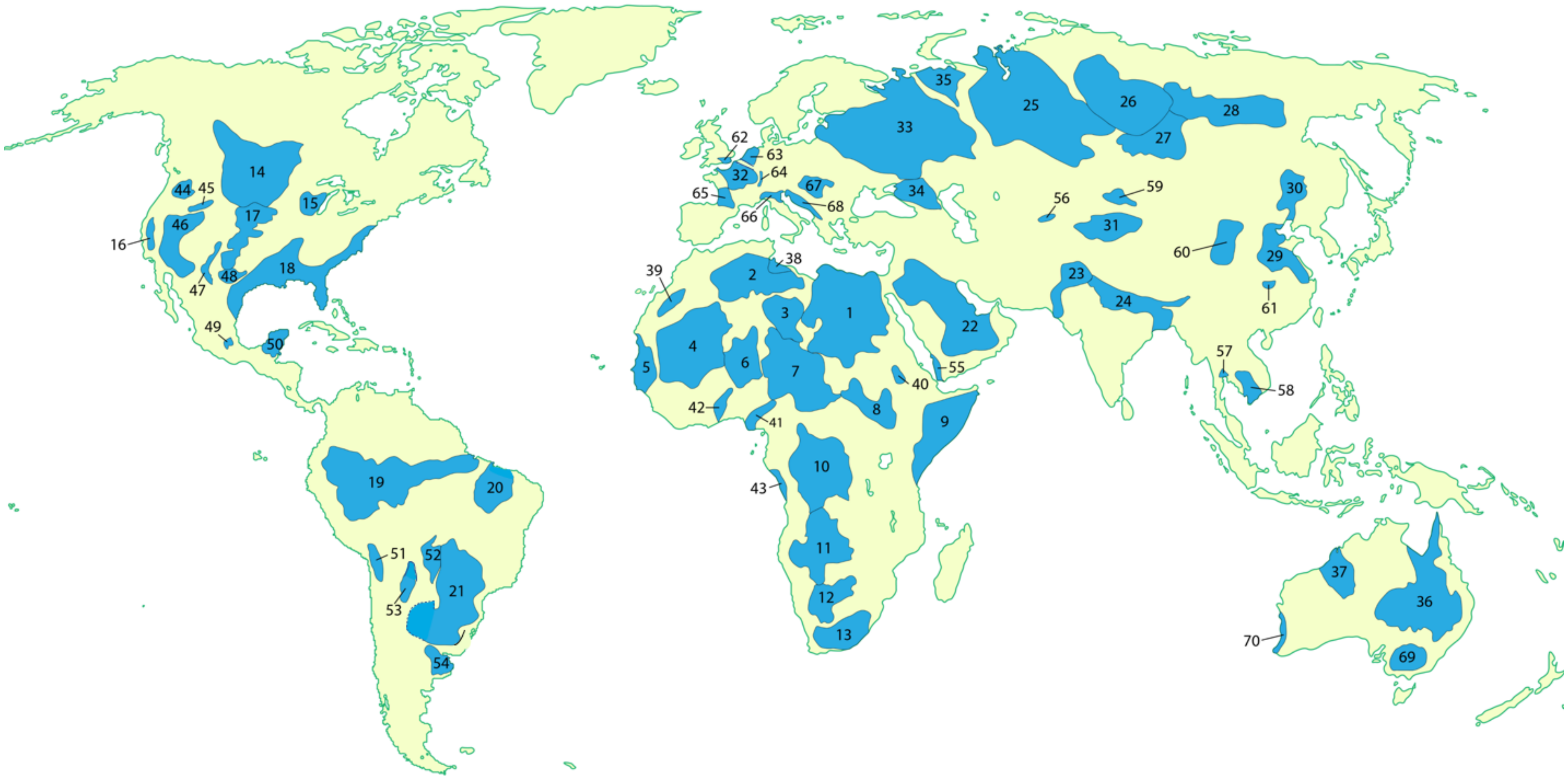

Figure 8 - Mega aquifer systems and selected other large aquifers/aquifer systems around the globe (**Table 3** associates names with the numbers)

Table 3 - Mega aquifer systems and selected other large aquifers/aquifer systems.

#	Mega aquifer systems	#	Other large aquifers/aquifer systems
	AFRICA		**AFRICA**
1	Nubian Aquifer System (NAS)	38	Djeffara Aquifer System
2	North-Western Sahara Aquifer System	39	Tindouf Basin
3	Murzuk–Djado Basin	40	Gedaref Basin
4	Taoudeni-Tanezrouft Basin	41	Vallée de la Bénoué
5	Senegalo-Mauritanian Basin	42	Volta Basin
6	Iullemeden–Irhazer Aquifer System	43	Aquifère côtier
7	Lake Chad Basin		
8	Sudd Basin (Umm Ruwaba Aquifer)		
9	Ogaden-Juba Basin		
10	Congo Basin		
11	Cuvelai-Upper Zambezi Basin (Upper Kalahari)		
12	Stampriet-Kalahari Basin (Lower Kalahari)		
13	Karoo Basin		
	NORTH AMERICA		**NORTH AMERICA**
14	Northern Great Plains Aquifer System	44	Columbia Plateau aquifer system
15	Cambrian-Ordovician Aquifer System	45	Snake River Plain aquifer system
16	California's Central Valley Aquifer System	46	Basin and Range aquifer system
17	High Plains Aquifer (Ogallala)	47	Rio Grande aquifer system
18	Atlantic and Gulf Coastal Aquifer System	48	Edwards-Trinity aquifer system
		49	Mexico Basin
		50	Yucatán karst aquifer system
	SOUTH AMERICA		**SOUTH AMERICA**
19	Amazon Basin	51	Andean Altiplano aquifer
20	Maranhão Basin (Parnaíba Basin)	52	Pantanal aquifer system
21	Guarani Basin (Paraná Basin)	53	Yrendá-Toba-Tarijeño aquifer system
		54	Puelche aquifer
	ASIA		**ASIA**
22	Arabian Aquifer System	55	Tihama aquifer
23	Indus Basin	56	Pretashkent aquifer system
24	Ganges-Brahmaputra Basin	57	Lower Central Plain aquifer
25	West Siberian Basin	58	Cambodia-Mekong Delta aquifer
26	Tunguss Basin	59	Junggur Basin
27	Angara-Lena Basin	60	Ordos Basin
28	Yakut Basin	61	Jianghan-Dongting Plain aquifer system
29	Greater North China Plain Aquifer System		
30	Song-Liao Plain (NE China Plain)		
31	Tarim Basin		
	EUROPE		**EUROPE**
32	Paris Basin	62	London Basin
33	Russian Platform Basins	63	Belgian-Dutch-German Lowland aquifer
34	North Caucasus Basin	64	Upper Rhine Graben aquifer
35	Pechora Basin	65	Aquitanian Basin
		66	Po Valley aquifer system
		67	Pannonian aquifer system
		68	Dinaric karst aquifer system
	AUSTRALIA		**AUSTRALIA**
36	Great Artesian Basin	69	Murray Basin
37	Canning Basin	70	Perth Basin

Some well-known aquifer systems are not shown by name in Table 3, because they are implicitly included as components of the listed and mapped large aquifer systems. Examples include the Dakota Aquifer (partly) and the Canadian Paskapoo aquifer as components of the Northern Great Plains Aquifer System; the Floridan Aquifer System and the Mississippi Embayment Aquifer System as components of the Gulf and Atlantic Coastal Aquifer System; and the Saq-Ram, Wajid and Umm er Radhuma-Dammam Aquifer Systems as components of the Arabian Aquifer System.

In principle, this book uses the aquifer and aquifer system names used in the consulted literature, except when that use would lead to confusion or when deemed unsatisfactory for other reasons. A few mega aquifer systems have been renamed, as indicated and explained in Section 2. Sections 2 and 3 focus exclusively on the mega aquifer systems.

1.5 Opportunities to Test Knowledge Gained in this Section

To exercise the knowledge gained while reading this section, investigate exercises 1 through 4. Links are provided to each exercise below.

Exercise 1↴

Exercise 2↴

Exercise 3↴

Exercise 4↴

2 Mega Aquifer Systems

The term 'mega aquifer systems' is used here to denote the world's largest aquifer systems. This section identifies the thirty-seven largest aquifer systems followed by a concise description of some of their main characteristics. These include horizontal extent, thickness, geological characteristics, estimated fresh groundwater reserves and groundwater quality. The compilation is constrained by the scarcity of publicly accessible information on some of the mega aquifer systems, written in a language understood by the author. Exploration and assessment of the mega aquifer systems have advanced to varying degrees, but in all cases, much remains unknown because of the huge size and great depth of these aquifer systems.

2.1 Margat's Inventory of Mega Aquifer Systems

In his world-wide inventory of large aquifer systems, Margat (2006; 2008) identified thirty-seven large aquifer systems and classified them as *'les très grands systèmes aquifères du monde'* (the world's very large aquifer systems). Later, Margat and Van der Gun (2013) introduced the term '*mega aquifer systems*' for this category of very large aquifer systems. Figure 9 shows the location of these mega aquifer systems (projected on WHYMAP's hydrogeological world map), while Table 4 lists their names and approximate size.

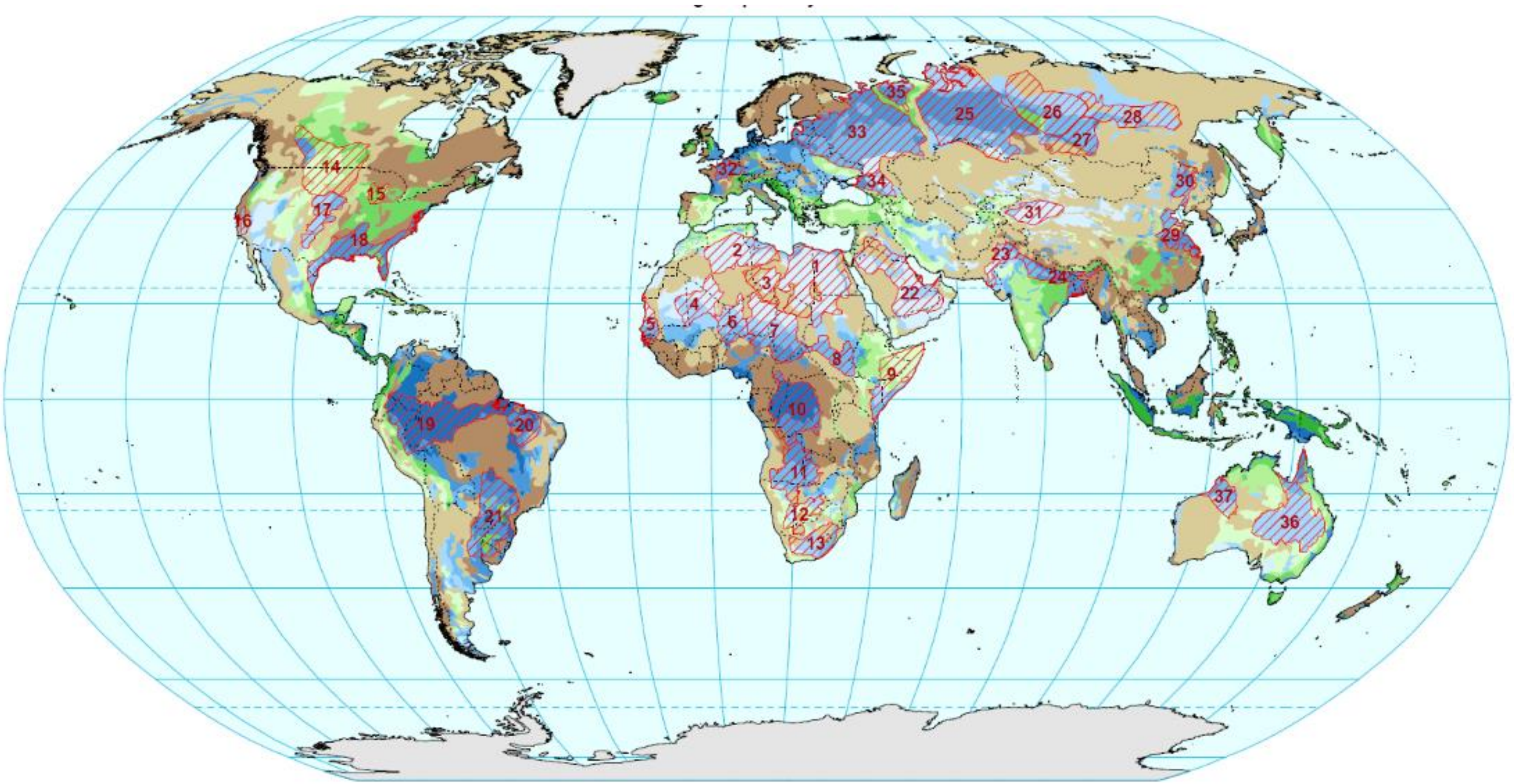

Figure 9 - The world's mega aquifer systems (after Margat, 2008; WHYMAP, 2008).

Table 4 - The Earth's mega aquifer systems (after Margat and Van der Gun, 2013, modified).

#	Aquifer System	Area (x 1 000 km^2)	Maximum thickness (m)	Countries involved (ISO-3 alpha code)
	AFRICA			
1	Nubian Aquifer System (NAS) (Nubian and Post-Nubian Systems)	2 199	3 500	EGY, LBY, SDN, TCD
2	North-Western Sahara Aquifer System	1 019	1 600	DZA, LBY, TUN
3	Murzuk-Djado Basin	450	2 500	DZA, LBY, NER
4	Taoudeni-Tanezrouft Basin	2 000	4 000	DZA, MRT, MLI
5	Senegalo-Mauritanian Basin	300	500	MRT, SEN, GMB, GNB
6	Iullemeden-Irhazer Aquifer System	635	1 500	NER, DZA, MLI, NGA
7	Lake Chad Basin	1 917	7 000	NER, NGA, TCD, CMR, CAF
8	Sudd Basin (Umm Ruwaba Aquifer)	365	3 000	SSD, SDN, ETH
9	Ogaden-Juba Basin	~1 000	12 000	ETH, SOM, KEN
10	Congo Basin	~1450	3 500	COG, COD, AGO, RAF, GAB
11	Cuvelai-Upper Zambezi Basin (Upper Kalahari)	~900		AGO, BWA, NAM, ZMB, ZWE
12	Stampriet-Kalahari Basin (Lower Kalahari)	~350		ZAF, BWA, NAM
13	Karoo Basin	600	7 000	ZAF
	NORTH AMERICA			
14	Northern Great Plains Aquifer System	770	2 000	CAN, USA
15	Cambrian-Ordovician Aquifer System	250	1 000	USA
16	California's Central Valley Aquifer System	52	600	USA
17	High Plains Aquifer (Ogallala)	450	150	USA
18	Atlantic and Gulf Coastal Aquifer System	1 150	12 000	USA, MEX
	SOUTH AMERICA			
19	Amazon Basin	2000	7 000	BRA, COL, PER, BOL
20	Maranhão Basin (ParnaÍba Basin)	700	3 000	BRA
21	Guarani Basin (Paraná Basin)	1 195	800	BRA, ARG, PRY, URY
	ASIA			
22	Arabian Aquifer System	> 1 485	6 500	SAU, JOR, KWT, BHR, QTR
23	Indus Basin	~ 320	300	PAK, IND
24	Ganges-Brahmaputra Basin	~ 600	600	IND, NPL, BGD
25	West Siberian Basin	3 200	6 000	RUS
26	Tunguss Basin	1 000	4 000	RUS
27	Angara-Lena Basin	600	3 000	RUS
28	Yakut Basin	720	1 200	RUS
29	Greater North China Plain Aquifer System (Huang Huai Hai Plain)	320	600	CHN
30	Song-Liao Plain (NE China Plain)	311	300	CHN
31	Tarim Basin	520	1 200	CHN
	EUROPE			
32	Paris Basin	190	3 200	FRA
33	Russian Platform Basins	~ 3 100	20 000	RUS, EST, LVA,LTU,BLR, UKR
34	North Caucasus Basin	230	10 000	RUS
35	Pechora Basin	350	3 000	RUS
	AUSTRALIA			
36	Great Artesian Basin	1 700	3 000	AUS
37	Canning Basin	430	1 000	AUS

The names of four of these systems require some clarification. First, in publications system number 1 is alternately called 'Nubian Aquifer System' and 'Nubian Sandstones Aquifer System', often indiscriminately. Here, the name 'Nubian Aquifer System' is used to indicate the total system extending northward to the Mediterranean Sea, including both the Nubian Sandstones and the Post-Nubian sediments which overly and confine the northward dipping Nubian Sandstones to the north of roughly 26°N. Second, system number 18, originally called the 'Atlantic and Gulf Coastal Plains Aquifer System', has been renamed to 'Atlantic and Gulf Coastal Aquifer System', to better represent all included aquifer units. Third, system number 21 is renamed here to 'Guarani Basin', because the name 'Guarani Aquifer System' – used by Margat and Van der Gun (2013) – refers in most publications only to the largely confined Guarani aquifer, without including other aquifers in the basin such as those present in the overlying Serra Geral Basalts and Bauru-Caiuá sediments. The Guaraní Basin is also known as Paraná Basin (Rebouças,1999; Feitosa *et al*, 2016). Fourth, publications alternately use the name 'North China Plain' to indicate either the Huang Huai Hai Plain (320,000 km^2 in extent) or – in most cases – only the northern part of this area (Hai Plain, 136,000 km^2). Therefore, the name 'Greater North China Plain' is used here to indicate mega aquifer system number 29, as an English equivalent of the name Huang Huai Hai Plain.

2.2 Horizontal Extent and Thickness

As Table 4 shows, the mega aquifer systems are very large, but their sizes vary considerably. Fourteen of them have an extent of one million square kilometers or more. The largest aquifer system – the West-Siberian Basin – measures 3.2 million km^2, while the smallest one – California's Central Valley Aquifer System – measures only 52 thousand km^2. These and other numbers in Table 4 are subject to considerable uncertainty because detailed assessment of an entire mega aquifer system requires far more financial resources and efforts than are usually available. It is therefore likely that several of the listed mega aquifer systems in reality do not form a single hydraulically continuous system but consist of several neighboring, hydraulically unconnected, or poorly connected, aquifer systems composed of similar geological formations. For the same reason, parts of the lateral boundaries undoubtedly have been deduced from secondary information rather than defined and confirmed by field work. Together, the 37 mega aquifer systems cover an area of around 35 million km^2, which is almost 26 percent of the total land surface on earth excluding Antarctica (136 million km^2).

It is difficult to accurately define the mean thickness of the mega aquifer systems. The estimates of maximum thickness for many of the systems listed in Table 4 are large, but the lack of field observations limits the accuracy of most of these values. Furthermore, most of the values probably refer to the entire sedimentary sequence of aquifers and confining units (e.g., Atlantic and Gulf Coastal Aquifer System) rather than to only the aquifer beds (e.g., High Plains Aquifer), but this is often not clearly stated in the publications. Note that the mean thickness of mega aquifer systems is usually substantially less than their maximum thickness, in particular in sedimentary basins. This is illustrated in Figure 10 for the Paris Basin, where the maximum thickness of the sedimentary sequence is perhaps four to five times its mean thickness. In addition, the mean cumulative thickness of productive aquifer rocks is even less because a significant part of the vertical lithological sequence is occupied by confining beds. Finally, the deeper aquifer beds in the majority of the mega aquifer systems tend to contain brackish or saline water, and occasionally hydrocarbons.

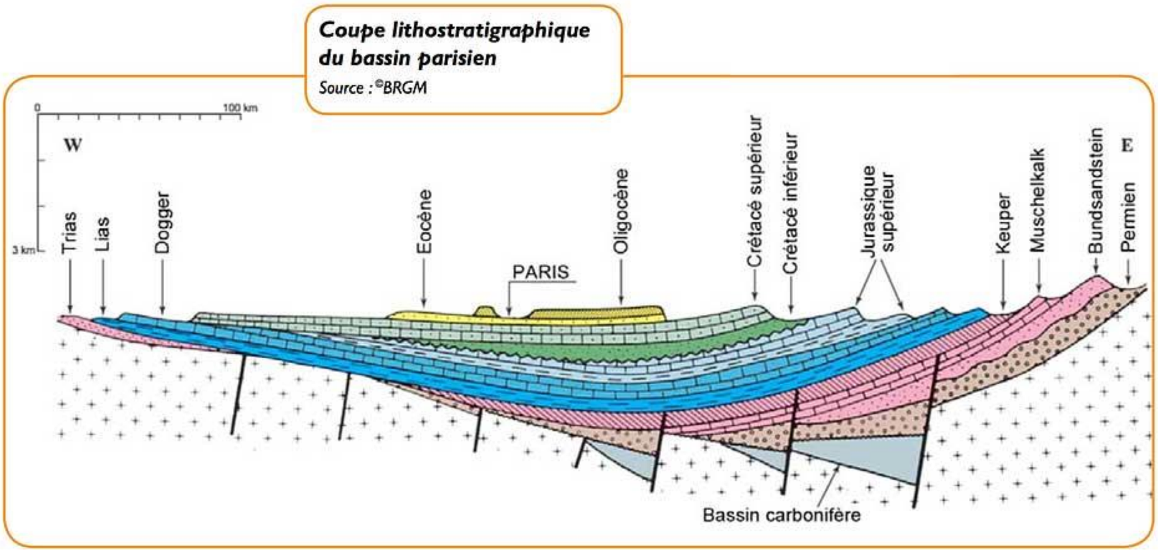

Figure 10 - Simplified geological section across the Paris Basin (Hanot et al., 2011).

2.3 Geology: Age, Lithology and Structural Setting

Table 5 summarizes the geological characteristics of each of the mega aquifer systems through two attributes: age and lithology. The aquifer units included in these systems consist mainly of sediments, among which sandstones and sands are predominant, in several cases in combination with carbonates. Most of these aquifer units form, together with interbedded clays and shales, a complex multilayer sedimentary aquifer system. The age of these sediments varies, but in most cases, their deposition spans a very long period, that began long ago. Millions of years of deposition (in some cases even 600 million years) resulted in thick sedimentary sequences, as indicated in Table 4.

Table 5 - Geological characteristics of the mega aquifer systems (after Margat and Van der Gun, 2013; modified).

#	Aquifer System	Geological Characteristics of the Aquifer Units	
		Age	**Predominant Lithology**
	AFRICA		
1	Nubian Aquifer System (Nubian and Post-Nubian)	Cambro-Ordovician to Oligocene	Continental sandstones
2	North-Western Sahara Aquifer System (NWSAS)	Cambro-Ordovician to Miocene	Sandstones, carbonates and clastic sediments
3	Murzuk-Djado Basin	Cambro-Ordovician to Cretaceous	Sandstones
4	Taoudeni-Tanezrouft Basin	Infra-Cambrian* to Tertiary	Sandstones, carbonates and clastic sediments
5	Senegalo-Mauritanian Basin	Cretaceous to Miocene	Sands
6	Iullemeden-Irhazer Aquifer System	Cambro-Ordovician to Eocene	Sandstones and sands
7	Lake Chad Basin	Cretaceous to Quaternary	Sandstones and sands
8	Sudd Basin (Umm Ruwaba)	Neogene-Quaternary	Sand and gravel, sandstones
9	Ogaden-Juba Basin	Jurassic to Quaternary	Limestones, sandstones, sands
10	Congo Basin	Mesozoic to Quaternary	Sandstones, sand and gravel
11	Cuvelai-Upper Zambezi Basin (Upper Kalahari)	Carboniferous to Jurassic, Late Cretaceous to Neogene	Sandstones, basalts and sands
12	Stampriet-Kalahari Basin (Lower Kalahari)	Carboniferous to Jurassic, Late Cretaceous to Neogene	Sandstones, basalts and sands
13	Karoo Basin	Late Carboniferous to Mid Jurassic	Sandstones with interbedded shales, basalt lava capping, dolerite dykes
	NORTH AMERICA		
14	Northern Great Plains Aquifer	Palaeozoic, and Cretaceous to Eocene	Carbonate rocks and sandstones
15	Cambrian-Ordovician Aquifer System	Cambrian-Ordovician	Marine sandstones and carbonates
16	California's Central Valley Aquifer System	Quaternary	Sand and gravel (multi-layer)
17	High Plains Aquifer (Ogallala)	Tertiary	Sand and gravel
18	Atlantic and Gulf Coastal Aquifer System	Jurassic to Holocene	Un-/semi-consolidated sand and gravel & carbonate rocks
	SOUTH AMERICA		
19	Amazon Basin	Ordovician to Tertiary	Sandstones (fine-grained) and sands
20	Maranhão Basin	Silurian to Cretaceous	Sandstones
21	Guarani Basin	Ordovician to Cretaceous	Sandstones and basalts
	ASIA		
22	Arabian Aquifer System	Cambrian to Neogene	Sandstones, limestones
23	Indus Basin	Miocene to Holocene	Unconfined alluvial deposits
24	Ganges-Brahmaputra Basin	Miocene to Holocene	Unconfined alluvial deposits
25	West Siberian Basin	Paleozoic to Cainozoic	Sediments (partly sub-permafrost)
26	Tungus Basin	Cambrian to Triassic	Sediments (sub-permafrost)
27	Angara-Lena Basin	Cambrian to Jurassic	Sediments

Continued – Table 5 Geological characteristics of the mega aquifer systems (after Margat and Van der Gun, 2013; modified).

#	Aquifer System	Geological Characteristics of the Aquifer Units	
		Age	**Predominant Lithology**
28	Yakut Basin	Upper-Cambrian to Cretaceous	Sediments (sub-permafrost)
29	Greater North China Plain (Huang Huai Hai Plain)	Quaternary	Confined and unconfined alluvial deposits
30	Song-Liao Plain	Quaternary	Confined and unconfined alluvial deposits
31	Tarim Basin	Quaternary	Confined and unconfined alluvial deposits
	EUROPE		
32	Paris Basin	Triassic to Neogene	Sand, chalk, sandstone
33	Russian Platform Basins	Infra-Cambrian to Quaternary	Sediments, part of them metamorphosed
34	North Caucasus Basin	Carboniferous to Neogene	Sediments
35	Pechora Basin	Ordovician to Tertiary	Sediments
	AUSTRALIA		
36	Great Artesian Basin	Triassic to Cretaceous	Sandstones
37	Canning Basin	Devonian to Cretaceous	Sandstones

* 'Infra-Cambrian' refers to the Late Ediacaran and Early Cambrian intervals between circa 585-530 million years ago (Al-Husseini, 2010).

The mega aquifer systems are embedded in structural geologic units that favor the accumulation of thick sequences of sediments over large areas. Such settings include sedimentary basins, such as the Congo, Paris and Tarim basins. Other typical settings of mega aquifer systems are rifted depressions in which sediments accumulate (e.g., California's Central Valley and the North China Plain Aquifer System), and platforms covered by thick blankets of sediments deposited in piedmont, alluvial or glacial plain environments (e.g., High Plains Aquifer System, West Siberian Basin). Mixed setting types also occur. This characterization may give the impression of rather simple structural features of the mega aquifer systems but these are often much more complex.

In the first place, complexity occurs because many of these sedimentary basins consist of several subbasins, with different degrees of hydraulic interconnection. For instance, the:

- Dakhla, Kufra and Northern Sudan Platform subbasins in the Nubian Aquifer System;
- Great Western Erg and Great Eastern Erg in the North-Western Sahara Aquifer System;
- many subbasins included in the Russian Platform Basins;
- subbasins of the Great Artesian Basin (Surat, Eromanga, Carpentaria and part of the Clarence-Moreton geological basins);
- four subbasins of the Canning Basin (Kidson Basin, Willara Basin, Broome Platform and Fitzroy/Gregory Basin); and the,

- downfaulted Central Valley trough in California includes three distinct zones (Sacramento Valley, Sacramento-San Joaquin Delta and San Joaquin Valley).

In the second place, there is complexity because the mega aquifer systems often contain a large number of aquifers and aquitards, producing considerable lithological and hydraulic diversity. Examples are the:

- Arabian Aquifer System;
- Paris Basin; and the,
- Atlantic and Gulf Coastal Plains Aquifer System (consisting of several distinct zones: Gulf Coastal Plain, Mississippi Embayment, Florida, Atlantic Coastal Plain, each including a variety of aquifers).

Among all the mega aquifer systems considered, the High Plains Aquifer System seems to be the simplest, in terms of structure and lithostratigraphic variation.

2.4 Recoverable Volumes of Stored Groundwater: Groundwater Reserves

2.4.1 Total Stored Volume Versus Groundwater Reserves

Before focusing on the recoverable volumes of groundwater stored in the mega aquifer systems, it is useful to give some thought to what is meant by the term '*volume of stored groundwater*. The most obvious interpretation is that this includes all water present in the interstices of the saturated rock formations in the area or aquifer system concerned. In its most simple form: the volume of groundwater storage equals the bulk volume of saturated rock times mean porosity. Although usually not explicitly mentioned, this seems to be the idea underlying the various estimates of the global volume of groundwater made since the 1960s (e.g., Nace, 1969; NRC, 1986; Shiklomanov and Rodda, 2003; Margat and Van der Gun, 2013; Gleeson et al., 2016). These estimates are no more than educated guesses, based on generic assumptions about the subsurface rather than on area-specific geological data and information, but they have contributed to a widely accepted belief among the global groundwater community that the total volume of groundwater on Earth is approximately 23 million km^3, of which between 8 and 9 million km^3 is fresh.

However, one should be aware that a considerable share of all groundwater cannot be abstracted by wells, nor drained under gravity, due to matrix forces that keep a fraction of the water trapped in the pores of saturated formations (represented by the parameter *specific retention*). These matrix forces are particularly strong and effective in fine-grained formations such as clays and shales that form aquitards. For this reason, more relevant than the total volume of groundwater is the '*theoretically recoverable groundwater volume*' (or '*groundwater reserves*'), which is calculated as the product of the bulk volume of saturated rock and its specific yield. Estimates of stored groundwater volumes made in the framework of regional or aquifer-specific studies commonly are based on this interpretation of groundwater storage; although often not explicitly mentioned, this can usually be concluded from the text or data presented in the report or paper. When producing their estimates for aquifer systems that contain both aquifers and aquitards, hydrogeologists usually disregard the aquitards, since their contribution to the total theoretically recoverable volume of groundwater is minimal. Permafrost in several of the Russian mega aquifer systems creates special conditions that significantly reduce the aquifer volume occupied by drainable groundwater, as illustrated in Box 1⤵. In practice, only a minor part of the groundwater reserves is available for exploitation, due to technical, financial and water quality constraints as well as the need to avoid undesired side effects such as land subsidence and harmful impacts on surface water and aquatic ecosystems (Alley, 2007).

2.4.2 Assessing Groundwater Reserves

The volume of recoverable groundwater stored in the mega aquifer systems is difficult to assess, given the vast extent and considerable thickness of the systems. Nevertheless, several scientists attempted to do so. For instance, MacDonald and others (2012) have mapped groundwater storage in Africa, based on their assessment of saturated aquifer thickness and effective porosity (Figure 11). The African mega aquifer systems are visible on this map. The authors estimate total recoverable groundwater storage in Africa to be 0.66 million km^3, and the greatest mean equivalent water depths (> 25 m) are found in the Nubian Aquifer System, the North-Western Sahara Aquifer System, the Murzuk-Djado Basin, the Senegalo-Mauritanian Basin and the Lower Kalahari-Stampriet Basin. Richey and others (2015a) estimated recoverable groundwater storage for all 37 mega aquifer systems considered in this book, but their estimates seem to be poorly underpinned by geological data and they are presented for each aquifer system in the form of minimum and maximum values that differ mostly by two orders of magnitude. Therefore, for a closer look at groundwater reserves, the focus here will be on estimates produced by hydro-geologists investigating individual mega aquifer systems and assumed to be familiar with the geology of these systems.

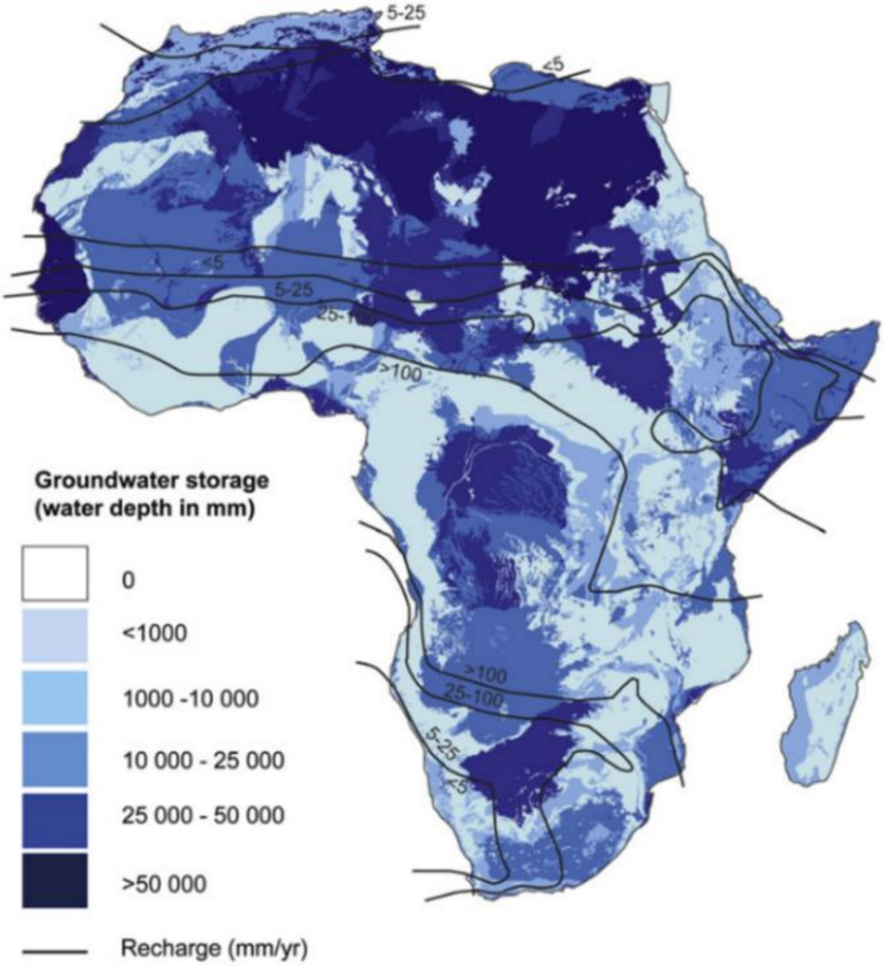

Figure 11 - Estimated equivalent depth of recoverable water stored in Africa's aquifers (MacDonald et al., 2012).

Groundwater assessments of aquifers and aquifer systems only rarely include estimates of recoverable groundwater storage. Consequently, reports and publications presenting such estimates are not abundant, and therefore estimates of recoverable groundwater storage have only been found for approximately half of the mega aquifer systems, in some cases including only parts of these systems. These estimates are presented in Table 6, expressed in thousands of cubic kilometers (third column), and – to facilitate comparison and analysis – converted (in the fourth column) to an equivalent mean depth of water over the entire horizontal area occupied by the aquifer system. Although detailed explanations are missing in the majority of the publications, it is assumed that all estimates refer to fresh groundwater reserves stored in aquifers.

Table 6 - Estimates of theoretically recoverable groundwater storage ('groundwater reserves') for selected mega aquifer systems (or parts of these systems).

#	Aquifer System	Groundwater storage		Source	Comments
		10^3 km^3	Equivalent depth (m)		
1	Nubian Aquifer System (NSAS)	457	208	Bakhbakhi, 2006	Only fresh groundwater (saline water = 68 m)
		542	247	Salem, 2005	Only fresh groundwater
		500	227	OSS, 2020	
2	NW Sahara (NWSAS)	31	30	Baba Sy, 2010	
		60	59	Zektser & Everett, 2004; OSS, 2020	
3	Murzuk-Djado Basin	4.8	11	Salem, 2005; OSS, 2020	
4	Taoudeni-Tanezrouft	10	3.0	OSS, 2020	
5	Senegalo-Mauritanian	9 – 10	30 – 33	Diagana, 2005b	
		1.5	5.0	OSS, 2020	
6	Iullemeden-Irhazer	4.95	7.8	Baba Sy, 2010; OSS, 2020	
7	Lake Chad Basin	5.8	3.0	OSS, 2020	
8	Sudd Basin	11.5	32	RSS, 2015	Area 432,700 km^2
16	Central Valley	0.86	16.5	Scanlon et al., 2012	Predevelopment (1860s): 1000 km^3 (19.2 m)
		1.02	19.6	Kang & Jackson, 2016	Fresh in upper 1000 m (TDS < 3000 ppm)
		2.7	51.9	Kang & Jackson, 2016	Fresh down to 3000 m (TDS < 3000 ppm)
17	High Plains	3.67	8.2	Scanlon et al., 2012	Predevelopment (1950s): 4000 km^3 (8.9 m)
19	Amazon Basin	32.5	21.7	Rebouças, 1999	Only Cenozoic strata
20	Maranhão Basin	17.5	25.0	Rebouças, 1999	
21	Guarani Basin	40	33.5	Tujchneider et al., 2010	
		30	25.2	Hirata & Foster, 2020	
22	Arabian Aquifer System	253	171	Chowdhury & Zahrani, 2013; Frenken, 2009	Water Atlas of Saudi Arabia (only share of Saudi Arabia)
		338	228	Chowdhury & Zahrani, 2013; Frenken, 2009	Ministry of Planning SAU (only share of Saudi Arabia)
23	Indus Basin	10.4	33	MacDonald et al., 2012	Only upper 200 m of 3000 m of sediments
24	Ganges-Brahmaputra Basin	19.6	33	MacDonald et al., 2012	Only upper 200 m of 3000 m of sediments
29	Greater N. China Plain	3.96	29	Cao et al., 2013	Only Hai Plain (136,000 km^2)
32	Paris Basin	> 0.68	> 3.6	König, 2015	Only Lower Cretaceous Albien (425 km^3) and Néocomien (230 km^3), plus Tertiary Nappe de Beauce (20 km^3)
		0.70	4.0	SIGES, 2021	Albien and Néocomien
36	Great Artesian Basin	87	51	Habermehl, no date	Earliest estimate
		64.9	38	Hillier & Foster, 2002	

2.4.3 Comparison and Analysis of the Estimates of Groundwater Reserves

Purposefully, Table 6 shows alternative estimates for several of the aquifer systems. This is done not only to avoid choosing between alternatives without careful analysis but more to emphasize that the estimates are subject to a large degree of uncertainty, caused by the scarcity of geological data and the unavoidable subjectivity of their hydrogeological interpretation. Despite the uncertainties, the set of estimates suggests that most of the mega aquifer systems have groundwater reserves equivalent to a mean depth of water of tens to hundreds of meters. The area-weighted average equivalent thickness for all the mega aquifer systems is 69 m. That value would certainly have been 10 to 20 percent more if the total thickness of the Amazon, Indus and Ganges-Brahmaputra basins had been included in the table.

By extrapolation one may estimate that the groundwater reserves of the 37 mega aquifer systems together are between 2 and 3 million km^3. Among the mega aquifer systems listed in Table 6, the largest reserves are present in order of their magnitude in the:

- Nubian Aquifer System;
- Arabian Aquifer System;
- Great Artesian Basin;
- North-Western Sahara Aquifer System;
- Guaraní Basin;

and if the entire sedimentary sequences are taken into account, they are probably followed by the:

- Amazon Basin;
- Indus Basin; and,
- Ganges-Brahmaputra Basin.

Among the aquifer systems that are not listed, most likely the Russian Platform Basins and the West-Siberian Basin contain huge reserves, given their enormous extent and large thickness of accumulated porous sediments. Nevertheless, the fresh groundwater reserves of the latter may be much smaller than expected at first glance, because large parts of the aquifer interstices are filled with ice (as discussed in Box 1) or saline water (Foley et al, 1994).

What share of the total groundwater reserves of the world's continents is stored in the 37 mega aquifer systems? This question is difficult to answer in the absence of reliable data on the total volume of theoretically recoverable groundwater on earth. Nevertheless, an educated guess can be made by using the Groundwater Resources Map prepared by WYMAP (WHYMAP, 2008; Richts et al., 2011). This map divides the earth's land area (excluding Antarctica) based on groundwater occurrence into three main classes: major groundwater basins (35%), areas with complex hydrogeological structure (18%) and areas with only local and shallow aquifers (47%). Assuming the mean theoretically recoverable groundwater volume per square kilometer for the first class to be equal to that of the mega aquifers (which is probably an overestimate), and for the second and third classes to be 20% and 1% of that value, respectively, leads to the estimate that the 37 mega aquifer systems contain 64% of the world's total fresh groundwater reserves. As mentioned before, this percentage is only an educated guess and thus subject to a large margin of uncertainty, but it is plausible to conclude that the 37 mega aquifer systems contain more than half of the world's fresh groundwater reserves, perhaps even two-thirds. It is useful to note that offshore fresh groundwater has not been taken into account in this analysis.

2.4.4 Age of Stored Groundwater

The volume of groundwater reserves in these mega aquifer systems exceeds the annual recharge volumes by several orders of magnitude, as will follow from comparing the above-presented estimates with recharge estimates in Section 3.1. This implies that the age of groundwater (i.e., the time elapsed since it entered the aquifer system) varies enormously within each aquifer system; in particular, water may be very old in zones of stagnant water and zones where groundwater has already traveled over long flow paths. Indeed, groundwater investigations using environmental isotope techniques have confirmed the presence of very old groundwater in certain zones of large aquifers systems, in combination with rather young water elsewhere within the same systems (Matray and Chery, 1998; Thorweihe and Heinl, 2002; IAEA, 2017a). As reported by Voss and Soliman (2014), groundwater below oases in Egypt has been interpreted to be on the order of 1 million years old. As can be expected based on hydrological and hydraulic considerations, the youngest waters tend to be dominant at shallow depths while groundwater ages statistically increase with depth. Jasechko and others (2017) established – based on groundwater carbon isotope data from thousands of wells in 62 aquifers around the globe – the predominance of modern water at shallow depths and demonstrated that below a certain depth (varying from 50 to 550 m) the majority of the wells in each of these aquifers are dominated by groundwater older than 15,000 years.

2.5 Groundwater Quality

Groundwater quality in the mega aquifer systems can be viewed from different angles: natural or geogenic quality on the one hand, and groundwater quality as modified (usually polluted) by anthropogenic factors on the other. Below, a few aspects of groundwater quality in the mega aquifers systems are briefly reviewed. The main purpose is to provide an impression of the macro-variation of important water quality parameters that determine the suitability of these groundwater resources for human uses, such as domestic and irrigation water use.

2.5.1 Groundwater Salinity

The total concentration of dissolved solids or salts (TDS, expressed in mg/L or ppm) is a widely used water quality indicator. Commonly, three main classes are distinguished: fresh, brackish and saline water. Saline water is sometimes subdivided into subclasses like slightly to moderately saline, highly saline and hypersaline. The class limits are not rigorously standardized. The level of 1000 mg/L of dissolved solids is usually adopted as the limit between fresh and brackish water, but some sources prefer the stricter limit of 500 mg/L. Likewise diverging are the concentrations adopted for distinguishing between brackish and saline water: these values range from 3,000 to 10,000 mg/L (the latter is most commonly adopted). Hypersaline water (brine) has a significantly higher salt concentration than ordinary seawater (35 g/L, on average). Many publications dealing with brackish or saline groundwater do not specify the adopted class limits.

Most human water uses require or prefer freshwater. Although the mega aquifer systems contain fresh groundwater in abundance, significant quantities of brackish and/or saline groundwater are also present in virtually all of them. The occurrence of saline or brackish groundwater resulting from natural processes is briefly outlined in Box 2↴ for the majority of the mega aquifer systems, mainly based on papers and reports accessible on the internet. The information reviewed for these aquifer systems confirms the general idea that the upper parts of the aquifer systems (usually hydrologically dynamic) tend to contain fresh groundwater, while the probability of high mineralization levels increases with depth and is higher for low-permeability formations (aquitards) than for permeable ones (aquifers). Nevertheless, exceptions to this generalized pattern do occur, as pointed out by Van Weert and others (2009) and by Van Weert and Van der Gun (2012), among others. Examples of mega aquifer systems where saline or brackish groundwater is predominant at shallow depths are the Ogaden-Juba Basin, the Stampriet-Lower Kalahari Basin, the Northern Great Plains Aquifer System, the Arabian Aquifer System and the Great Artesian Basin (Box 2).

Quite a few different origins of groundwater salinity have been identified: both marine and terrestrial ones, the latter either natural or anthropogenic. Important genetic types of marine origin are *connate saline water* (entrapped in marine sedimentary formations) and saline water intruded into formations during *marine transgressions* or during *incidental flooding by the sea* (such as caused by tsunamis or spring tides). Such saline waters (often paleowater) are observed in many of the mega aquifer systems (e.g., in the northern confined part of the Nubian Aquifer System, the southern part of the Iullemeden-Irhazer Aquifer System, the southern part of the Ogaden-Juba Basin, the Gulf and Atlantic Coastal Aquifer System, the Senegalo-Mauritanian Basin and the North China Plain Aquifer System). Lateral intrusion of seawater, caused by differences in density between seawater and fresh groundwater, may occur where aquifers border the sea. Since most of the mega aquifer systems are continental, this is only relevant for a few of them, in particular the Nubian Aquifer System, the Senegalo-Mauritanian Aquifer System, the Gulf and Atlantic Coastal Aquifer System, the Indus and Ganges-Brahmaputra Basins and the North China Plain Aquifer System. Intensive groundwater abstraction in the coastal zones has triggered and intensified seawater intrusion in several aquifers (e.g., the Biscayne aquifer in Southern Florida, the Nile Delta aquifers, and the coastal aquifers of the Senegalo-Mauritanian Basin).

Groundwater salinity of various natural terrestrial origins is observed in many of the mega aquifer systems. Evaporites play an important role. They have been formed throughout geological history; the chotts of North Africa, the sabkhas of the Arabian Peninsula and the playas in the Americas testify that such processes continue today. Dissolution of salts from evaporites (or other naturally occurring soluble minerals) and their subsequent migration by groundwater flow is a major source of groundwater salinity in the Northern Great Plains, the Cambrian Ordovician Aquifer System and the eastern part of the Arabian Aquifer System. More or less contemporaneous salinization of shallow groundwater may take place by evaporation from a shallow water table or stagnant surface water bodies under endorheic conditions. This is observed in the Nubian Aquifer System (Natrun and Qattara depressions), the North-Western Sahara Aquifer System (Chott el Djerid and other chotts along the northern boundary), the topographically lower part of the Lake Chad Basin (around Lake Chad), and the central part of the Sudd Basin.

Finally, the salinity level of groundwater may also increase as a result of human activities. Apart from the intensification of seawater intrusion by groundwater abstraction in the coastal zone (enhanced by sea-level rise), this category includes in particular the gradual increase of shallow groundwater salinity by irrigation return flow. Large areas may become salinized in this way, for instance in the Central Valley and High Plains of the USA, in the lower part of the Indus Basin, in the zone where the Indus and Gangetic-Brahmaputra basins meet (Haryana and Punjab) and on the North China Plain (FAO, 2011). Numerous other human activities cause an increase in groundwater salinity, often with harmful local impact, but the affected areas usually are a small fraction of the total horizontal extent of the mega aquifer systems.

2.5.2 Arsenic and Fluoride

Arsenic (As) is one of the geogenic contaminants that can cause severe health problems to humans (cancer and non-cancerous disorders) if present in water in relatively high concentrations (Nordstrom and Smedley, 2022). The WHO provisional guideline for drinking water currently allows a maximum value of 10 μg/L (Smedley, 2008). Although the presence of arsenic in concentrations exceeding this limit has been observed in many parts of the world, only a few of the 37 mega aquifer systems have extensive zones of high-arsenic groundwater. Most notable is the widespread arsenic pollution in shallow groundwater throughout the floodplains of the Bengal Basin, located in the eastern part of the Ganges-Brahmaputra Basin (MacDonald et al., 2015 and 2016). Since the 1980s, millions of people there have suffered from arsenic poisoning by drinking this water that commonly contains arsenic in concentrations between 10 and 1000 μg/L. As shown in Figure 12, large zones of high levels of arsenic in shallow groundwater are also present in other parts of the Ganges Brahmaputra Basin and the adjoining Indus Basin.

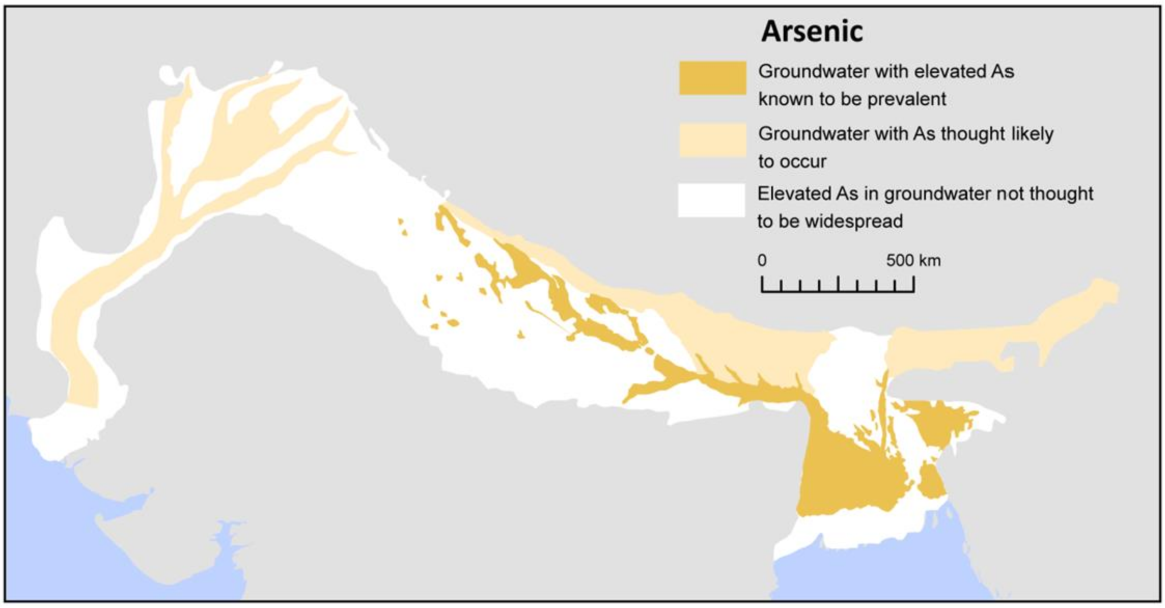

Figure 12 - Known or expected levels of arsenic in shallow groundwater in the Indus-Ganges-Brahmaputra Aquifer System (MacDonald et al., 2015; reproduced with permission of BGS © UKRI http://nora.nerc.ac.uk/id/eprint/511898/↗).

Other mega aquifer systems where zones of excessive arsenic levels are known to be present are the High Plains Aquifer and California's Central Valley; where 9 percent and 8 percent, respectively, of the wells sampled in a national groundwater quality survey, showed arsenic contents exceeding the WHO limit in those areas (DeSimone et al., 2014).

A second important geogenic contaminant is fluoride (F). Continued consumption of high-fluoride water may cause dental fluorosis and in extreme cases even skeletal fluorosis (Feenstra et al., 2007; Edmunds and Smedley, 2013). A fluoride concentration below 1.5 mg/L is commonly considered safe for potable water. Global hotspot zones of excessive fluoride in groundwater have been mapped by Edmunds and Smedley (2013). Some of these are located inside the boundaries of the mega aquifer systems: zones in central-western Senegal (Senegalo-Mauritanian Basin), at selected locations in Algeria, Libya, Egypt and Sudan (NWSAS and NAS) as well as in Uttar Pradesh (Ganges-Brahmaputra Basin), and zones in the middle and lower Indus Basin (IAEA, 2017a; Edmunds and Smedley, 2013). Other sources (Kut et al., 2016; GWP, 2013; Woodford and Chevallier, 2002; GGRETA, 2016) also mention excessive fluoride levels in groundwater of northern and central Somalia (Ogaden-Juba Basin), the Tchad Basin, the South African Karoo Basin, the Stampriet Basin (especially the Nossab aquifer) and in some places of the North China Plain Aquifer System.

In addition, Nordstrom and Smedley (2022) presented a literature review demonstrating increased interest in fluoride contamination worldwide within the scientific literature. Their analysis included data for 85 countries, demonstrating that in recent decades the number of publications almost doubled. They mention that there are well over 1000 reports on the subject from China and India combined.

2.5.3 Anthropogenic Groundwater Pollution

The causes and mechanisms of anthropogenic groundwater pollution are numerous, and there is a large diversity of pollutants. Households, industries, mining and agriculture produce enormous quantities of waste and wastewater. Fetter (1993) distinguished six categories of sources of anthropogenic groundwater contamination:

- sources designed to discharge substances (septic tanks, injection wells, land application of wastewater);
- sources designed to store, treat and/or dispose of substances (landfills, open dumps, residential disposal, surface impoundments, mining waste and stockpiles, graveyards, storage tanks, incineration and detonation sites, radioactive waste disposal sites);
- sources to retain substances during transport (pipelines, trucks and trains);
- sources discharging substances as a consequence of other planned activities (irrigation, use of pesticides and fertilizers, farm animal wastes, road salting, percolation of atmospheric pollutants, mine drainage, etc.);
- sources providing a conduit for contaminated water to enter aquifers (wells, construction excavations); and,
- naturally occurring sources whose discharge is created or acerbated by human activity (interaction with polluted surface water, natural leaching enhanced by acid rain, saltwater intrusion).

It is beyond the scope of this section to go into details, but a few comments can be made on the risk of anthropogenic groundwater pollution. This risk on one hand depends on aquifer system properties (in particular its vulnerability to pollution) and, on the other hand, on human presence and activities. It is likely positively correlated with the mean population density in the corresponding area. In this regard, three mega aquifer systems belong to the high-density category (300 to 1000 persons per km^2): the North China Plain, the Ganges-Brahmaputra Basin and the Indus Basin, while three are in the moderately-high population density category (100 to 300 persons per km^2): the Paris Basin, the Atlantic and Gulf Coastal Aquifer System, and the Central Valley of California. In contrast, the mean population density of several other mega aquifer systems – such as the Amazon basin, the North-Russian basins and the two Australian mega aquifer systems – is very low (less than 10 persons per km^2).

Furthermore, intensive agriculture (often in combination with irrigation) increases the groundwater pollution risk. This is the case in mentioned areas of the North China

Plain, the Ganges-Brahmaputra Basin, the Indus Basin, California's Central Valley and the Paris Basin, but also on the sparsely populated High Plains. Anthropogenic pollution is high throughout the area of the systems with very high population density but tends to be limited to minor parts of the area of most mega aquifer systems of sparse to moderately-high population density because they are so large.

Finally, it should be pointed out that the deeper parts of the sedimentary basins are target zones for oil and gas development, geothermal energy recovery and permanent storage of hazardous substances. Information on these potentially polluting activities is only scarcely and fragmentarily available in the public domain.

2.6 Opportunities to Test Knowledge Gained in this Section

To exercise the knowledge gained while reading this section, investigate exercises 5 through 10. Links are provided to each exercise below.

Exercise 5↴

Exercise 6↴

Exercise 7↴

Exercise 8↴

Exercise 9↴

Exercise 10↴

3 Hydrological Regime of the Mega Aquifer Systems

The hydrological regime of an aquifer system characterizes its dynamics and is defined by the system's water inflows (recharge), outflows (discharge) and the resulting changes over time in the volume of stored groundwater. In principle, all these terms are subject to spatial and temporal variation. For practical reasons, however, this section pays hardly any attention to the variations inside each of the mega aquifer systems. The horizontal spatial variations are ignored by adopting a lumped approach to the individual mega aquifer systems. Occasionally some differentiation is made between the shallow and deeper domains of the aquifer systems, but otherwise vertical variations are ignored. Regarding the variations over time, only the changes in groundwater storage are considered in some detail; storage variations have been monitored by the GRACE satellite (over the period 2002–2016) for all mega aquifer systems, and for a few, area-wide terrestrial-monitoring records cover rather long periods. To quantify groundwater recharge and discharge, more or less synchronous estimates are presented, that are reasonably representative of average conditions during the first two decades of the 21st century. Despite these simplifications, it has not been possible to find information on most of the relevant variables for some of the mega aquifer systems, while the available information for some others does not always appear to be reliable. Nevertheless, the contents of this section will give a first impression of the mega aquifer system hydrological regimes, which is a first step towards understanding their dynamics and their relevance for humans, the biosphere and the environment.

3.1 Groundwater Recharge

3.1.1 Estimates of Current Recharge

Groundwater recharge cannot be measured directly, except in very small experimental settings such as a lysimeter[2]. Consequently, in practice, numerical values of recharge are indirectly established and are subject to a large margin of uncertainty. Groundwater recharge varies over time, both in the short- to intermediate-term (day-to-day, seasonal, interannual, etc.) and in the very long term (on a millennial to geological time scale). Recent estimates of the mean value of the *current global groundwater recharge* (excluding Antarctica) vary between approximately 11 and 15 thousand km^3/year

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[2] A lysimeter is a device (usually a tank or container no more than a few meters high) that allows the components of the soil water balance to be monitored, in particular evaporation/evapotranspiration, downward percolation (source of groundwater recharge) and changes in stored soil moisture. It is set up outside in the open air (to be exposed to the local weather) and it is filled with soil of composition and vegetation cover comparable to that of the soils in the surroundings for which the lysimeter is considered to be representative https://en.wikipedia.org/wiki/Lysimeter↗.

(Margat and Van der Gun, 2013). An assumed mean value of 13,000 km^3/year corresponds to an equivalent mean annual recharge depth of 87 mm averaged over the global land area.

How do recharge estimates of the mega aquifer systems compare to this global average? Table 7 lists estimates of mean recharge as found in the literature or produced based on relevant sources. Since the reported values have different origins, they are based on different estimation methods, but often the method is not specified in the publications. Furthermore, some of the reported values include natural recharge (direct and indirect) plus anthropogenic inflows from used waters, induced recharge or artificial recharge, while other estimates refer only to natural recharge, or even to only direct natural recharge, which is recharge produced by locally infiltrating precipitation. Unfortunately, the publications do not always specify what is included in 'recharge'. All reported recharge values in Table 7 have been rounded to no more than two significant digits because suggesting a higher degree of precision is not realistic.

Table 7 - Estimated current mean recharge and abstraction rates *(all reported values have been rounded to no more than two significant digits)*.

#	Aquifer System	Estimated Mean Recharge		Estimates of Abstraction (circa 2010)		
		mm/yr	Source	km^3/yr	mm/yr	Source
1	Nubian Aquifer System	1.2	Voss & Soliman, 2014	6.3	2.9	Voss & Soliman, 2014
2	North-Western Sahara Aquifer System	2.1 0.98	Gonçalves et al., 2013 OSS, 2020	2.8	2.7	Gonçalves et al., 2013
3	Murzuk-Djado Basin	0.33	OSS, 2020	1.7	3.8	Seguin, 2016
4	Taoudeni-Tanezrouft Basin	5.5	OSS, 2020	0.06	0.03	Seguin, 2016
5	Senegalo-Mauritanian Basin	0.43	OSS, 2020	0.26 0.87[1]	0.87 2.9[1]	Seguin, 2016 NTALT[2]
6	Iullemeden-Irhazer Basin	13	OSS, 2020	0.28	0.43	Seguin, 2016
7	Lake Chad Basin	3.6 1.9	OSS, 2020 UNEP, 2008	0.25 0.5[1]	0.13 0.3[1]	Seguin, 2016 IBDR, 2020
8	Sudd Basin	0.93 1.4	Salama, 1976 RSS, 2015 (Omar, 2009)	0.03 0.014	0.08 0.04	RSS, 2015 (Y & A, 2010) RSS, 2015 (Omar, 2009)
9	Ogaden-Juba Basin	5[1]	WHYMAP, 2008	0.38[1]	0.38[1]	NTALT[2]
10	Congo Basin	> 400[1]	WHYMAP, 2008; Margat & Van der Gun, 2013	0.95[1]	0.65[1]	NTALT[2]
11	Cuvelai-Upper Zambezi Basin (Upper Kalahari)	15	UNEP, 2008	0.19[1]	0.21[1]	NTALT[2]
12	Stampriet-Kalahari Basin (Lower Kalahari)	6.0	UNEP, 2008	0.04[1]	0.12[1]	NTALT[2]
13	Karoo Basin	35	UNEP, 2008	1.02[1]	1.70[1]	NTALT[2]
14	Northern Great Plains	10?[1]	Reitz et al., 2017; WHYMAP, 2008; Rivera, 2017	0.50[1]	0.66[1]	NTALT[2]; Maupin & Barber, 2005; Lovelace et al., 2020
15	Cambrian-Ordovician	150[1]	Reitz et al., 2017; WHYMAP, 2008	1.3[1]	5.1[1]	Maupin & Barber, 2005; Lovelace et al., 2020
16	Central Valley	320	Meixner et al., 2016	15[1] 14 18	280[1] 260 350	Maupin & Barber, 2005; Lovelace et al., 2020 USGS/Maven, 2020 Meixner et al., 2016
17	High Plains Aquifer	42	Meixner et al., 2016	19[1] 26 24	43[1] 58 54	Maupin & Barber, 2005; Lovelace et al., 2020 McGuire, 2017 Meixner et al., 2016
18	Atlantic & Gulf Coastal Aquifer System	180[1]	Reitz et al., 2017; WHYMAP, 2008	30[1]	26[1]	Maupin & Barber, 2005; Lovelace et al., 2020
19	Amazon Basin	> 400[1]	WHYMAP, 2008; Margat & Van der Gun, 2013	0.59[1]	0.29[1]	Feitosa et al., 2016; NTALT[2]
20	Maranhão Basin	50[1]	Antunes et al., 2005; WHYMAP, 2008	0.59[1]	0.85[1]	Feitosa et al., 2016; NTALT[2]
21	Guarani Basin	250	Antunes et al., 2005; WHYMAP, 2008	2.6[1]	2.4[1]	Feitosa et al., 2016; NTALT[2]

Continued – Table 7 - Estimated current mean recharge and abstraction rates (all reported values have been rounded to no more than two significant digits).

#	Aquifer System	Estimated Mean Recharge		Estimates of Abstraction (circa 2010)		
		mm/yr	Source	km^3/yr	mm/yr	Source
21a	Guarani Aquifer System[3]	0.50	Gonçalves et al., 2020	1.00	0.84	Munier et al., 2012
22	Arabian Aquifer System	1.8	Odhiambo, 2016	16[1]	11[1]	UN-ESCWA & BGR, 2013
23	Indus Basin	160	CGWB, 2019; Margat & Van der Gun, 2013	96[1]	300[1]	MacDonald et al., 2015; CGWB, 2014
24	Ganges-Brahmaputra Basin	280	CGWB, 2019; Margat & Van der Gun, 2013	110[1]	180[1]	MacDonald et al., 2015; CGWB, 2014
25	West-Siberian Basin	?		1.3[1]	0.39[1]	NTALT[2]; Pykhtin et al., 2019
26	Tungus Basin	?		0.12[1]	0.12[1]	NTALT[2]; Pykhtin et al., 2019
27	Angara-Lena Basin	?		0.22[1]	0.37[1]	NTALT[2]; Pykhtin et al., 2019
28	Yakut Basin	?		< 0.1[1]	< 0.2[1]	NTALT[2]; Pykhtin et al., 2019
29	Greater North China Plain	200[1]	Chen et al., 2012	37[1]	120[1]	Chen et al., 2012
29a	North China Plain (Hai Plain only)[4]	130 200	Liu et al., 2011 Cao et al., 2013	22 22	160 160	Gong et al., 2018 Liu et al, 2011
30	Song-Liao Plain	75	Chen et al., 2012	13[1]	43[1]	Chen et al., 2012
31	Tarim Basin	32 2[1]	Chen et al., 2012 Huang & Pang, 2013	3.1 2.5	6.0[1] 4.8[1]	Chen et al., 2012 NTALT[2]
32	Paris Basin	130[1]	Bodelle & Margat, 1980	2.7[1]	14[1]	NTALT[2]
33	Russian Platform Basins	120[1]	WHYMAP, 2008	8.5[1]	2.7[1]	NTALT[2]; Pykhtin et al., 2019
34	North Caucasus Basin	25[1]	WHYMAP, 2008	1.3[1]	5.5[1]	NTALT[2]; Pykhtin et al., 2019
35	Pechora Basin	?		< 0.1[1]	<0.4[1]	NTALT[2]; Pykhtin et al., 2019
36	Great Artesian Basin	0.59	Hillier & Foster, 2002	0.55	0.32	Habermehl, 2006;2020
37	Canning Basin	2–10[1]	WHYMAP, 2008; Munier et al., 2012	< 0.1	< 0.23	Munier et al., 2012

[1] Value not explicitly mentioned in cited sources but derived from the information they present.

[2] NTALT (national-to-aquifer-level transfer): approach to estimating groundwater abstraction from an aquifer by using demographic and irrigated land statistics of its composing sub-national zones, assuming that groundwater abstraction for irrigation is proportional to the area of groundwater-irrigation and that domestic and industrial groundwater abstraction is proportional to population. Unless indicated otherwise, use is made of national groundwater abstraction estimates for 2010 presented by Margat and Van der Gun (2013), demographic data from a census as close to 2010 as possible, and data on areas equipped for groundwater irrigation as presented by Siebert and others (2010).

[3] The data shown for Guarani Aquifer System (21a) do not include overlying post-GAS units such as the Serra Geral basalts and Bauru-Caiuá sandstone.

[4] Data refer to the Hai Plain (136,000 km^2), which covers only 42.5 percent of the Greater North China Plain.

Mean annual recharge estimates have not been found in the literature for almost half of the mega aquifer systems. For most of these systems, provisional estimates have been made based on information presented in relevant papers or have been adopted from summarizing publications such as Margat and Van der Gun (2013) and WHYMAP (2008). The latter, in turn, relies on diffuse recharge modeling by Döll and Fiedler (2008). This was not attempted for the five northernmost Russian mega aquifer systems, located in zones of boreal and polar climates, because permafrost and semi-permafrost conditions present an extremely complicating factor, which precludes groundwater recharge from being estimated reliably without more detailed area-specific information. The presented recharge values form a heterogeneous set, and they are far from accurate. They are nevertheless shown here to give an impression of the order of magnitude of the mean recharge rates of the different aquifer systems and to help understand where and to what extent recharge may be or become a constraint to sustainable groundwater development. To facilitate easy interpretation and comparison, all recharge values are expressed as mean water heights per annum (i.e., total annual recharge volume divided by the horizontal area of the aquifer system).

3.1.2 Interpreting and Comparing the Estimates

As shown in Table 7, the estimates of mean groundwater recharge for the individual mega aquifer systems cover a wide range of values, both above and below the mean global value, which is to a great extent due to differences in climate. Three categories can be distinguished:

1. *Aquifer systems receiving significant to abundant recharge (mean recharge rates > 100 mm/year).* This category includes the Congo and Amazon basins which enjoy by far the most abundant recharge rates, followed (in order of decreasing rates) by the Central Valley, the Ganges-Brahmaputra Basin, the Guarani Basin, the Maranhão Basin, the Atlantic and Gulf Coastal Plains, the Indus Basin, the Cambrian-Ordovician Aquifer System, the Paris Basin, the Russian Platform Basins and the North China Plain. Almost all these aquifer systems are located in humid climates, which explains their significant to abundant recharge rates. Exceptions are the Central Valley, the Indus Basin and the North China Plain, located in semi-arid regions (at least partly); more than half of their recharge consists of return flows from irrigation.
2. *Aquifer systems receiving insignificant modern recharge (mean annual rates < 5 mm/year).* This category includes the Nubian and North-Western Sahara aquifer systems and the Murzuk-Djado, Senegalo-Mauritanian, Lake Chad and Sudd basins in Africa; the Arabian Aquifer System and the Tarim Basin in Asia; and the Canning and Great Artesian Basins in Australia. The very low rates of recharge are in most cases mainly explained by dry climatological conditions.

Confining layers rejecting potential recharge may also play a role in the Senegalo-Mauritanian and Sudd basins.

3. *Poorly recharged aquifer systems (mean annual rates between 5 and 100 mm/year).* This category includes the Taoudeni-Tanezrouft, Iullemeden-Irhazer, Ogaden-Juba, Upper Kalahari-Cuvelai-Upper Zambezi, Stampriet-Lower Kalahari and Karoo basins in Africa; the Northern Great Plains and High Plains in North-America; the North Caucasus aquifer system in Europe and the Song-Liao plain in Asia. The majority of these systems are located in semi-arid to arid climates, which is the main reason for their very modest recharge rates.

Highly simplifying, the groundwater resources of these three categories may be classified as renewable, non-renewable and weakly-renewable, respectively. In practice, estimating mean aquifer recharge rates is usually very difficult, which results in a high degree of uncertainty in most of the estimates.

3.1.3 Groundwater Recharge during Previous Geological Epochs and in the Near Future

As mentioned earlier, the greater part of groundwater stored in the mega aquifer systems is many thousands of years old and thus is either connate water or entered the aquifer system as recharge during previous geological epochs (paleo-recharge). Since climate has varied significantly throughout geological history, the rates of recharge of each aquifer system have varied over time. This has repercussions not only for the total volume of groundwater presently stored and groundwater quality but also for groundwater flow and the groundwater budgets of the aquifer systems. Mainly due to their large size, the present-day groundwater flow regimes and groundwater budgets of the mega aquifer systems may remain markedly influenced by recharge events that took place in the very remote past. This 'large hydraulic memory' of mega aquifer systems can be illustrated by an example from Northern Africa, as presented by Voss and others (2014). In this region, the alternating glacial and interglacial periods during the Quaternary had pluvial-humid and arid climates, respectively. It is assumed that the latest pluvial period took place from 10,000 to 5,000 years ago (Gossel et al., 2004; Voss and Soliman, 2014), or ended approximately 8,000 years ago (Thorweihe and Heinl, 2002). Model simulations by each of the three cited teams of investigators showed that the natural groundwater flow regime and discharge in the Nubian Aquifer System had not yet reached a new equilibrium in 1960 which is considered the beginning of groundwater development in the area, but were still in transient conditions, in response to groundwater recharge during the latest pluvial period. Figure 13 shows the simulated natural discharge during the Holocene past and its predicted continuation for 10,000 years into the future, as presented by Voss and Soliman (2014).

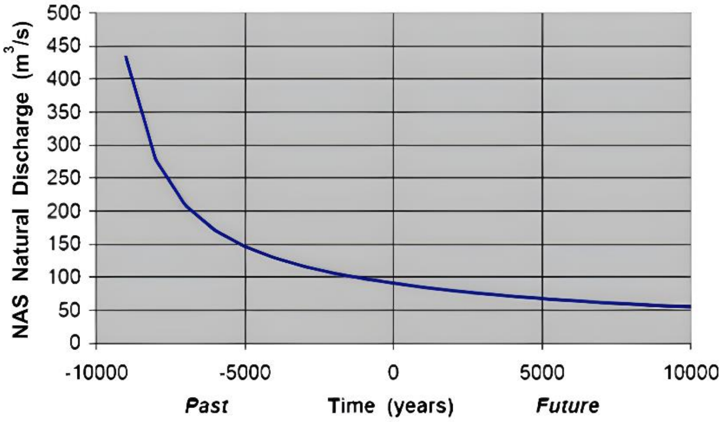

Figure 13 - Modeled decay of the natural Nubian Aquifer System discharge, assuming recharge stopped 10 thousand years ago under full-aquifer conditions (Voss and Soliman, 2014).

Looking towards the near future, say the next 50 years, recharge of the groundwater resources of most of the mega aquifer systems is expected to change over time for several reasons. In the first place, groundwater and surface water use are likely to increase in most areas, which may lead to more intensive irrigation return flows and other anthropogenic inflows (such as wastewater) into the groundwater systems. Next, Managed Aquifer Recharge (MAR) has proven to be an effective tool for enhancing groundwater recharge in many areas and there is ample scope for expanding the approach to other parts of the world (Dillon et al., 2018). Furthermore, there are also human activities that may reduce groundwater recharge, such as enhancing irrigation water use efficiencies, and other anthropogenic factors (e.g., changes in land use or land-use practices) that may affect groundwater recharge either positively or negatively. Finally, climate change is currently perceived as a prominent game changer. It will certainly have a significant impact on the recharge of the individual mega aquifer systems, but predicting for each of them whether recharge will increase or decrease and to what degree remains very difficult.

3.2 Groundwater Abstraction

3.2.1 Groundwater Abstraction Estimates

Assessing groundwater abstraction from an aquifer or aquifer system is rather difficult, too, although somewhat easier than assessing groundwater recharge. Most reliable data are obtained if the wells are equipped with flow meters, but this is expensive and in practice mostly limited to important groundwater production wells or wellfields (e.g., public water supplies). Metering is relatively rare among the myriads of privately owned and/or operated wells. A comprehensive well inventory (including measurement of well yields and enquiring about the average daily number of hours of pump operation) is another reliable method to estimate groundwater abstraction in a particular area, but this approach needs to be carried out within a restricted time frame, it requires considerable effort and financing and becomes impracticable if the aquifers are large. Therefore, many estimates of groundwater abstraction from aquifers are based on indirect monitoring methods, including sampling among main categories of groundwater users to define representative unit groundwater-use values; extrapolating or disaggregating based on demographic, land use, irrigation and agricultural/industrial production data; correlation with energy consumption records or well-licensing data; remote sensing (satellite or airborne sensors).

For this overview, an attempt has been made to collect or produce estimates of the annual groundwater abstraction rates for the mega aquifer systems. The results are presented in the fifth and sixth columns of Table 7, showing groundwater abstraction rates in km^3/year and mm/year, respectively. Since groundwater abstraction is time-dependent, synchronization has been pursued, with the year 2010 chosen as the preferred common reference year. Nevertheless, for several mega aquifer systems, the only available estimates refer to another year; these estimates are included in cases when the other year was close enough to 2010 to assume the abstraction rate would be similar, or the estimates have been extrapolated, using an assumed annual growth rate. As was done with the recharge estimates, all reported abstraction estimates have been rounded to no more than two significant digits in Table 7, because more precision is not realistic.

The groundwater abstraction estimates shown in Table 7 can be divided broadly into four categories.

1. *Tailor-made estimates* for the individual mega aquifers system as provided by authors of aquifer-specific papers or reports. On average, these are probably the most reliable estimates, but the margins of uncertainty are still considerable, as is suggested by the differences between alternative estimates made for single mega aquifer systems. Values are only included if they were found in publications of satisfactory professional standard.
2. Estimates as produced by *combining groundwater abstraction statistics* reported for separate sub-national administrative areas or separate aquifer units that form parts of the mega aquifer system being considered. Such estimates tend to be reliable as well, provided that the abstraction statistics are of good quality, and that the mentioned administrative areas, or aquifer units, represent the mega aquifer system comprehensively and correctly.
3. Estimates as produced by *disaggregating national groundwater abstraction statistics*. The adopted approach assumes that groundwater abstraction for irrigation is proportional to the area irrigated with groundwater and that domestic plus industrial groundwater abstraction is proportional to population size. The method is illustrated in Box 3⤵, using the Paris Basin as an example. These indirectly obtained estimates are no more than 'educated guesses', satisfactory for a first impression. Nevertheless, their reliability may be rather high if the mega aquifer system considered (or its national segments) covers a greater part of the national territory (or territories).

4. Estimates as produced by combining some of the former three approaches.

Although it is not easy to define the reliability of the groundwater abstraction estimates, the consulted literature supports the impression that those of the Nubian Aquifer System, the Northern Sahara Aquifer System, the Central Valley, the High Plains, the Paris Basin, the Arabian Aquifer System, the Indus and Gangetic-Brahmaputra Basins, the North China Plain (Hai Plain) and the Great Artesian Basin are reasonably reliable. In contrast, estimates for the Ogaden-Juba, Sudd and Congo Basins, the Northern Great Plains, the Cambrian-Ordovician Basin and the Song-Liao Plain carry a large margin of uncertainty, although there is little doubt that the order of magnitude of all presented estimates is correct.

A few comments on missing estimates. Statistics on population and groundwater-irrigated land suggest that groundwater abstraction in the Greater North China Plain is almost twice that in the North China Plain (Hai Plain), thus it is estimated to be approximately 40 km^3/year. Groundwater abstraction in the five easternmost mega aquifer systems of the Russian Federation is likely very low since there are no significant areas of irrigated land and only a limited population. The total population of all five areas was approximately 23 million in 2010 (16 percent of the Russian Federation's population), of which 17 million live in the huge West-Siberian Basin (mostly in its southern part). The combined abstraction of these five mega aquifer systems, therefore, is unlikely to have exceeded 2 km^3 in 2010.

3.2.2 Interpreting and Comparing the Estimates

Share of the Mega Aquifer Systems in Global Groundwater Abstraction

Based on the estimates shown in Table 7, the total rate of groundwater abstraction from the 37 mega aquifer systems (for the reference year 2010) is calculated as approximately 375 km^3/year, which is 38 percent of the global rate of groundwater abstraction of 982 km^3/year estimated for the same year 2010 (Margat and Van der Gun, 2022). Using 375 km^3/year abstraction from 35 million km^2 of mega aquifer area, the average depth of water extracted is 10.7 mm/yr. Then the remaining 607 km^3/year of groundwater abstraction comes from the remaining 99 million km^2 of continental surface (excluding Antarctica) for which the average depth of water extracted thus is 6.1 mm/yr. Despite the uncertainties in the estimates, it is reasonable to conclude that the average intensity of groundwater abstraction in the areas of mega aquifer systems is substantially greater than in other areas (almost twice). This is no surprise as the mega aquifer systems offer comparatively favorable conditions for groundwater abstraction. The mega aquifer systems thus play a prominent role in global groundwater development by providing a very significant share of all abstracted groundwater.

Variation of Abstraction Rates and Mean Abstraction Intensity

What catches the eye in Table 7 is the large variation in the rates of groundwater abstraction. Eight mega aquifer systems have very high estimated abstraction rates (above 10 km^3/year); in decreasing order: the Ganges-Brahmaputra Basin (110 km^3/year), the Indus basin, the Greater Northern China Plain, the Atlantic and Gulf Coastal Aquifer System, the High Plains, the Arabian Aquifer System, the Central Valley and the Song-Liao Plain (13 km^3/year). Together they produce around 340 km^3/year, which is 90 percent of the combined abstraction from all 37 mega aquifer systems, or 35 percent of the global groundwater abstraction. These intensively exploited systems are supplying groundwater to very large areas of irrigated lands and most of them have a huge number of people within their boundaries. The estimated abstraction rates are much lower (ranging from 10 down to 1 km^3/year), but still considerable, for eleven other aquifer systems; in decreasing order: the Russian Platform Basins (8 km^3/year), the Nubian Aquifer System, the Tarim Basin, the North-Western Sahara Aquifer System, the Paris Basin, the Guarani Basin, the Murzuk-Djado Basin, the Cambrian-Ordovician Aquifer System, the North Caucasus Basin, the West-Siberian Basin and the Karoo Basin (1 km^3/year). The estimated abstraction rates of the remaining eighteen mega aquifer systems are relatively low, below 1 km^3/year. The lowest abstraction rate (no more than 0.1 million km^3/year) probably corresponds to the Pechora Basin, 350 thousand square kilometers in size but with only a few hundred thousand inhabitants. In terms of groundwater abstraction intensity, expressed in mm/year (equivalent to thousands of m^3 per year per square kilometer), the ranking is led by the Indus Basin (300 mm/year), followed by the Central Valley, the Ganges-Brahmaputra Basin and the Greater North China Plain (120 mm/year), as shown in Table 7 and Figure 14.

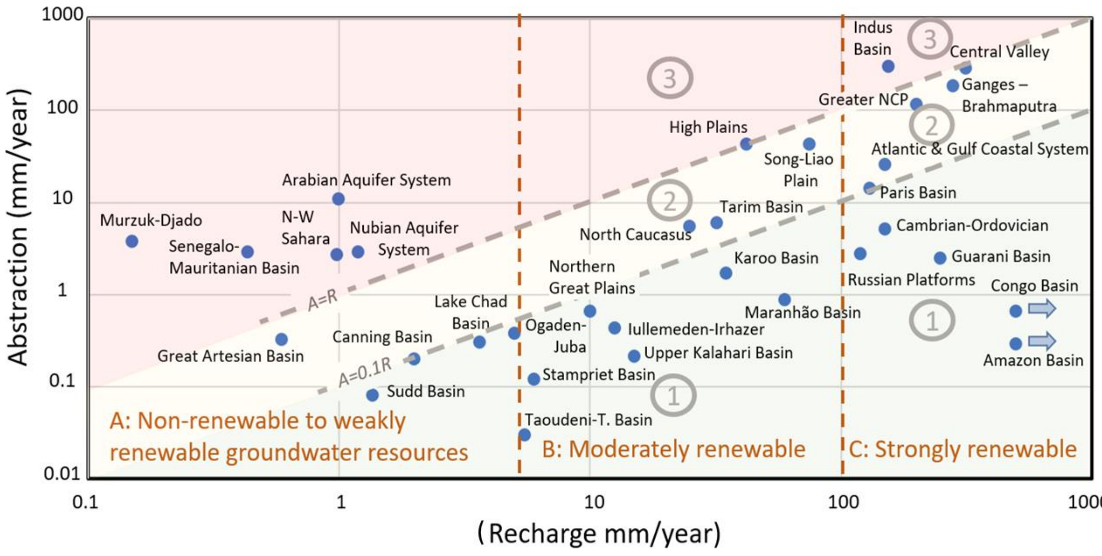

Figure 14 - Classification of the mega aquifer systems according to their mean rate of groundwater recharge and renewable groundwater development stress (reference year: 2010). Note that the differently colored zones 1, 2 and 3 represent distinct groundwater development stress intervals.

Classification According to Mean Recharge and Renewable Groundwater Development Stress (RGDS)

It is interesting to explore to what extent groundwater abstraction is modifying the overall regime of the mega aquifer systems. For this purpose, the estimates of groundwater recharge and abstraction estimates in Table 7 are both shown in mm/year. Figure 14 presents these values graphically, which facilitates classifying and comparing them provisionally, assuming that the estimates do not diverge too much from the corresponding true values.

A few comments may be helpful for properly understanding the diversity of conditions:

- Class A in Figure 14 includes aquifers with non-renewable or only weakly renewable groundwater resources (recharge rate R < 5 mm/year), typical for regions with a very dry climate. Most of the mega aquifer systems of Northern Africa, as well as those on the Arabian Peninsula and in Australia belong to this class. The hydrological impact of continuing and increasing abstraction from aquifers in this category will mainly consist of groundwater storage depletion at rates close to the abstraction rates.
- Class B represents moderately recharged aquifer systems (R between 5 and 100 mm/year) and is subdivided into three subclasses, according to the renewable groundwater development stress RGDS (defined as the quotient of groundwater abstraction over mean recharge, often expressed as a percentage). Sub-class B1 (RGDS < 10 percent) includes mega aquifer systems that are developed at only rather low rates (such as the remaining aquifer systems in dry regions of Africa), while those in the sub-classes B2 and B3 (RGDS > 100 percent) are characterized by moderate to intensive and very intensive total abstraction rates, respectively, associated with high population density and/or large extents of irrigated lands. Groundwater abstraction is balanced by both a reduction of natural groundwater discharge and groundwater storage depletion, but the latter becomes dominant under intensive groundwater abstraction regimes, which is most pronounced in the High Plains aquifer.
- The mega aquifer systems in class C enjoy higher mean recharge rates than those in class B (> 100 mm/year), but they are subdivided similarly into three subclasses. The overall hydrological regimes of the mega aquifer systems in sub-class C1, in particular the Amazon and Congo basins, are still close to pristine. However, groundwater development stress increases steadily with increasing groundwater abstraction intensities and has significant impacts on the hydrological regimes of the mega aquifer systems in the sub-classes C2 and C3.

- Theoretically, the mega aquifer systems in the subclasses B3 (High Plains aquifer), C3 (Indus Basin, Central Valley) and several in class A (Arabian Aquifer System, Murzuk-Djado and the Senegalo-Mauritanian basins, the North-Western Sahara Aquifer System and the Nubian Aquifer System) will never reach a dynamic hydrological equilibrium under current recharge and abstraction rates. They are the first ones where storage depletion trends are to be expected. Nevertheless, considerable storage depletion may also occur at lower development stress levels, in particular in aquifer systems in the B2 and C2 subclasses.
- It is emphasized that the above characterization refers only to the macro-behavior of the mega aquifer systems (at a spatially lumped scale). At local scales, parts of the aquifer systems may face entirely different conditions, for example, significant local storage depletion in aquifer systems that have a low overall RGDS.
- It is reiterated here that most of the estimates – especially those of recharge – are subject to considerable uncertainty. The classification is therefore only tentative and may for some aquifer systems diverge from reality. Furthermore, conditions in specific aquifer segments may significantly differ from those aggregated for the entire aquifer system.

3.3 Dynamics of Groundwater Storage

3.3.1 Observing Groundwater Storage Variation Over Time by In-Situ Monitoring

Groundwater levels and the volume of groundwater stored in an aquifer vary continuously over time, in response to recharge from different sources (natural recharge, artificial recharge, irrigation return flows and other anthropogenic sources), groundwater abstraction and natural discharge (regulated by system-specific characteristics). In-situ monitoring (i.e., monitoring groundwater levels in wells) forms the most direct and commonly used method to observe these variations. The water level observations are point values that in principle reveal local conditions only, but by interpolating between the data of nearby monitoring wells a spatially continuous picture of the potentiometric surface can be derived for aquifer zones that are adequately covered by monitoring wells. Sets of monitoring records that can provide an aquifer-wide picture of the groundwater storage dynamics are available for many relatively small aquifers around the world, but not for the majority of the mega aquifer systems. The enormous size of those systems makes it very difficult and costly to obtain good coverage with reasonably simultaneous field observations. Nevertheless, long-term groundwater level monitoring records with good spatial resolution and area-wide coverage are available for some of the mega-aquifer systems. This is briefly illustrated below for a few mega aquifer systems.

The first example is the *North China Plain Aquifer System*, 136,000 km^2 in extent. This is a multilayer aquifer system, with a shallow aquifer consisting of interconnected layers and separated from the deep aquifers by confining layers. The shallow and deep aquifers are hydraulically connected only in the piedmont region in the western and northern part of the plain. Gong and others (2018) derived a time series of groundwater storage anomalies for the entire North China Plain from historical monthly groundwater level data for the period 1971 to 2013. This time series indicates a prolonged declining trend of groundwater storage. On average, the volume lost from the groundwater system is equivalent to a depth of water throughout the plain of 17.8 mm/year, which corresponds to an average storage depletion of 2.4 km^3/year. The anomalies are correlated with groundwater abstraction and precipitation; consequently, the average volumetric decline in equivalent depth of water throughout the plain varies between sub-periods: 6.2 mm/year from 1971 to 1980, 20.6 mm/year from 1981 to 2002, and 18.2 mm/year from 2003 to 2015.

Yang and others (2021) created time-series graphs for water levels in typical monitoring wells as shown for shallow and deep aquifers (Figure 15 and Figure 16, respectively) during the period from 1990 to 2020. In addition to seasonal fluctuations and variation between wet and dry years, the graphs related to the deeper aquifers show pronounced declining trends, but this is observed in only one of the selected wells in the shallow aquifer. Figure 17 shows the cumulative changes in groundwater levels over the period 1980 to 2020 for the shallow and the deeper aquifers, derived from in-situ monitoring records (Yang et al., 2021). The groundwater levels in the deep aquifers declined more, especially in the central and eastern regions.

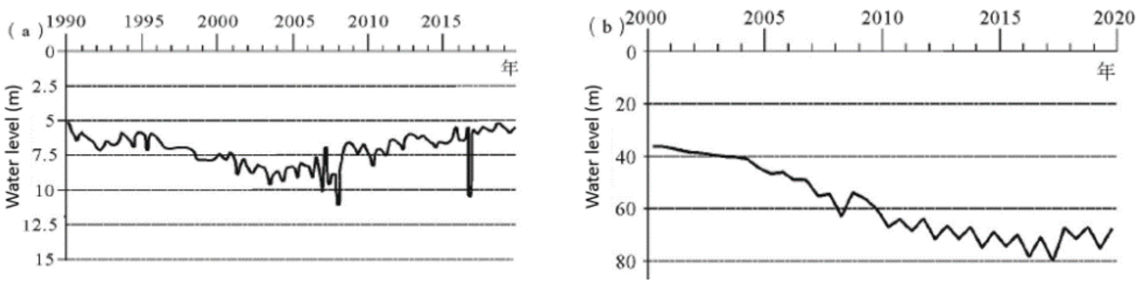

Figure 15 - Groundwater levels in typical monitoring wells in the shallow aquifer, North China Plain (after Yang *et al*, 2021)

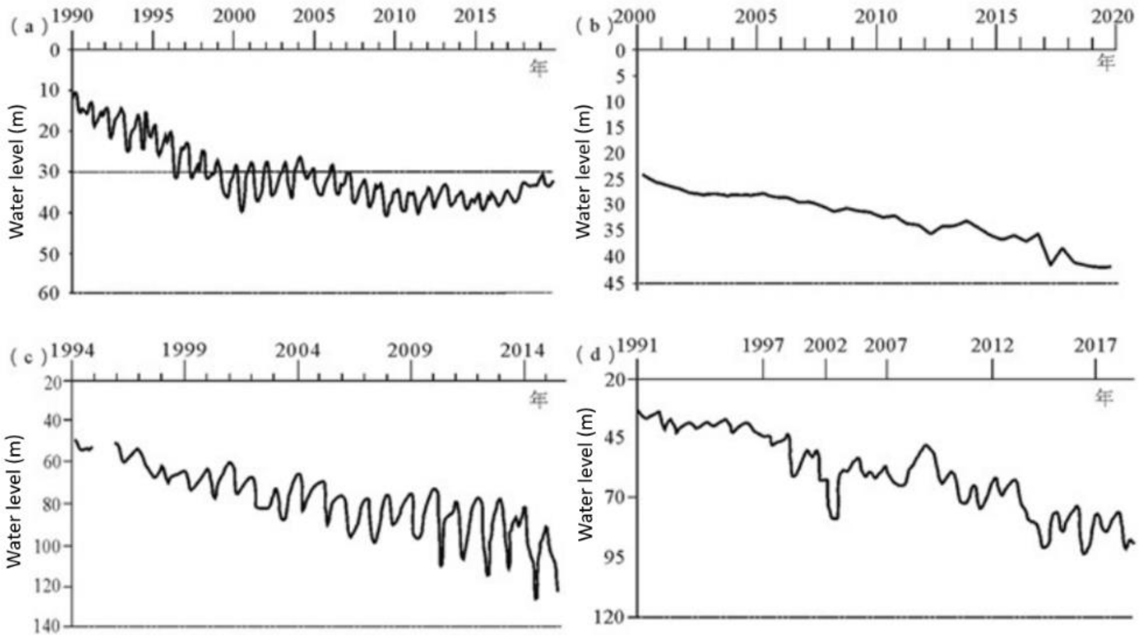

Figure 16 - Groundwater levels in typical monitoring wells in the deep aquifers, North China Plain (after Yang et al., 2021)

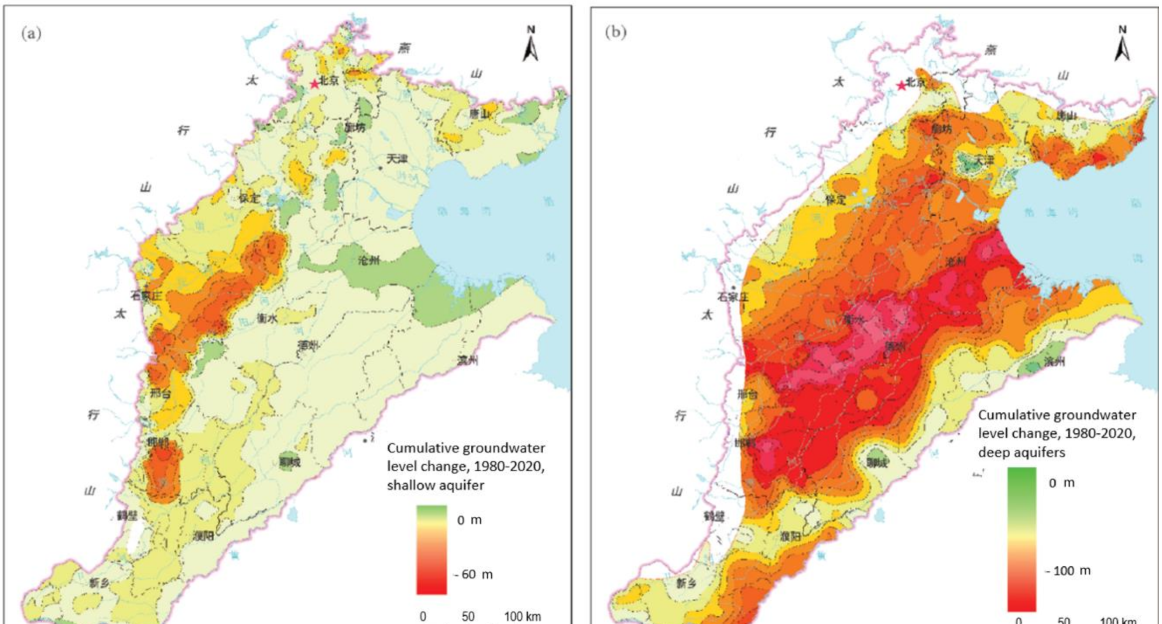

Figure 17 - Cumulative decline of groundwater levels in: a) shallow; and, b) deep aquifers of the North China Plain during the period from 1980 to 2020 (after Yang et al., 2021).

Another mega aquifer system with widespread long-term groundwater monitoring records is the *High Plains Aquifer*. This aquifer is 175,000 square miles in extent (around 450,000 km^2) and consists of unconsolidated or partly consolidated clastic sediments of Tertiary and Quaternary age. Groundwater is generally under unconfined conditions and the saturated thickness of the aquifer varies from nearly zero to 1200 ft (366 m). Figure 18 shows cumulative changes in the groundwater levels between predevelopment time (around 1950) and 2015. This map, based on water levels from 3164 wells and other published data, shows a highly variable pattern, with zones of largest water-level declines in the southern half of the plains, where groundwater recharge is lower than in the north. Water-level changes, by well, ranged over the indicated period from a rise of 54 feet (16 m) to a decline of 234 feet (71 m), with an area-weighted average of 15.8 feet (4.8 m) decline. The monitoring data – in combination with specific yield estimates – allowed estimation of net groundwater storage depletion as 273.2 million acre-feet (337 km^3) for the period from predevelopment time (around 1950) to 2015, and 10.7 million acre-feet (13.2 km^3) for 2013 to 2015. In some zones, especially in Texas, the aquifer's saturated thickness has declined by more than 50% since predevelopment (Scanlon et al., 2012; McGuire, 2017).

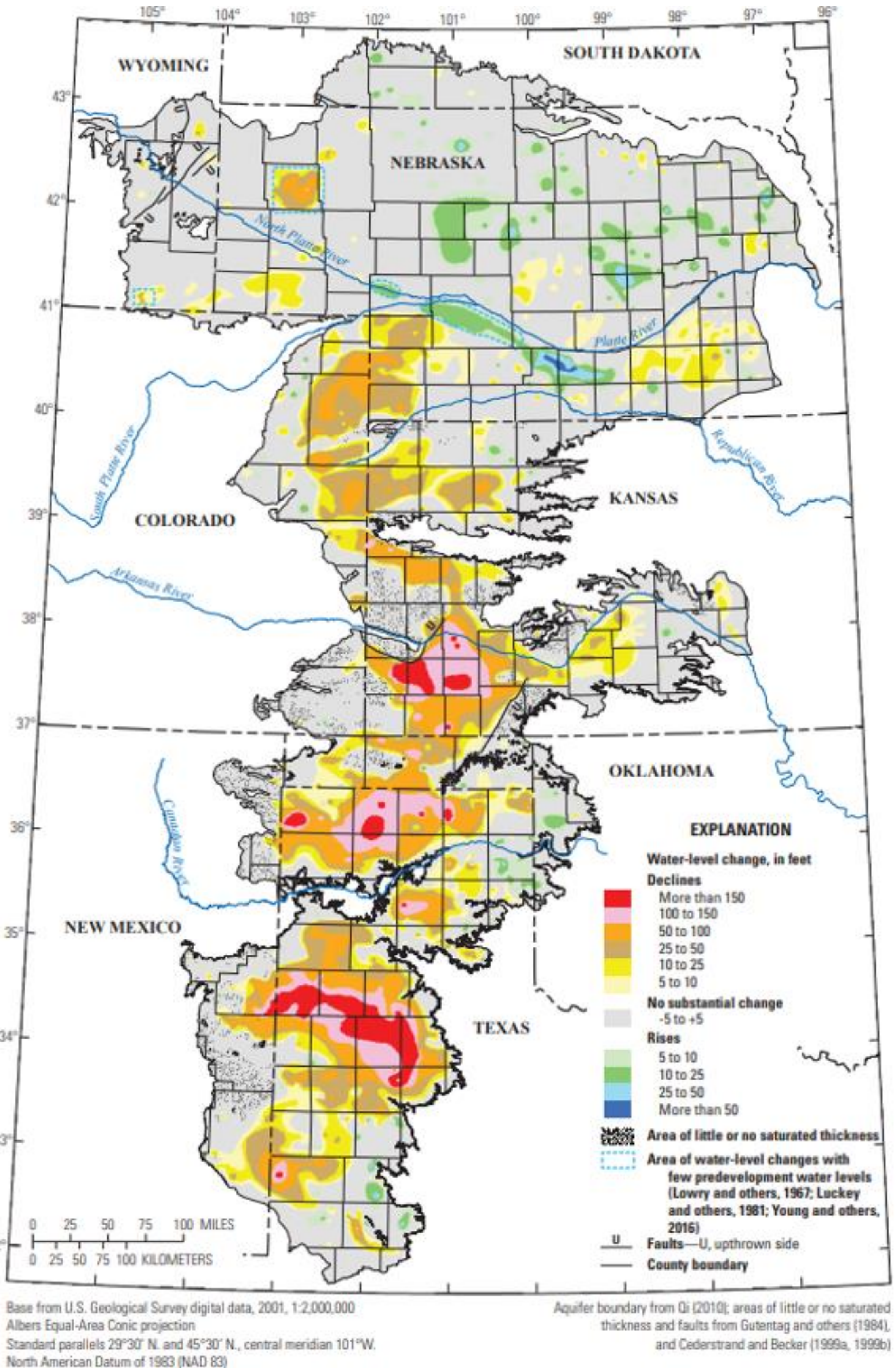

Figure 18 - Water-level changes in the High Plains aquifer, predevelopment (about 1950) to 2015 (McGuire, 2017).

The *Indus and Ganges-Brahmaputra Basins* (the mega aquifer systems 23 and 24 combined, extending over around 920,000 km^2) form another large region where groundwater levels have been monitored for many years and with high spatial resolution. Most groundwater abstraction wells in this region tap from the upper 200 m of the thick series of alluvial sediments accumulated in the foredeep depression south of the Himalayas. Groundwater levels are predominantly shallow (< 5 m) and they are monitored monthly or quarterly mainly in shallow tube wells (0-100 m deep). Based on published national assessments and a subset of 2300 higher-quality monitoring records, MacDonald and others (2015) defined and mapped the long-term trends in groundwater levels (Figure 19). The map shows a significant decline in groundwater levels in the western half of the Ganges Basin and the upper part of the Indus Basin, which is strongly correlated with the areas of most intensive groundwater abstraction. On the other hand, groundwater levels in the lower part of the Indus Basin show a rising trend, driven by leakage from surface water irrigation canals (MacDonald et al., 2015). The estimated net annual groundwater depletion in the Indo-Gangetic basin amounts to some 8 km^3 (MacDonald et al., 2016).

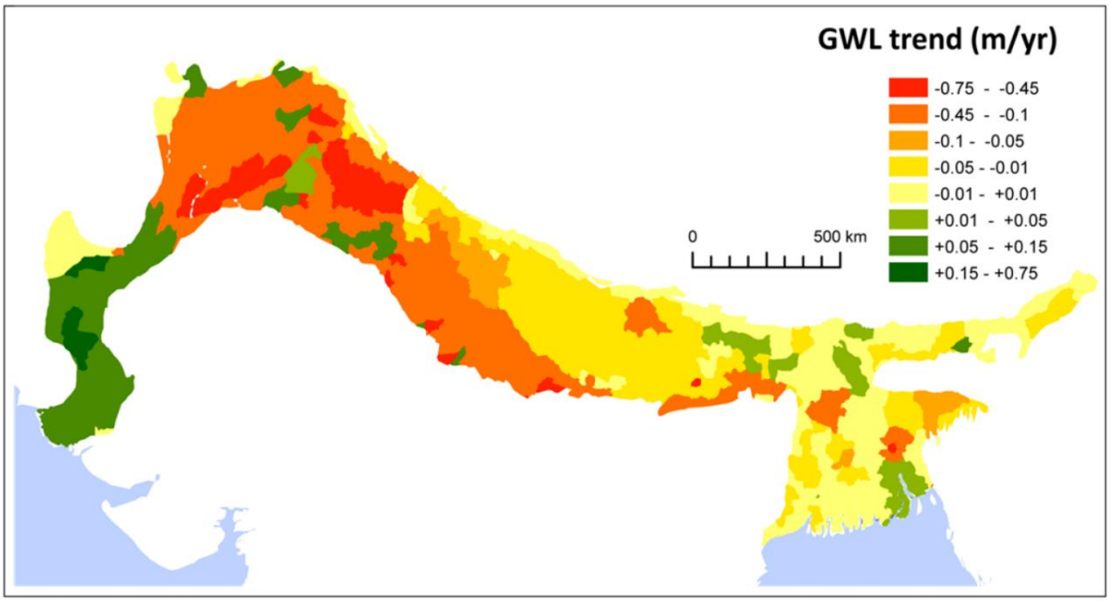

Figure 19 - Long-term trends of groundwater-level change on the Indus-Ganges-Brahmaputra basin, from high-resolution, 25-year series in situ monitoring data sets (MacDonald et al., 2015; reproduced with permission of BGS © UKRI, http://nora.nerc.ac.uk/id/eprint/511898/↗).

3.3.2 Groundwater Storage Variations Derived from GRACE Observations

The Gravity Recovery and Climate Experiment (GRACE) satellite mission, operational from March 2002 to October 2017, has produced a new category of data that can be used to estimate changes in groundwater storage. This innovative project monitored changes in gravity (gravity anomalies) around the globe with low spatial resolution. These anomalies can be transformed into low spatial resolution estimates of changes in total water storage (ΔTWS), from which, in turn, changes in groundwater storage (ΔGWS) can be obtained. The latter is done by subtracting estimated changes in stored surface water, soil moisture and snow/ice from the changes in total water storage. Despite many uncertainties related to the data processing and interpretation methods, these estimates provide interesting information on the variations over time of the aggregated groundwater storage in each of the mega aquifer systems. A GRACE Follow-On mission (GFO) was started in May 2018 to continue the observations. A brief overview of the history and scientific-technical principles of GRACE, as well as its application to global groundwater investigations, is presented by Chen and Rodell (2020). A recent study by Rateb and others (2020) compared GRACE estimates of storage anomalies with those from intensely monitored aquifers in the United States and found generally good agreement.

Figure 20 shows GRACE results obtained and interpreted for the High Plains Aquifer (Ogallala Aquifer, USA), as presented by Shamsudduha and Taylor (2020). The marked seasonal variation of both ΔTWS and ΔGWS is evident, while also significant interannual variation is observed, correlated with annual deviations from the long-term annual average rainfall. As could be expected, ΔGWS constitutes the lion's share of ΔTWS, which causes both time series to be very similar. The ΔGWS time series suggests long-term groundwater storage depletion, but the time series is too short and too much dominated by seasonal and interannual fluctuations for estimating a linear trend representing the long-term depletion rate reliably and accurately. Similar time series of ΔGWS for the other 36 mega aquifer systems are presented in Figure 21 and Figure 22.

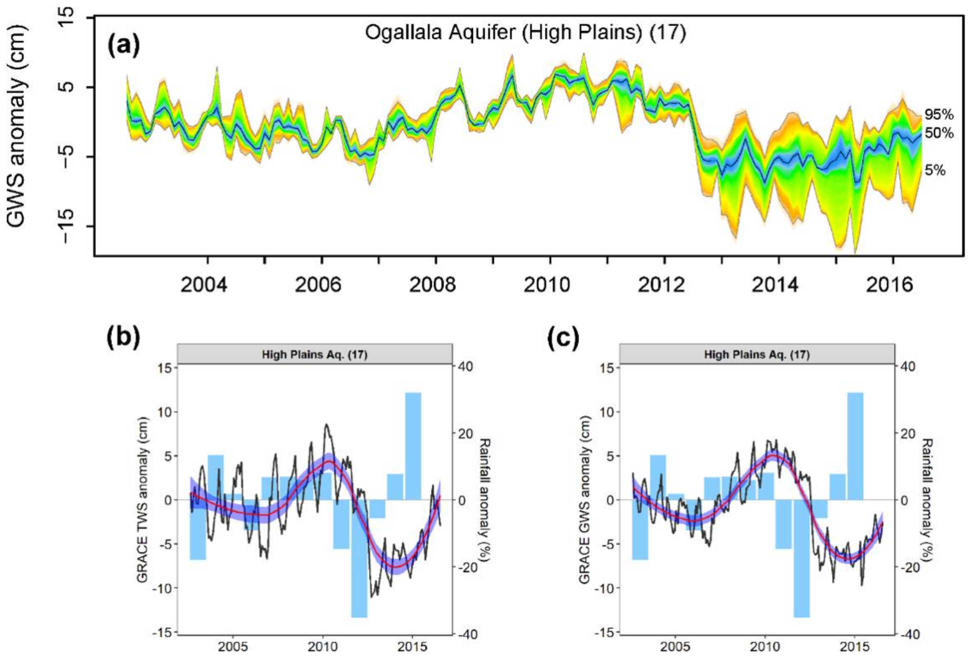

Figure 20 - Monthly time series of groundwater and total water storage anomalies derived from GRACE for the High Plains Aquifer (USA), August 2002 to July 2016: a) Groundwater storage (GWS) anomaly and range of uncertainty from 20 realizations; b) Ensemble Total water storage (TWS) fitted with a non-linear trend curve and annual precipitation anomalies; and, c) Ensemble GRACE-derived GWS fitted with a non-linear trend curve and annual precipitation anomalies (Adapted from Shamsudduha and Taylor, 2020).

Figure 21 - Monthly time series of groundwater storage anomalies derived from GRACE for the mega aquifers 1 through 19 (except number 16), August 2002 to July 2016. The ensemble GRACE-derived ΔGWS (in black) is fitted with a non-linear trend curve (the area shaded in semi-transparent gold shows the 95 percent confidence interval) and annual precipitation anomalies (i.e., percentage deviation from the mean precipitation for the period of 1901 to 2016) are shown as bars (Adapted from Shamsudduha and Taylor, 2020).

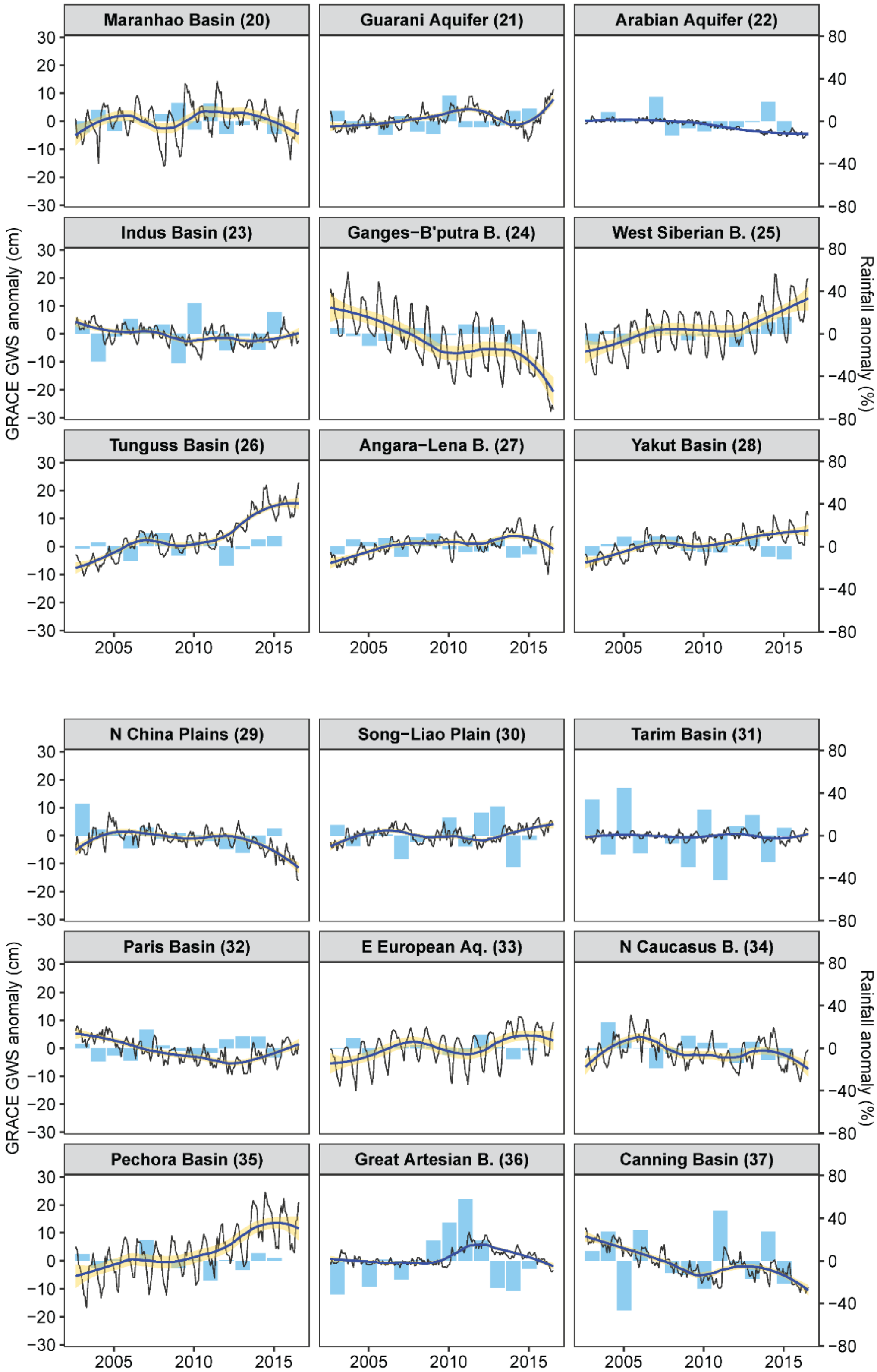

Figure 22 - Monthly time series of groundwater storage anomalies derived from GRACE for the mega aquifers 20 through 37, August 2002 to July 2016. The ensemble GRACE-derived ΔGWS (in black) is fitted with a non-linear trend curve (the area shaded in semi-transparent gold shows the 95 percent confidence interval) and annual precipitation anomalies (i.e., percentage deviation from the mean precipitation for the period of 1901 to 2016) are shown as bars (Adapted from Shamsudduha and Taylor, 2020).

The set of ΔGWS graphs for all 37 mega aquifer systems shows a diversity of groundwater storage regimes. In the first place, different intensities of *seasonal variation* led to large differences in the annual range of groundwater storage variation. Seasonal variation is nearly non-existent in nine aquifer systems: six in Northern and Eastern Africa (numbers 1, 2, 3, 4, 6, 9), one in Southern Africa (number 12), one on the Arabian Peninsula (number 22), and one in Central Asia (number 31). All these are located in zones with hyper-arid or arid climates. The absence of significant seasonal variation in groundwater storage in these aquifer systems is consistent with their low ranking on the recharge intensity scale (Table 7) and with their groundwater resources being classified as non- or weakly renewable. More clearly visible, but still very modest (mean range less than 100 mm) is the seasonal storage fluctuation in sixteen other mega aquifer systems: four in arid and semi-arid Africa (numbers 5, 7, 12, 13), three in North America (numbers 14, 17 and 18; in semi-arid, sub-humid and humid climates, respectively), one in South America (number 21), six in Asia (numbers 23, 26, 27, 28, 29 and 30), and two in Australia (numbers 36 and 37). The remaining twelve mega aquifer systems show a mean annual groundwater storage fluctuation range greater than 100 mm. The largest mean annual ranges are observed in the Amazon Basin (~300 mm), Ganges-Brahmaputra Basin (~220 mm), Pechora Basin (~180 mm), West-Siberian Basin (~180 mm) and California's Central Valley (~175 mm). The seasonal variation looks regular in some aquifer systems (e.g., numbers 19, 24, 25 and 33), but irregular in others (e.g., numbers 10, 11, 15, 20 and 23).

The fitted non-linear trend curves reflect *interannual meteorological oscillations*: alternations of relatively dry and wet years within the period of observation. In addition, several mega aquifer systems reveal a significant overall *linear trend*: some of them show storage depletion (for instance, California's Central Valley, the Ganges-Brahmaputra Basin, the North China Plain Aquifer, the High Plains Aquifer, the Arabian Aquifer System and the Canning Basin), which is in contrast with increases in groundwater storage in several other aquifer systems (in particular the Upper Kalahari, Amazon Basin, Tungus Basin, Yakut Basin and Pechora Basin). These longer-term trends can only be defined, interpreted, confirmed and explained reliably after studying in more detail the specific conditions of the aquifer systems. Analyzing information on renewable groundwater development stress (as presented in the Section 'Interpreting and Comparing the Estimates' and in particular Figure 14) can serve as a first step toward predicting and confirming a long-term trend.

3.3.3 Groundwater Storage Depletion

Several researchers have identified or studied groundwater storage depletion trends in one or more mega aquifer systems. Table 8 summarizes their estimates of the rate of depletion, averaged over the specified periods. The estimates are expressed both in cubic kilometers per year and in mm per year, to facilitate comparisons.

Table 8 - Estimates of groundwater storage depletion trends in selected mega aquifer systems.

	Estimates for 21st century periods				**Estimates for periods before 2000**			
	Period	**Methods used[1]**	**Storage depletion[2]**		**Period**	**Methods used[1]**	**Storage depletion[2]**	
References			**km^3/yr**	**mm/yr**			**km^3/yr**	**mm/yr**
1 Nubian Aquifer System (NAS)								
Konikow, 2011	2000-2008	3,5,7	2.36	*1.07*	1900-2000	3,5,7	0.80	*0.36*
Richey et al., 2015b	2003-2013	2	*6.40*	2.91				
Mohamed et al., 2016	2003-2013	2	*0.69*	0.32				
Shamsudduha & Taylor, 2020	2002-2016	2	*4.40*	2.00				
2 North-Western Sahara Aquifer System (NWSAS)								
Konikow, 2011	2000-2008	5	2.20	*2.16*	1900-2000	5	0.53	*0.52*
Gonçalves et al., 2013	2003-2010	2	*0.55*	0.54				
Richey et al., 2015b	2003-2013	2	*2.86*	2.81				
Shamsudduha & Taylor, 2020	2002-2016	2	*2.04*	2.00				
16 California's Central Valley Aquifer System								
Konikow, 2011	2000-2008	2,3	3.93	*75.5*	1900-2000	3	1.13	*21.8*
Scanlon et al., 2012					1860s-1961	3	1.46	*28.1*
Scanlon et al., 2012					1962-2003	3	1.95	*37.5*
Konikow, 2013	2000-2008	2,3	3.93	*75.5*	1900-2000	3	1.13	*21.8*
Faunt et al., 2015					1962-2014	9	1.85	*35.6*
Hanak et al., 2015					1921-2009	9	2.15	*41.3*
Richey et al., 2015b	2003-2013	2	*0.46*	8.89				
Shamsudduha & Taylor, 2020	2002-2016	2	*0.64*	12.3				
Rateb et al, 2020	2003-2017	1,2,3	1.7	33.2				
17 High Plains Aquifer (Ogallala)								
Konikow, 2011	2000-2008	1	11.8	*26.3*	1900-2000	1	2.59	*5.75*
Scanlon et al., 2012					1950-2007	1	5.79	*12.9*
Konikow, 2013	2000-2008	1	10.2	*22.7*	1900-2000	1	2.59	*5.76*
Richey et al., 2015b	2003-2013	2	-0.14	-0.31				
Shamsudduha & Taylor, 2020	2002-2016	2	*3.00*	6.67				
Rateb et al, 2020	2003-2017	1,2,3	1.2	2.67				
18 Atlantic & Gulf Coastal Aquifer System								
Konikow, 2011&2013	2000-2008	1,3,4,7,8	8.78	*7.63*	1900-2000	1,3,4,7,8	2.13	*1.85*
Richey et al., 2015b	2003-2013	2	*6.82*	5.93				
Shamsudduha & Taylor, 2020	2002-2016	2	*-4.93*	-4.29				
22 Arabian Aquifer System								
Konikow, 2011	2000-2008	3,5,7	13.6	*9.18*	1900-2000	3,5,7	3.59	*2.41*
Richey et al., 2015b	2003-2013	2	*13.6*	9.13				
Shamsudduha & Taylor, 2020	2002-2016	2	*4.90*	3.30				
23 Indus Basin								
Richey et al., 2015	2003-2013	2	*1.36*	4.26				
Shamsudduha & Taylor, 2020	2002-2016	2	*1.60*	5.00				
Sattar & Khalid, 2020	2005-2015	2	*0.64*	2.00				
24 Ganges-Brahmaputra Basin								
Richey et al., 2015	2003-2013	2	*11.7*	19. 6				
Shamsudduha & Taylor, 2020	2002-2016	2	*10.0*	16.7				

Continued – Table 8 - Estimates of groundwater storage depletion trends in selected mega aquifer systems.

References	Estimates for 21st century periods				Estimates for periods before 2000			
	Period	Methods used[1]	Storage depletion[2] km^3/yr	Storage depletion[2] mm/yr	Period	Methods used[1]	Storage depletion[2] km^3/yr	Storage depletion[2] mm/yr
29 Greater North China Plain Aquifer System (Huang-Huai-Hai Plain)								
Konikow, 2011	2000-2008	1,3,7	5.00	*15.6*	1900-2000	1,3,7	1.30	4.07
Richey et al., 2015b	2003-2013	2	*2.40*	7.50				
Shamsudduha & Taylor, 2020	2002-2016	2	*4.05*	12.7				
29a North China Plain Aquifer System (Hai Plain only)								
Gong et al., 2018	2003-2015	1,2	2.53	18.6	1971-2015	1,2	2.42	17.8
Kinzelbach et al., 2021	2004-2020	2	*3.32*	24.4				
31 Tarim Basin								
Richey et al., 2015b	2003-2013	2	*0.12*	0.23				
Shamsudduha & Taylor, 2020	2002-2016	2	*0.00*	0.00				
Hu et al., 2019	2003-2016	2	*1.52*	2.93				
34 North Caucasus Basin								
Richey et al., 2015b	2003-2013	2	*3.70*	16.1				
Shamsudduha & Taylor, 2020	2002-2016	2	*2.61*	11.3				
36 Great Artesian Basin								
Welsh et al., 2012					1965-1999	3	0.31	*0.18*
Richey et al., 2015b	2003-2013	2	*-18.0*	-10.6				
Shamsudduha & Taylor, 2020	2002-2016	2	0.00	0.00				
37 Canning Basin								
Munier et al., 2012	2003-2009	2	*11.00*	25.6				
Richey et al., 2015b	2003-2013	2	*4.05*	9.41				
Shamsudduha & Taylor, 2020	2002-2016	2	*5.16*	12.0				

[1] Methods adopted from Konikow (2011):
1 = water level changes times storativity, integrated over area;
2 = gravity changes over time (GRACE);
3 = calibrated flow model;
4 = confining unit analysis;
5 = pumpage data combined with water budget analysis;
6 = extrapolating fraction of pumpage derived from storage to other areas;
7 = partial record extrapolation;
8 = from land subsidence volume;
9 = unknown.

[2] Values as reported by authors are in roman font; values derived by conversion or interpreted from graphs are in *italics*. Negative values indicate an increase in storage.

The information presented in Table 8 gives rise to the following comments and conclusions.

- <u>*A diversity of methods has been used.*</u> The different methods are listed at the bottom of Table 8. As Konikow (2011) commented, methods 1 through 3 are generally the most reliable ones, but much depends on the quantity and quality of the available data, and on the skills of those who process and interpret the data. The second method (interpreting gravity anomalies observed by GRACE) has become prominent since GRACE's introduction in 2002, but as Figure 20 through Figure 22 show, decomposition of the ΔGWS time series into its different components (long-term trend, seasonal and inter-annual fluctuations) is often not easy and rather arbitrary, and the current period of data availability (2002 to 2016) is relatively short for defining a long-term trend. GRACE and InSAR[3] (that can be used in method 8) are satellite observation techniques for estimating storage depletion that complement the classical in-situ or terrestrial observation techniques on which most of the methods rely.

- *Alternative depletion estimates for the same aquifer system tend to differ considerably, even if they refer to approximately the same period.* The conclusion is that these estimates of storage depletion are subject to a large degree of uncertainty. Their accuracy is much lower than some researchers seem to suggest in their papers. None of the current methods of estimation produces accurate results and each has weaknesses. For example, in the GRACE method, the calculation of the ΔGWS time series from observational data is accompanied by significant uncertainty. Furthermore, as can be inferred from Figure 20 through Figure 22, it is difficult to disentangle a long-term trend from seasonal and interannual variations if the ranges of such variations are comparatively large, and/or if the total period of observation is rather small. Moving average schemes, as well as statistical and stochastic techniques for trend detection and analysis, may be helpful in this task. Analysis outcomes based on relatively short periods of observation (such as Figure 6b in Richey et al., 2015b) should therefore be presented and interpreted with utmost caution. The graph for the Paris Basin in Figure 22 is an eloquent demonstration of the importance of the length of the observation period: a trend of storage depletion would have seemed a plausible interpretation if the observation period ended in 2013, but its continuation from 2014 through 2017 makes this interpretation less credible.
- *Nevertheless, long periods of observation confirm a long-term trend of groundwater depletion in several mega aquifer systems.* These mega aquifer systems include the Nubian Aquifer System, the North-Western Sahara Aquifer System, Central Valley, the High Plains, the Atlantic and Gulf Coastal Aquifer System, the Arabian Aquifer System, the Ganges-Brahmaputra Basin and the North China Plain Aquifer System. Long periods of in-situ observation and hydrological data (Sections 3.2 and 3.3), contextual information and model simulations support this conclusion. Three of these aquifer systems (numbers 1, 2 and 22) are characterized by non-renewable groundwater resources, the other ones receive significant groundwater recharge, but are intensively exploited.
- *A long-term linear trend (or its absence) may be hidden or be made otherwise undetectable by interannual fluctuations that last for several years.* This is obvious in the case of the Atlantic and Gulf Coastal Aquifer System and the Canning Basin. In the former case,

[3] InSAR is Interferometric Synthetic Aperture Radar, a geodetic technique that can identify changes in the Earth's surface.

the long-term-observation record leaves no doubt about long-term depletion (which is supported by the level of renewable groundwater development stress), but climatic variability produces an apparent trend in the opposite direction during the period from 2003 to 2016 (as indicated by the GRACE record, Figure 21). The rate of groundwater depletion interpreted from the GRACE record for the Canning Basin since 2003 exceeds the rate of abstraction by at least two orders of magnitude (Table 7), thus cannot be explained by groundwater withdrawal, but most likely by climatic variability.

- *Recent massive groundwater level recovery in the Great Artesian Basin may partly be explained by groundwater conservation activities.* Artesian pressure (thus also the stored groundwater volume) has declined gradually in the Great Artesian Basin since the late nineteenth century, in response to groundwater withdrawal through wells. Substantial waste of groundwater was occurring for a long time by freely flowing artesian wells and a poor water conveyance infrastructure, but large government interventions beginning in the 21st century have reduced the losses significantly, leading to partial recovery (Habermehl, 2018).

3.4 Benefits and Side-Effects of Intensive Groundwater Abstraction

3.4.1 Benefits of Intensive Groundwater Abstraction

The use of groundwater withdrawn from the mega aquifers produces huge benefits to humanity. In the first place, as a source of domestic water for a large part of the 1.6 to 1.8 billion people that live within the boundaries of the 37 mega aquifer systems. Second, as a source of water for approximately 46 million hectares of groundwater-irrigated agricultural land (40 percent of the global area equipped for groundwater irrigation). Third, as a source of water for a wide gamut of industrial, mining, geo-energy development and other human activities. These services contribute significantly to human health and well-being, as well as to job opportunities and economic development of the areas concerned.

The level and intensity of groundwater withdrawal and use vary enormously among the 37 mega aquifer systems. The top three in this respect are the Ganges-Brahmaputra Basin, the Indus Basin and the Greater North China Plain Aquifer system, with around 600, 300 and 300 million people living within their boundaries, respectively, and with approximately 17, 10 and 4 million hectares of land equipped for groundwater irrigation, respectively. These impressive figures explain their estimated combined share of about two-thirds of the cumulative groundwater abstraction rates of the 37 mega aquifer systems.

The benefits accruing from groundwater are not only related to the volumes of groundwater withdrawn, but also to the invaluable buffer function provided by the mega aquifer systems. A notable example is California's Central Valley, a major agricultural producer exposed to extended periods of drought, most recently during the periods

2006-2010, 2011-2017 and 2020 until present (2021), where temporary increased groundwater pumping has contributed to reducing damages, together with other measures. As presented in Section 3.2 and Table 7, groundwater abstraction intensity is extremely low for several other mega aquifer systems, which suggests that there may be scope for enhancing their profitable exploitation. However, such a hypothesis can only be confirmed after a thorough analysis of the individual aquifer systems, and their current and potential interactions within the local hydrological setting.

3.4.2 Hydrological Responses to Intensive Groundwater Abstraction

Intensive groundwater abstraction modifies the hydrological regime of an aquifer. Direct hydrological responses include:

- depletion of stored volumes of groundwater (accompanied by declining groundwater levels and pressures);
- intrusion of seawater or water from other hydraulically connected water bodies (not only surface water but also groundwater from overlying or underlying strata)
- reduction of natural groundwater discharge (by springs, baseflows of streams, evapotranspiration and evaporation from shallow water tables, outflow into lakes or the sea); and,
- increased recharge from connected components of the hydrological system (streams, lakes, other hydrogeological units).

These hydrological responses, in turn, have their impacts on human society (in particular on groundwater users) and the environment. Figure 23 lists the most common impacts. Some brief explanatory comments will follow, with selected references to mega aquifer systems for which the impacts have been reported.

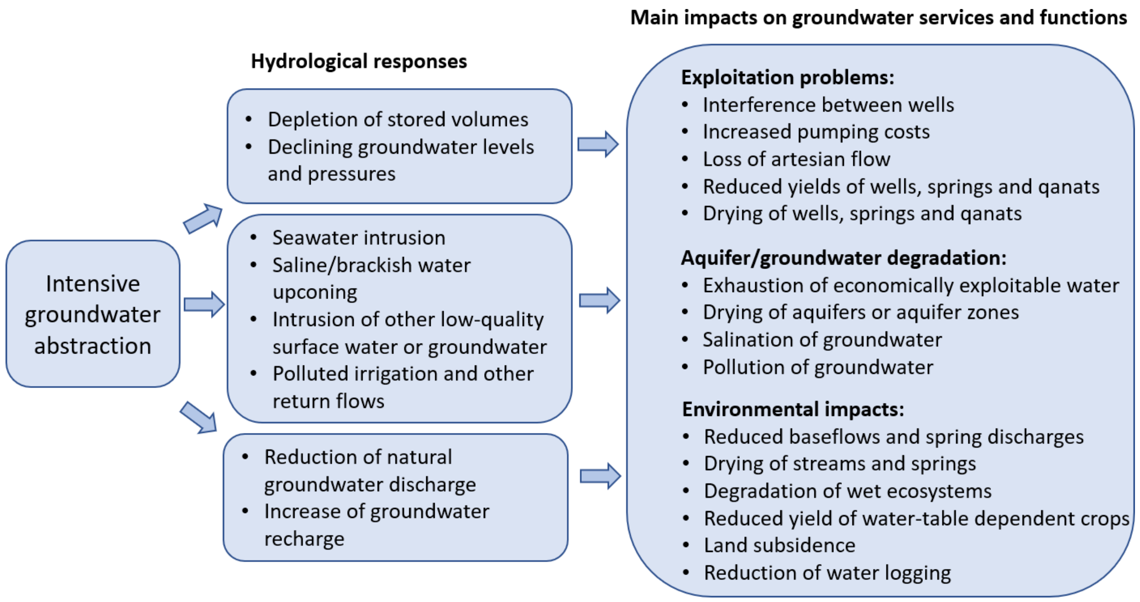

Figure 23 - Side-effects of intensive groundwater abstraction including hydrological responses and the main impacts on groundwater services and functions.

3.4.3 Impacts of Intensive Groundwater Abstraction

These impacts vary in scale and perspective, ranging from the level and perspective of individual groundwater users to those of aquifers and interconnected environmental systems.

Declining groundwater levels – either caused by hydraulic interference between neighboring wells or by depletion of stored groundwater on a larger scale – occur in all intensively exploited mega aquifer systems and lead to higher cost of groundwater pumped from wells in the affected zones. This higher cost arises because of the increased height groundwater has to be lifted to bring it to the surface, the decline in well productivity, the need to replace the pump with one of higher capacity, or the need to deepen the well to keep it reasonably productive. Under similar abstraction rates, groundwater levels decline much more quickly in confined aquifers than in unconfined aquifers, especially when initial potentiometric levels reach far above the top of the aquifer and the confining layer is thick and poorly permeable, such as applies to much of the Guarani aquifer (Amore, 2018; Hirata and Foster, 2020).

Furthermore, groundwater users who draw their water from flowing wells, springs or qanats experience a gradual reduction in the yield of their source of water when groundwater levels in their area decline. A clear example is the Great Artesian Basin, where between 1878 and 2000 almost 5,000 flowing artesian boreholes were drilled, of which by the year 2000 only some 2,000 were still flowing, with a total yield less than half that of the 2,000 artesian wells that were in flowing conditions around the year 1920 (Habermehl, 2006). Other mega aquifer systems with large zones of artesian conditions where wells may stop flowing under continued current or increased groundwater abstraction rates include the Nubian Aquifer System, the North-Western Sahara Aquifer System, the Iullemeden Basin, the Lower Kalahari Basin, the Cambrian-Ordovician Aquifer System, the Maranhão Basin, the Guarani Basin and the Paris Basin (Margat and Van der Gun, 2013; Hirata and Foster, 2020). In the Paris Basin, deep artesian wells have tapped groundwater from the Albian greensands since the first half of the 19th century. Although still flowing, their flow rates have declined over time (Margat et al., 2013; Wikipedia, 2021). Regarding the North-Western Sahara Aquifer System, however, conditions are less favorable. Artesian conditions in the Algerian–Tunisian Chott region are likely to disappear under current groundwater withdrawal rates (OSS, 2008; Gonçalves et al., 2013).

Intensive groundwater abstraction over a wide areal extent may eventually lead to significant aquifer zones (or even entire aquifers) becoming incapable of serving as a source of water supply. Often this will be when static water levels fall below critical depths of economically exploitable groundwater, but in other cases it could be due to physical exhaustion (i.e., insufficient groundwater left for withdrawal). For instance, extrapolations by Scanlon and others (2012) predict that the saturated aquifer thickness in 35 percent of the southern High Plains will be less than 6 m by the year 2040, thus unable to support irrigation. For the Central Valley, these authors calculate that between the 1860s and 2003 14 percent of the estimated groundwater in storage before groundwater irrigation started has been depleted; within the Tulare Basin (southern part of the Valley) groundwater levels have declined more than 30 m in the unconfined and more than 120 m in the deeper confined aquifer. Other mega aquifer systems with a long-term depletion history (as mentioned in Section 3.3) are likely to eventually experience similar problems, leading to either groundwater abstraction for several types of water use becoming economically unfeasible, or certain aquifer zones becoming largely dewatered.

Another form of aquifer degradation triggered by intensive groundwater abstraction is the encroachment of saline or brackish water into certain freshwater aquifer zones. A prominent mechanism in this category is seawater intrusion. Since half of all mega aquifer systems are landlocked, seawater intrusion is a potential risk for no more than 18 of them, and only for coastal zones that in most cases occupy only a minor part of the aquifer system. Nevertheless, seawater intrusion is an important potential side-effect of intensive groundwater abstraction, as reported for several coastal zones of mega aquifer systems, such as the Nubian Aquifer System (Sherif et al., 2012), the Gulf and Atlantic Coastal Aquifer System (Barlow, 2003; Rosenshein and Moore, 2013), the Indus and Ganges-Brahmaputra Basins (MacDonald et al., 2016) and the North China Plain Aquifer System (Shi and Jiao, 2014). More widespread are zones where saline or brackish groundwater of connate, transgression, or terrestrial origin may encroach into the freshwater domains as a result of intensive groundwater abstraction, either by upconing or by lateral migration. Such mineralized groundwater is not only common in coastal areas (e.g., in the northern zone of the Nubian Aquifer System, the western half of the Senegal-Mauritanian Basin, the Gulf and Atlantic Coastal Plains, and the Arabian Aquifer System), but also elsewhere, at greater depths in almost all deep sedimentary basins and numerous zones at shallower depths (Van Weert et al., 2009). The third source of groundwater salinization produced by groundwater abstraction (at least partly) consists of irrigation return flows. These have been enriched in dissolved solids content during the irrigation process and contribute to a gradual increase of salinity and agrochemicals in soils and shallow aquifer zones. This source of salinity and pollution is particularly relevant in aquifer systems intensively tapped for irrigation, such as the Central Valley, the High Plains, the Indus Basin, the Ganges-Brahmaputra Basin and the Greater North China Plain Aquifer System. It is not uncommon for several of these sources of salinization to contribute simultaneously, sometimes in combination with other mechanisms unrelated to groundwater abstraction, such as flooding by seawater, dissolution of evaporite layers or high rates of evaporation at the land surface.

As indicated in Figure 23, intensive groundwater abstraction also has environmental impacts. In the first place, it produces reduction of natural groundwater discharge, which leads to the degradation or disappearance of wet environmental features such as baseflows of streams, spring flows, wetlands, oases and sabkhas. The Great Artesian Basin, for instance, feeds more than 460 groups of springs, most of them in the marginal areas of the basin, essential for maintaining groundwater-dependent ecosystems with unique fauna and flora. Continued groundwater exploitation by wells has reduced the discharge of many of these springs over time. Many of the springs are therefore protected now under the Environment Protection and Biodiversity Conservation Act of 1999 (Australian Government, 2018; Habermehl, 2020). Other flux-related impacts of intensive groundwater abstraction are the degradation of oases in northern Africa, for example, in the North-Western Sahara Aquifer System (Corsale, 2009; Sghaier, 2010), and wetland degradation, for example, the Azraq wetland in Jordan, at the northern edge of the Arabian Aquifer System (Molle et al., 2017). In areas where crops benefit from shallow water tables for their continuous subsurface water supply, such as in most of The Netherlands, even minor declines of the water table by groundwater abstraction may lead to damage, in the form of crop yield reduction. Intensive groundwater abstraction may, in exceptional cases, lead to positive environmental impacts, such as the reduction of water-logged land area in the Indian state of Haryana (Indus Basin).

A rather different environmental impact of intensive groundwater abstraction is land subsidence. Rather than being related to reduced fluxes, it is triggered by declines of pore water pressures in compressible formations, such as Quaternary clays. It is a major impact of intensive groundwater abstraction in the Central Valley of California (Faunt et al., 2015) and in the North China Plain (Guo et al., 2015), The subsidence-affected area in the North China Plain extends over approximately 120,00 km^2 (Gong et al, 2018), half of which had subsided more than 200 mm by the year 2010 (Zheng et al., 2010). Other man-induced forms of land subsidence may simultaneously take place, caused by activities such as land drainage, construction works and the development of oil or gas. Hydrocarbons have been discovered at depth in several of the sedimentary basins hosting mega aquifer systems, and in a number of them these energy resources are intensively exploited (e.g., in the Arabian Aquifer System, the US Gulf Coast and offshore, and the West-Siberian Basin).

3.5 Opportunities to Test Knowledge Gained in this Section

To exercise the knowledge gained while reading this section, investigate exercises 11 through 16. Links are provided to each exercise below.

Exercise 11↴

Exercise 12↴

Exercise 13↴

Exercise 14↴

Exercise 15↴

Exercise 16↴

4 Epilogue

4.1 Existing Information and Knowledge about Large Aquifer Systems

The preceding sections form only an introduction to the subject of large aquifer systems. They intend to clarify what is meant by 'large aquifer systems', and to make the reader more familiar with the world's largerategst aquifer systems. The latter is done by a systematic inventory, review and comparison of several important macroscopic characteristics of a selected set of very large aquifers (mega aquifer systems).

What is presented in these sections summarizes only a very minor fraction of what is known about these systems. Numerous scientists and organizations have been and are still engaged in exploring, assessing and studying large aquifer systems or parts of such systems, at a variety of spatial scales and covering a wide range of themes or aspects. A significant part of the knowledge and information they acquire in this way is publicly shared in the form of reports and papers that are increasingly accessible via the internet. For some large aquifer systems, it is difficult to find such sources of information, perhaps because of the language used for reporting or restrictive policies on sharing information, or simply because the aquifer system has been hardly explored and studied so far. For other aquifers, on the other hand, it is possible to access large numbers of publications. In some cases, organizations and scientists have made special efforts to concentrate relevant information on the aquifer systems of their concern in the form of dedicated information systems (e.g., USGS, 2021 and BGS, 2021), monographs (e.g., UN-ESCWA and BGR, 2013; Ransley et al., 2015) or special issues of scientific journals (e.g., IAH, 2018, 2020).

4.2 Uncertainty

If one salient property of information and knowledge on large aquifer systems has to be mentioned and highlighted here, then it is *uncertainty*. Anyone who has been professionally involved in detailed field exploration and assessment of a groundwater system knows that:

- field observations meant to determine parameters and variables tend in practice to be limited in number (due to financial and other constraints);
- sampling locations and depths (e.g., for exploratory boreholes) are often not optimal;
- commonly used methods of observation tend to produce outcomes of only limited accuracy;
- significant methodological, observational, processing and interpretation errors are not uncommon; and,
- the conversion of point observations to spatially continuous maps of aquifer properties and conceptual models requires assumptions based on sound professional expertise, thus is inherently subjective.

Uncertainty may be reduced to some extent (but not eliminated) by additional data acquisition programs, but especially for large and deep aquifer systems these involve major efforts and major financial investment. Observation by remote sensing techniques provides useful complementary information but is similarly subject to methodological, observational, processing and interpretation errors. The GRACE examples presented in Section 3.3 illustrate this.

In summary, uncertainty is part and parcel of information and knowledge on aquifer systems. It is inherent to virtually all components, ranging from assumptions on aquifer delineation and hydraulic continuity of the rock masses within the defined system boundaries to numerical values obtained by using advanced and sophisticated observational techniques. Therefore, critical thinking is needed regarding all information presented in the literature on aquifer systems, and the presence of significant margins of error should always be taken into account.

4.3 Viewing Large Aquifer Systems at Different Spatial Scales

The information on large aquifers systems presented in this book takes a macroscopic perspective. This enables a view of the aquifer systems in a global context, to compare the different aquifer systems and their state based on simple indicators, and to get an idea of the magnitude of the opportunities and challenges they offer. While providing these interesting insights, information at this spatial scale has its limitations. It is of little direct use for practical activities such as planning for groundwater abstraction wells or defining and designing groundwater management interventions. Such activities need to be guided by more detailed information on a local, sub-regional or regional scale, paying ample attention to the spatial variations of aquifer properties, groundwater state variables and interactions with people and the environment. Assessment studies and monitoring activities in support of such practical activities usually cover areas of limited extent, much smaller than the size of large aquifers systems. Information acquired at different spatial scales is complementary, with the data from each scale serving different types of analysis or decisions, and together they cover the entire field from local to global.

4.4 Groundwater Governance and Management

Concerning groundwater governance and management there are no fundamental differences between large and small aquifers. Consequently, what is presented in publications like Findidakis and Sato (2011), Jakeman and others (2016), and Villholth and others (2018) is in principle valid for aquifer systems of all sizes.

Nevertheless, large and very large aquifer systems are particularly challenging for several reasons.

- Their large dimensions contribute to a high degree of physical complexity, which requires major efforts and financing for assessment and monitoring.

- With increasing aquifer size, communication between stakeholders becomes more difficult and is an obstacle to the development of consensus and solidarity between stakeholder groups living far from each other.
- Issues have to be addressed in a coordinated way at a diversity of spatial scales, not only at the local and aquifer system levels.
- Many of the large aquifer systems are *transboundary*, which introduces additional dimensions to groundwater governance (Linton and Brooks, 2011; Fried and Ganoulis, 2016; UNESCO-IHP, 2016; Albrecht et al., 2017; Puri and Villholth, 2018). Even more important than a formal interstate agreement and a dedicated coordinating body for transboundary cooperation is mutual trust between the neighboring countries and the willingness to cooperate.
- Deep sedimentary basins in which many large aquifers systems are situated are usually also favorable environments for hydrocarbon exploration and exploitation, making the aquifers more vulnerable to contamination.

Large aquifer systems are likely to play an ever-increasing role in the future, with their vast strategic water reserves and their ample capacities to contribute to climate change adaptation. The enormous importance of the world's large aquifer systems justifies the major efforts needed for addressing these challenges energetically and effectively.

4.5 Mega Aquifer Systems and Climate Change

The current state of individual mega aquifer systems may still reflect climatic conditions of past geological periods because complete adaptation to the current climate has not yet been achieved. This is because physical processes tend to propagate extremely slowly across the entire domain of mega aquifer systems, which is partly due to their huge size. Examples are the slow decay of natural groundwater discharge from the Nubian Aquifer System (Figure 13) and the continuous degradation of permafrost (thawing) in the West Siberian Basin (Box 1), both in progress for approximately 10,000 years.

Current and projected anthropogenic climate change (IPCC, 2021a) is super-imposed on the long-term natural climate variations. Significant impacts are expected to develop during the present century. This includes a reduction in groundwater recharge due to warming (which causes an increase in evaporation and evapotranspiration) that will be exacerbated in regions where the annual precipitation also decreases. The impacts will be amplified by increased groundwater abstraction to meet water demands given the higher temperatures and lower precipitation. Both the reduced groundwater recharge and increased abstraction will contribute to higher groundwater development stress in many of the mega aquifer systems. Fact sheets prepared by the Intergovernmental Panel on Climate Change (IPCC, 2021b) provide a summary of the climate change prognosis for each of the mega aquifer systems.

Finally, some comments related to the influence of climate change on three specific categories of mega aquifer systems. First, aquifer systems containing only non-renewable groundwater are not threatened by changes in recharge, which implies that accelerated groundwater resource declines there will result only from increases in groundwater abstraction. Second, mega aquifer systems bordering the sea will be affected by sea-level rise induced by climate change, which leads to increased risk of seawater intrusion and seawater flooding. Finally, degeneration of permafrost in the three northernmost mega aquifer systems in Asia will, in principle, cause groundwater recharge to increase and the discharge of groundwater and its dissolved solids will also increase (Box 1).

5 Exercises

5.1 Exercises Pertinent to Section 1

Exercise 1

Although the terms 'groundwater system' and 'aquifer' or 'aquifer system' are not synonymous, you may perceive them to have significant overlap, in practice. What do they have in common, and what are the differences in your opinion? Can you give examples of cases where the term 'groundwater system' applies, but 'aquifer' or 'aquifer system' does not? Can you give examples of cases where the term 'aquifer' is appropriate, but the term 'groundwater system' is not appropriate?

Back to where the text links to Exercise 1↑

Click for solution to Exercise 1↓

Exercise 2

Look at the aquifer definitions in Table 1. Which one of these definitions is closest to your interpretation of the term, or to the interpretation that prevails in groundwater agencies in your country or area?

Back to where the text links to Exercise 2↑

Click for solution to Exercise 2↓

Exercise 3

Explain the relation between groundwater age and factors such as groundwater flow pattern, groundwater flow intensity and groundwater depth. Why are high groundwater ages more likely to occur in large aquifer systems than in smaller ones?

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Click for solution to Exercise 3↓

Exercise 4

Identify at least two aquifers in your country, preferably very different ones. Prepare a table summarizing information or lumped attributes, in terms of geology, lithology, hydraulic properties, hydraulic state (unconfined/semi-confined/confined), groundwater mineralization level (fresh/brackish/saline), rate of groundwater abstraction as well as the rate of recharge, discharge and change of the amount of water stored. Which differences between these aquifers do you consider most relevant to groundwater development and management?

Back to where the text links to Exercise 4↑

Click for solution to Exercise 4↓

5.2 Exercises Pertinent to Section 2

Exercise 5

Using a world map of geologic provinces similar to the one on Wikipedia↗ that shows major geologic structural units, compare the location of the mega aquifer systems with that of continental shields, volcanic rock areas and folded mountain regions. What do you observe and what are your conclusions?

Back to where the text links to Exercise 5↥

Click for solution to Exercise 5↧

Exercise 6

The oldest sediments in some of the mega aquifer systems date back from the first period of the Paleozoic Era, or they are even older. Identify, by name, a few systems where this is the case.

Back to where the text links to Exercise 6↥

Click for solution to Exercise 6↧

Exercise 7

Define the following terms related to aquifer systems and indicate how they differ from each other: a) stored groundwater volume; b) groundwater reserves; c) exploitable groundwater reserves; and, d) exploitable groundwater resources.

Back to where the text links to Exercise 7↥

Click for solution to Exercise 7↧

Exercise 8

Compare the theoretically recoverable groundwater storage estimates listed in Table 6 (‘reserves’) with the graphical presentation of groundwater reserves in Africa in Figure 11. Are they in reasonable agreement? For which mega aquifer systems is the agreement good and for which ones is it less satisfactory?

Back to where the text links to Exercise 8↥

Click for solution to Exercise 8↧

Exercise 9

Richey and others (2015a; doi:10.1002/2015WR017351↗) produced groundwater storage estimates for the 37 mega aquifer systems, using different methods. Give your opinion on the methods used and the credibility of the outcomes reported by the authors (subdivided into historical, regional, and revised estimates).

Back to where the text links to Exercise 9↥

Click for solution to Exercise 9↧

Exercise 10

Which of the mega aquifer systems have brackish or saline groundwater in the upper aquifer(s) in at least a significant part of their total area, overlying extensive fresh groundwater reserves?

Back to where the text links to Exercise 10↥

Click for solution to Exercise 10↧

5.3 Exercises Pertinent to Section 3

Exercise 11

The majority of the papers on a particular mega aquifer reporting a value of mean groundwater recharge do not specify how this estimate has been derived. This raises questions regarding the reliability and accuracy of the reported estimate. Outline ideas and steps that can help evaluate the plausibility of the reported value.

Back to where the text links to Exercise 11↥

Click for solution to Exercise 11↧

Exercise 12

Non-renewability of groundwater resources under present-day conditions may have different causes. List three such causes, and give examples among the mega aquifer systems or the aquifers they include.

Back to where the text links to Exercise 12↥

Click for solution to Exercise 12↧

Exercise 13

Are water quantity policies and management for non-renewable groundwater similar to or fundamentally different from those for renewable groundwater? Please explain.

Back to where the text links to Exercise 13↥

Click for solution to Exercise 13↧

Exercise 14

When groundwater abstraction records are not available for a large aquifer system of concern, it may be possible to produce a reasonable estimate of abstraction by disaggregating national groundwater abstraction statistics under the assumption that abstraction is strongly correlated with population size and groundwater-irrigated area. Box 3↓ shows the approach in practice, with the Paris Basin as an example. As an exercise, use this approach to estimate abstraction for one of the other mega aquifer systems, for example, the Maranhão basin or the Ganges-Brahmaputra Basin. It is convenient to consult Margat and Van der Gun (2013), Siebert and others (2010, Supplement S2), and the internet for statistics on national groundwater abstraction, areas equipped for groundwater irrigation, and population, respectively. Compare your outcomes with the values listed in Table 7 and comment on the differences.

Back to where the text links to Exercise 14↑

Click for solution to Exercise 14↓

Exercise 15

Methodological flaws and inadequate data may explain (at least partly) the often significant divergence of storage depletion trend estimates for the same mega aquifer system, as listed in Table 8. Identify the main flaws and data deficiencies commonly encountered when applying method 1 (multiplying water level changes by storativity and integrating over the aquifer area); method 2 (evaluating gravity changes over time using GRACE data); and method 3 (using a calibrated flow model).

Back to where the text links to Exercise 15↑

Click for solution to Exercise 15↓

Exercise 16

Among the mega aquifer systems with renewable groundwater resources, several systems are facing exceptional water quantity sustainability challenges, in response to intensive groundwater development. Select five such stressed systems and consult a few relevant papers on each of the selected systems (the Reference Section will help you identify potential papers). What are the main impacts observed or anticipated in each of them? What options exist to control the related problems to some extent?

Back to where the text links to Exercise 16↑

Click for solution to Exercise 16↓

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7 Boxes

Box 1 - Modern and Relict Permafrost in the Aquifers of the West Siberian Basin

The West Siberian Basin forms a huge mega aquifer system, 3.2 million km^2 in extent and filled with Triassic to Quaternary deposits, reaching a maximum of approximately 6 km unfrozen thickness.

Modern discontinuous permafrost covers the northern one-third of the basin (north of approximately 61°N), while relict Late Pleistocene permafrost buried to depths ranging from 50 to 400 m is reported to occur as far south as 55°N, encompassing more than three-quarters of the basin. The area occupied by the relict Late Pleistocene permafrost includes three distinct zones (Figure Box 1-1). In the northernmost zone, both types of permafrost (modern and relict) form a more or less monolithic structure. The mid-zone, south of the Arctic Circle (66.5°N), is primarily a two-layered structure with a thawed layer between the surficial frozen layer and the relict Pleistocene frozen layer below. In the southernmost third zone, only relict permafrost is present, with its top between 150 and 230 m deep, and its base down to 400 to 500 m in depth (Foley et al., 1994).

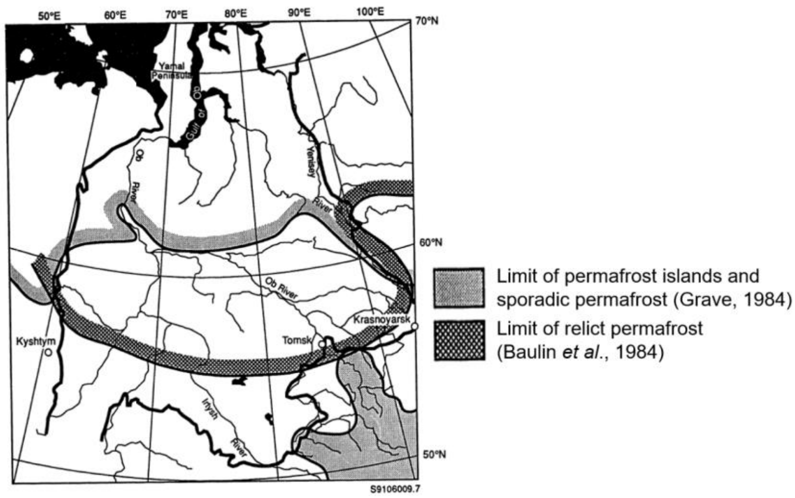

Figure Box 1-1 - Permafrost limits (Foley et al., 1994).

The West Siberian region was affected by rapid permafrost degradation and peatland expansion during the Early Holocene; the region's response to current anthropogenic warming is expected to be rather similar (Li et al, 2021; Teshebaeva et al. 2021). Frey et al (2007) concluded that the rapid warming and degradation of permafrost will increase the transport of dissolved solids to the Kara Sea and the adjacent Arctic Ocean, which may cause problems for future biological productivity in the waters from the arctic shelf of Eurasia and the interior of the Arctic Ocean Basin.

Return to where the text links to Box 1↥

Box 2 - Brief Characterization of the Variations in Geogenic Groundwater Mineralization in the Mega Aquifer Systems

(as indicated in consulted documents)

Nubian Aquifer System

According to Bakhbakhi (2006), the mineralization level of groundwater in the Nubian Aquifer System increases from a TDS of 500 ppm in the southern part to hypersaline water in the northern part. The confined part of the Nubian Aquifer System contains approximately 150 thousand km^3 of saline water, which is 25 percent of all groundwater in the Nubian Sandstone Aquifer System (Nubian and Post-Nubian combined). According to the OSS (Observatoire du Sahara et du Sahel, or in English, Sahara and Sahel Observatory) in 2020, groundwater is saline in a small part of the Post-Nubian aquifer, next to the Mediterranean Sea

North-Western Sahara Aquifer System

Along the northern margin of the North-Western Sahara Aquifer System (NWSAS), shallow evaporites are present in a west-east running zone of chotts (i.e., shallow saline lakes, often dry during part of the year), some of which are more than 5000 km^2 in extent. They threaten to salinize shallow fresh waters, and that risk can be exacerbated by intensive groundwater abstraction (Bryant et al., 1994; Mamou et al., 2006; OSS, 2020).

Senegalo-Mauritanian Basin

In the western part of the Senegalo-Mauritanian Basin, in a 100-150 km wide belt parallel to the coast, the Maastrichtian aquifers (dipping deep in a westward direction) contain saline groundwater of NaCl facies, assumed to be of connate origin. Evaporite dissolution and mixing with seawater from Quaternary transgressions have affected water quality in the Continental Terminal and Quaternary aquifers (IAEA, 2017a). Excessive withdrawals led to high drawdowns in the water table and the risk of marine intrusions in coastal areas (OSS, 2020).

Lake Chad Basin

The electrical conductivity level of groundwater in the Quaternary upper aquifer of the Lake Chad Basin is generally low (IAEA, 2017b), but is quite high in the center of the basin (IAEA, 2017). It is somewhat higher in the Lower Pliocene aquifer (IBRD, 2020). The Cretaceous Lower aquifer – still poorly explored – is highly mineralized (GWP, 2013).

Sudd Basin

Salama (1977) reports that groundwater mineralization in the Sudd Basin gradually increases with depth. Furthermore, it varies laterally from 200 to 500 ppm in the peripheral zones to approximately 5000 ppm in the central part of the basin, where water flow is sluggish. A more recent report (RSS, 2015) mentions that groundwater with TDS between

1500 and 5000 mg/L and sometimes more, is encountered in the north-eastern zone of the basin.

Ogaden-Juba Basin

The total dissolved content of groundwater in the complex aquifer sequences of the Ogaden-Juba Basin is variable, but generally rather high to very high, especially at shallow depths. This is true for the Ogaden, Somalian and East-Kenyan shares of the basin (Pavelic et al., 2012). Kebede and Taye (2020) mention high salinity as one of the constraints to using groundwater from sedimentary aquifers in this region, but they are probably referring mainly to conditions in the shallow aquifers. Steyl and Dennis (2018) mention seawater intrusion in the drier countries and connate saline water affecting the Merti aquifer shared by Somalia and Kenya.

Stampriet-Lower Kalahari Basin

In its south-western part (the Stampriet basin) groundwater mineralization generally increases towards south-western Botswana and the north-western Cape in South Africa (i.e., the Salt Block zone). TDS-values are above 1000 mg/L in most of the Kalahari aquifer and reach values above 5000 in the south-western part of the area. Mineralization levels are generally lower in the artesian Auob and Nossob aquifers; in particular in the Auob aquifer (intercalated between the Kalahari and Nossob aquifers) with TDS values less than 1000 mg/L in more than half of its area (GGRETA, 2016).

Karoo Basin

Groundwater in most of the Karoo Basin is fresh (TDS between 450 and 1000 mg/L). Concentrations of dissolved constituents increase from east to west accompanied by decreasing precipitation. High concentrations are limited to the westernmost and southernmost edges of the basin, with mean TDS in the north-western zone (around 10 percent of the total area) exceeding 3400 mg/L. The water is partly of connate origin. Water quality in the sedimentary sequence is regarded as poorer than in the dolerite dykes, due to longer residence time (Woodford and Chevallier, 2002).

Northern Great Plains Aquifer System

Upper and lower Palaeozoic aquifers of the Northern Great Plains Aquifer System are saline to hypersaline (up to more than 300,000 ppm). Saline water from these confined aquifers seeps upward to lower and upper Cretaceous aquifers. The former are most widespread, with limited freshwater zones and TDS mostly above, or far above, 3000 ppm (up to more than 10,000 ppm). TDS in the upper Cretaceous aquifers is mostly between 1000 and 3000 ppm (USGS, 2021; Betcher, 1995).

Cambrian-Ordovician Aquifer System

Groundwater in large areas of the Cambrian-Ordovician Aquifer System is not used because of high salinity (high dissolved solids content). These areas cover half of the confined part of the aquifer system, including parts of Iowa, Missouri Illinois, Indiana and Wisconsin. Dissolved solids concentration tends to increase drastically with depth in these areas, up to 112,000 mg/L (Wilson, 2012).

California's Central Valley Aquifer System

Kang and Jackson (2016) report that groundwater salinity in California's Central Valley Aquifer System typically increases with depth. At depths less than 1000 m, TDS concentrations less than 10,000 ppm are more common than those exceeding 10,000 ppm, while at greater depths the latter are more frequently found. The southern counties have a larger proportion of fresher water (< 3000 ppm) at depths less than 1000m than the northern counties. A maximum dissolved solids concentration of 52,000 ppm has been observed in Fresno County in the San Joaquin Valley.

High Plains Aquifer

From north to south, TDS in domestic wells of the High Plains Aquifer tends to increase from less than 250 to more than 2000 ppm. At greater depths mineralization tends to become higher, especially in zones where underlying deep geological formations contain saline water (DeSimone et al., 2014). In the southern part of the plains, upward movement of saline water from deeper aquifers occurs (Scanlon et al., 2012).

Gulf and Atlantic Coastal Aquifer System

Fresh groundwater is present down to considerable depths and is underlain by salt groundwater in much of the Atlantic and Gulf Coastal Aquifer System. Depths below which chloride concentrations of 5,000 mg/L or greater occur increase with distance from the coast. Nevertheless, below this fresh-saline interface there are also zones of fresh water and of brines (Meisler et al., 1988).

Maranhão Basin

Groundwater of calcium bicarbonate type and good quality prevails in the upper 100 to 150 m below ground surface in the Maranhão Basin. Below that is a zone with a diversity of mixed water types, probably partly resulting from chemical reactions with clay layers. Below 1000 to 1500 m of depth, groundwater is usually saline, in some cases with mineral contents (TDS) exceeding 150,000 mg/L (Rebouças, 1976).

Guarani Basin

Natural groundwater quality is generally good, with low mineralization in most areas of the Guarani Basin. Hydrogeochemical and isotopic data show that formations underlying parts of the Guaraní Aquifer System (SAG) – mostly saline aquitards – contribute to observed salinity and significant trace element increases. Downdip increases in groundwater salinity are observed, with high salinities in the extreme southwest of the SAG in Argentina (Hirata and Foster, 2020).

Arabian Aquifer System

Groundwater mineralization in the Paleogene (Umm-er-Radhuma and Damman formations) and Neogene aquifers of the Arabian Aquifer System increases from approximately 1000 mg/L (at the western edge) to saline and hypersaline near the Arabian Gulf Coast. Salinity is related to upward flow of deep saline groundwater (of connate origin or salinized by dissolution of evaporites) and to evaporation at inland and coastal sabkhas (UN-ESCWA and BGR, 2013).

Indo-Gangetic-Brahmaputra Basin

In the Indo-Gangetic-Brahmaputra Aquifer System, 39, 38, 12 and 11 percent of the total volume in the upper 200 m has TDS of < 500; 500-1000; 1000-2500; and > 2500 mg/L, respectively. Groundwater with TDS > 1000 mg/L underlies 28 percent of the aquifer system area. The lower two-thirds of the Indus Basin aquifer area has predominantly saline groundwater (TDS > 2500 mg/L), partly caused by anthropogenic activities. Most of the Gangetic-Brahmaputra plains have fresh to very fresh groundwater, while brackish to saline groundwater (TDS > 1000 mg/L) is found in the northwestern part of the Ganges basin and in the coastal zone of Bangladesh (MacDonald et al., 2016).

West Siberian Basin

According to Foley and others (1994), in the West Siberian Basin, Oligocene to Quaternary deposits (only a minor fraction of the total sedimentary series) form an unconfined aquifer, whereas the Jurassic to Oligocene-age rocks contain confined aquifers and aquitards. These confined aquifers and aquitards are highly mineralized (with brines in the center of the basin), which is in line with the perception that they receive little recharge. Modern and relict permafrost are present in a large part of the basin (as indicated in Box 1).

North China Plain Aquifer System

Below most of the North China Plain (NCP) Aquifer System's alluvial plain and coastal strip, the hydrogeological sequence includes a brackish-water aquifer of large geographical extent. It overlies confined freshwater aquifers and is locally overlain by thin lenses of fresher groundwater (Foster et al., 2004). The Quaternary series of the NCP (150 to 600 m thick) contains four superimposed aquifers. Groundwater in the first one (unconfined) and the second one (shallow confined) contain fresh water in the piedmont plain zone, but it becomes saline (TDS > 2,000 mg/L) in the central alluvial and littoral plains. The third and the fourth aquifer (both confined) contain fresh water (TDS of 300-500 mg/L and < 1,000 mg/L, respectively) and form the main target for exploitation (Foster et al., 2003; Su et al., 2018). The brackish-water aquifer (locally overlain by thin lenses of fresher groundwater) is present below most of the alluvial plain and coastal strip.

It is of large geographical extent and originates from Quaternary marine transgressions. Modern seawater intrusion occurs near the Bohai Sea coast (Shi and Jao, 2014).

Paris Basin

Fresh groundwater is observed down to 1000 m of depth of the Paris Basin (Bodelle and Margat, 1980). Groundwater in the Middle Jurassic and Triassic aquifers is saline, reaching TDS values exceeding 200,000 mg/L in the deep center of the basin, but salinity decreases to only a few hundred mg/L along the edge of the aquifers (Matray and Chery, 1998). The saline Jurassic (Dogger) and Triassic (Keuper, Rhétien) aquifers are used for the production of geothermal energy (Kloppmann et al., 2010).

Great Artesian Basin

Groundwater of the main tapped Lower Cretaceous-Jurassic artesian aquifers of the Great Artesian Basin is characterized by low salinity at 500-1500 mg/L total dissolved solids in most of the area, but it is saline in large zones in the south-western and central-southern parts of the basin (where TDS increases downgradient along groundwater flowlines). The overlying Cretaceous aquifers have higher TDS and are generally brackish. Groundwater in the deeper aquifers in the Jurassic sequence range from fresh in the northern zone of the area to brackish in most of the south-western and southeastern zones (Ransley et al., 2015; Habermehl, 2020).

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Box 3 - Estimating Groundwater Abstraction in the Paris Basin in 2010

The applied 'national-to-aquifer-level transfer' approach (NTALT) assumes that the distribution of groundwater abstraction over sub-areas is proportional to population size and the area irrigated by groundwater. The relevant map of France is shown in Figure Box 3-1.

National statistics of France for 2010 are:

- groundwater abstraction: 5.71 km^3, of which 0.80 km^3 is for irrigation (Margat and Van der Gun, 2013, Appendix 5 therein);
- population: 62,787,000 (Census 2010; Margat and Van der Gun, 2013, Appendix 5 therein); and,
- area equipped for irrigation using groundwater (AEI_GW): 1,213,543 ha (Siebert et al., 2010).

Figure Box 2-1 - Paris Basin and the regions it includes entirely or partly.

Selected statistics for zones located within the boundaries of the Paris Basin

Regions	Share*	AEI_GW (ha)	Population 2010	Area (km^2)
Nord-Pas de Calais	100%	24,067	4,038,157	12,414
Picardie	100%	92,007	1,914,844	19,399
Haute Normandie	100%	12,451	1,836,954	12,317
Basse Normandie	40%	2,492	589,398	7,036
Pais de la Loire	40%	6,100	1,428,718	12,833
Poitou-Charentes	20%	15,768	354,073	5,162
Centre	100%	369,952	2,577,866	39,151
Bourgogne	75%	17,321	1,231,586	23,687
Ile de France	100%	41,559	11,786,234	12,012
Champagne-Ardennes	100%	37,689	1,335,923	25,606
Lorraine	80%	290	1,880,736	18,838
Subtotal:		619,696	28,974,488	188,454
% of France:		51.1	46.1	34.5

* *Share* is the percentage of the region located within the Paris Basin. Other columns indicate values for the portion of each region within the Paris Basin.

Note that Supplement S2 of Siebert et al (2010) has been used to define the AEI_GW for the eleven regions. Based on these collected data, groundwater abstraction for domestic and industrial uses in the Paris Basin for the year 2010 is estimated as the product of the population ratio (Population Paris Basin / Population France) and the volume of water used for domestic and industrial purposes in all of France.

$$(46.1 / 100) * (5.71 \text{ km}^3 - 0.80 \text{ km}^3) = 2.26 \text{ km}^3$$

Similarly, groundwater abstraction for irrigation in the Paris Basin for the year 2010 is estimated as the product of the AEI_GW ratio (AEI_GW Paris Basin / AEI_GW France) and the volume of water used for irrigation in all of France.

$$(51.1 / 100) * 0.80 \text{ km}^3 = 0.41 \text{ km}^3$$

Hence, the estimated total groundwater abstraction rate from the Paris Basin is approximately 2.7 km^3/year, which is equivalent to a water depth of 14 mm/year spread over the area of the Paris Basin.

Return to where the text links to Box 3↥

8 Exercise Solutions

8.1 Solutions Pertinent to Exercises Related to Section 1

Solution Exercise 1

Each of the terms 'groundwater system', 'aquifer' and 'aquifer system' refers to a subsurface domain containing groundwater. 'Groundwater system' is a more generic term, while 'aquifer' and 'aquifer system' are more specific: they have a hydraulic connotation since they are defined based on contrasts in hydraulic properties in the subsurface. The term 'groundwater system' can be used to indicate an aquifer or aquifer system, but it may also refer to conceptual groundwater models, such as a linear reservoir or other black-box models that simulate groundwater outflow to streams; groundwater flow systems as defined by Tóth; or groundwater bodies such as basic groundwater management units adopted under the European Union Water Framework Directive. In cases where aquifers are used to store carbon dioxide or substances other than water, the term 'groundwater system' is less appropriate.

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Return to Exercise 1↥

Solution Exercise 2

The reply to this question is specific to the individual reader and the country in which he or she resides.

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Return to Exercise 2↥

Solution Exercise 3

The flow pattern is defined by the flow paths between the zones of groundwater inflow (recharge zones) and groundwater outflow (discharge zones). Groundwater age is minimal in the recharge zones and steadily increases along the flow paths in the down-flow direction. The slower the groundwater flow rate, the higher the groundwater age along the flow path as groundwater approaches the discharge zones. Groundwater passing through deeper parts of the flow domain follows longer flow paths between recharge and discharge zones and the flow velocities are lower; in some cases, the flow even stagnates. Therefore, groundwater age at greater depth tends to be significantly higher than in shallow recharge areas. Similarly, water trapped in poorly permeable layers may be older than groundwater passing through neighboring aquifer beds because the latter is moving at higher velocities. It is clear that – on average – groundwater has to travel over longer distances between recharge and discharge zones in large aquifer systems, hence mean groundwater ages are likely to be higher in such systems.

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Return to Exercise 3↥

Solution Exercise 4

The reply to this question is specific to the individual reader and the country in which he or she resides.

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Return to Exercise 4↥

8.2 Solutions Pertinent to Exercises Related to Section 2

Solution Exercise 5

None of the mega aquifer systems are located in shield regions, large igneous provinces or high-relief folded mountain zones (although the Guarani Basin sediments are covered by volcanic rocks). Such structural zones are less suitable for the accumulation of large volumes of porous sediments.

Back to where the text links to Exercise 5↥

Return to Exercise 5↥

Solution Exercise 6

Aquifer systems with their oldest sediments being of Infra-Cambrian age include the Taoudeni-Tanezrouft Basin and the Russian Platform Basin. Aquifer systems with their oldest sediments of Cambrian age include the Nubian Aquifer System, North-Western Sahara Aquifer System, Murzuk Djado Basin, Iullemeden-Irhazer Aquifer System, Cambrian-Ordovician Aquifer System, Arabian Aquifer System, Tunguss Basin, Angara-Lena Basin and the Yakut Basin. Almost all these mega aquifer systems are located in Northern Africa or the northern part of Eurasia.

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Return to Exercise 6↑

Solution Exercise 7

(a) 'Stored groundwater volume' includes all water present in the subsurface below the groundwater table. In other words: the stored groundwater volume includes all subsurface water at pressure exceeding atmospheric pressure.

(b) The term 'groundwater reserves' refers to the theoretically recoverable part of the total stored groundwater volume; it excludes water that cannot flow freely under gravity (because it remains adsorbed within the interstices of the solid matrix or it is locked inside impermeable formations), and usually, it also excludes groundwater of such a quality that it is unsuitable for human use.

(c) Due to technical, economic and environmental constraints only a fraction of the groundwater reserves can be exploited in practice. The volume of this fraction is called 'exploitable groundwater reserves'. The constraints are time-dependent and case-specific, and partly depend on policy, thus the corresponding volumes are subjective.

(d) The term 'exploitable groundwater resources' takes into account both the groundwater reserves and groundwater recharge. It is usually expressed as the maximum volume of groundwater that can be abstracted on an annual basis, given physical, economic and environmental constraints. Annually exploitable groundwater resources of an aquifer usually correspond – if sustainable groundwater exploitation is pursued – to a fraction of the long-term mean annual recharge volume.

Back to where the text links to Exercise 7↑

Return to Exercise 7↑

Solution Exercise 8

The eight mega aquifer systems in the Northern half of Africa are all visible in Figure 11. In terms of mean equivalent water depth, the top three systems in the table coincide with the top three systems in the figure: the Nubian aquifer system, the North-Western Sahara Aquifer System and the Senegal-Mauritanian Basin (which has a rating similar to the Murzuk-Djado Basin in Figure 11). The lowest two systems in the figure (Iullemeden and Taoudeni-Tanezrouft aquifer systems) are among the lowest three in the table (Lake Chad, Taoudeni-Tanezrouft and Iullemeden). The rankings thus are in reasonable agreement, but the estimated values diverge, in some cases by an order of magnitude (Lake Chad). This is no surprise, given the arbitrary assumptions underlying the estimates.

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Solution Exercise 9

The so-called 'historical estimates' were obtained by allocating the total global storage estimates of Nace (1969) and Korzun (1978) entirely to the 37 mega aquifer systems, with shares in proportion to their areas. The implicit assumption is that no groundwater storage would be present outside these mega aquifer systems, thus groundwater storage would not occur under three-quarters of the global land surface. This is a very unrealistic assumption thus the results are not useful.

The second category, called 'regional estimates', includes estimates reported by researchers who studied individual mega aquifer systems or who cited the outcomes of such studies. Some of the papers mention only the estimate, others present extensive additional information on the aquifer system geology and hydraulic parameters. This category of estimates is likely to be based on area-specific information and knowledge, which contributes to confidence in the outcomes. There are a few flaws due to mismatches between areas: either by adopting an estimate for the mega aquifer system that pertains to a larger area of which it is only a part (e.g., the California estimate was assigned to the Central Valley, the Sahara estimate was assigned to the NWSAS), or by attributing an estimate made for only part of the mega aquifer system to the entire system.

The third category is called 'revised estimates', but these are not based on aquifer-specific information and knowledge, except for values of the area covered by the aquifer systems. There are two sub-categories, calculated according to the paper's equations 6 and 7, respectively. The former derives the mean specific yield of the aquifer from a soil map (which is meaningless, because geology varies with depth and soil maps reflect the top meter of material); and the latter assumes an average porosity of 0.01 over the total depth range for all aquifer systems considered. Values determined using equation 6 are calculated for a 200 m aquifer thickness along with minimum, mean and maximum specific yield values; while those determined using equation 7 are calculated for aquifer thicknesses of 20, 50, 100, 200, 500 and 1000 m. It is not clear why the authors use the term 'revised estimates' given that the estimates for each aquifer vary over two orders of magnitude, and there is no clear link with aquifer characteristics.

In summary, unlike what the authors seem to suggest, the so-called 'regional estimates' are the better estimates of those presented in the paper.

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Return to Exercise 9↥

Solution Exercise 10

Pronounced examples of systems with shallow brackish or saline groundwater overlying fresh groundwater are the North-Western Sahara Aquifer System (NWAS), the North China Plain Aquifer System (NCP) and the Great Artesian Basin (GAB).

The Chott region in the northern part of the NWSAS is characterized by salt flats (chotts), discontinuously fed by scarce rainfalls, and present-day formation of evaporites. Consequently, shallow groundwater in this region is saline and forms a potential risk if intensive exploitation of the underlying fresh artesian aquifers would lead to a reversal of the vertical flow component from upward to downward.

The Quaternary aquifer system of the NCP is traditionally divided into shallow and deep aquifers. The shallow aquifer (near the coast hundreds of meters thick) is largely filled with brackish water of recent and paleo-marine origin in the zones of coastal and alluvial plains, but not in the piedmont zones. The deeper aquifers, recharged only in the piedmont zones, contain fresh groundwater.

Back to where the text links to Exercise 10↥

Return to Exercise 10↥

8.3 Solutions Pertinent to Exercises Related to Section 3

Solution Exercise 11

Depending on circumstances and available data, there may be various options to test the plausibility of the reported values. First by comparing the recharge estimates with climatic data (rainfall and rainfall minus evapotranspiration). It is convenient to convert the volumetric recharge estimate (m^3/year) into an equivalent depth of water per unit area estimate (mm/year). The ratio of mean recharge over mean precipitation – both expressed in mm/year – should not diverge too much from such ratios calculated elsewhere in comparable climates unless the geology is completely different (e.g., impermeable formations near the surface in one case but not in the other). Alternatively, a water balance check can be made if, in addition to precipitation, areal evapotranspiration and direct runoff can be estimated with reasonable accuracy.

Another option is to compare the recharge estimate with the sum of baseflows and other natural groundwater discharge components in the area (springs and diffuse discharge) if such data are available. Under pre-development conditions, the long-term mean recharge should be balanced by total natural groundwater discharge; in intensively exploited aquifers, recharge is higher than the natural groundwater discharge.

In principle, observed groundwater level regimes offer additional options to test the plausibility of groundwater recharge estimates. Depending on conditions, the methods to do so vary from simple (e.g., estimating recharge contributions from rising groundwater level hydrograph limbs if the recharge is concentrated in short periods) to complex (e.g., using numerical simulation models). These options are only viable if sufficient groundwater level observations are available over a substantial extent of the aquifer system.

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Solution Exercise 12

Non-renewability of groundwater resources under present-day conditions is likely to occur: 1) in very dry climates (absence of significant recharge sources); 2) in permafrost regions (frozen soil and subsoil prevent water – if available in liquid form – to infiltrate); and, 3) in aquifers confined under impermeable formations. Examples for 1) are Nubian Aquifer System, NWSAS, Murzuk-Djado Aquifer System, Arabian Aquifer System; 2) Yakut Basin, West Siberian Basin (northern part); and, 3) Guaraní aquifer (confined under upper units of the Guaraní Basin).

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Solution Exercise 13

Groundwater quantity policy and management deal with stock (reserves) and flow (recharge, discharge) of the resource. If groundwater resources are renewable, then policies and management usually pursue sustainable groundwater development, which implies that part of the flow has to be captured and depletion of the reserves has to be avoided. Policies and management of non-renewable groundwater are fundamentally different: there is no significant recharge, thus sustainable groundwater development is not possible, and decisions have to be made on how to exploit the reserves as a function of time. It is essentially a 'mining' activity.

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Solution Exercise 14

The Maranhão Basin was chosen as an example elaborated below. Data from Margat and Van der Gun (2013), Siebert and others (2010), the internet and the methodology from Box 3↥ are used to estimate groundwater abstraction for the year 2010.

The basin is located in Brazil, for which the following national statistics have been found:

- groundwater abstraction: 10.06 km^3, of which 3.82 km^3 is for irrigation (Margat and Van der Gun, 2013, Appendix 5);
- population: 190,753,519 (Census 2010; Wikipedia[4]);
- area equipped for irrigation using groundwater (AEI_GW): 591,439 ha = 5,914 km^2 (Siebert et al., 2010, Supplement S2; It is assumed that the 1996 data are still representative for 2010);
- total area; 8,515,767 km^2 (Wikipedia[5])

As a next step, it is necessary to define which administrative areas are encompassed by the Maranhão Basin. From relevant maps it is deduced that the Maranhão Basin covers the States of Maranhão and Piaui entirely, as well as approximately 40% of the State of Tocantins.

[4] List of Brazilian States by Population↗

[5] List of Brazilian states by Area↗

The Maranhão Basin and the States it includes entirely or partly

Using the same sources of information (Siebert et al, 2010; Supplement S2; and Wikipedia) relevant statistics are defined for the three subzones of the Maranhão Basin. Their sums are compared to the corresponding national statistics for Brazil in the table below.

Selected statistics for zones located within the boundaries of the Maranhão Basin

State	Share*	AEI_GW (ha)	Population 2010	Area (km^2)
Maranhão	100%	19,415	6,574,789	331,112
Tocantins	40%	434	553,375	111,088
Piaui	100%	19,010	3,118,360	251,777
Subtotal:		38,859	10,246,527	693,549
% of Brazil:		6.8	5.4	8.1

* *Share* is the percentage of the State located within the Maranhão Basin. Other columns indicate values for the portion of each State within the Maranhão Basin (calculated as State statistic times share).

Based on these data, groundwater abstraction for domestic and industrial uses in the Maranhão Basin for the year 2010 is estimated as the product of the population ratio (Population Maranhão Basin / Population Brazil) and the volume of water used for domestic and industrial purposes in all of Brazil.

$$(5.4/100)\ (10.06\ km^3 - 3.82\ km^3) = 0.335\ km^3$$

Similarly, groundwater abstraction for irrigation in the Maranhão Basin for the year 2010 is estimated as the product of the AEI_GW ratio (AEI_GW Maranhão Basin / AEI_GW Brazil) and the volume of water used for irrigation in all of Brazil.

$$(6.8/100)\ 3.82\ km^3 = 0.258\ km^3$$

Hence, the estimated total groundwater abstraction rate from the Maranhão Basin is approximately 0.59 km^3/year, which is equivalent to a water depth of 0.85 mm/year spread over the area of the Maranhão Basin.

These values are identical to those included in Table 7, because exactly the same data and assumptions have been used. Relying on different data sources (statistics vary often slightly from one source to another) and/or different assumptions (e.g., on which areas to include in the basin) is likely to result in values that may differ from the ones shown above, even by a factor two.

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Solution Exercise 15

A potential source of error related to all methods is the difficulty to isolate the long-term trend from shorter-term water level variations (interannual variation, cyclic climatic variations). Data over a sufficiently long period of years are needed to derive a reliable medium- to long-term linear trend. Different trends may be calculated for different periods. The primary error sources specific to each of the three methods are listed below.

Method 1 (water level changes times storativity)

- The assumed mean value of specific yield is not sufficiently representative of the corresponding unconfined aquifer.
- Poor information on groundwater level variations in space and in time (insufficient areal coverage; observation wells not corresponding to the phreatic aquifer unit; a short period of observation).
- These flaws also apply to confined aquifers if these are expected to have a significant contribution to depletion (e.g., in cases of very thick and porous aquifers).

Method 2 (gravity changes over time - GRACE):

- Isolation of the groundwater-related component from the total gravity anomaly.
- Allocation of the calculated groundwater anomalies to the spatial unit covered by the mega aquifer system under consideration.

Method 3 (numerical modeling):

- Insufficient information/knowledge about the hydrogeological structure and hydraulic parameters of the aquifers concerned.
- Poor information/knowledge about the boundary conditions (especially their variation over time).

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Solution Exercise 16

Five intensively exploited mega aquifer systems facing exceptional water quantity sustainability challenges include the Central Valley (CV), the High Plains (HP), the Indus Basin (IB), the Ganges-Brahmaputra Basin (GBB) and the North China Plain Aquifer System (NCP).

Several current or anticipated impacts of intensive exploitation are shared by all five: falling water levels resulting in increased groundwater abstraction cost; wells running dry; exhaustion of certain aquifer zones in the longer term; migration of poor-quality water into zones with fresh groundwater of good quality; and, environmental degradation of groundwater-dependent ecosystems. Groundwater salinization by seawater intrusion is an issue in the coastal zone of the North China Plain (NCP), the Ganges-Brahmaputra delta (GBB) and the Indus coastal zone (IB). Land subsidence affecting large areas is a prominent impact of intensive groundwater development in the North China Plain and the southern half of the Central Valley (San Joaquin Valley). A major impact of intensive groundwater development in the Indus and Ganges-Brahmaputra basins is groundwater quality degradation by influxes of saline or brackish groundwater, natural contaminants (arsenic and fluoride) and/or anthropogenic pollutants. Continued groundwater storage depletion implies a finite lifespan of the aquifers. Groundwater storage depletion reached 14% of predevelopment storage in 2003 in the Central Valley and 8% in 2007 in the High Plains Aquifer System. In one-third of the southern part of the latter, the saturated aquifer thickness is expected to decrease to less than 6 m by 2040, thus putting an end to intensive groundwater abstraction.

Options for controlling the situation include managed aquifer recharge (MAR), but this is not practiced in any of the intensively exploited aquifer systems to an extent sufficient to establish sustainable conditions. Therefore, direct or indirect demand management measures are needed if control is pursued. These include strict regulation of groundwater pumping (only feasible in some areas), registration of wells, permits for new wells, water use fees, groundwater protection zones, recycling used water, substituting groundwater use with surface water use, using brackish groundwater (where feasible), increasing irrigation efficiencies, changing cropping patterns to those with lower water demand, water-saving techniques in households and industry, adequate practices in energy supply and modified subsidies related to groundwater development. Effective control requires the presence of good groundwater governance provisions and general public support.

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9 About the Author

Jac van der Gun is a Dutch groundwater hydrologist and water resources specialist, who graduated from Wageningen University, The Netherlands. He has been employed successively by a Dutch water supply company (WMG, Velp), UN-OTC (New York) and the Research and Development organization TNO (Delft/Utrecht). His professional career spans half a century and has focused on: 1) water resources exploration, water resources assessment and monitoring (including significant fieldwork components); 2) hydrogeological mapping; 3) water resources planning and management; and 4) training, capacity building and institutional development.

He has been involved actively in the Groundwater Reconnaissance and Mapping of The Netherlands and was entrusted with the overall responsibility for this program. His long-term assignments abroad include positions as a resident hydrologist in Bolivia and as a resident water resources assessment project manager in Yemen and in Paraguay. Investigating and documenting aquifers was a prominent activity in these projects. In addition, he carried out numerous short missions in Asia, Latin America, Africa and Europe for various international and national organizations, providing scientific-technical input, supervising projects, and formulating or evaluating projects and programs focusing on water resources. He has also lectured at UNESCO-IHE (Delft) on groundwater for more than thirty years. In 2003 he became the founding director of the International Groundwater Resources Assessment Centre (IGRAC) and since then he has been mainly active in groundwater-related projects of international organizations such as UNESCO, FAO, GEF and IGRAC (e.g., the Groundwater Governance Project, WWAP's Water Resources Development Reports, the Transboundary Water Assessment Project TWAP and GGRETA). Together with Jean Margat, he wrote the book 'Groundwater around the World' (2013). A few years later, in cooperation with Karen Villholth, Elena López-Gunn, Kirstin Conti and Alberto Garrido, he produced the book 'Advances in Groundwater Governance' (2018).

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THE GROUNDWATER PROJECT

Modifications to Original Release

Changes from the Original Version to Version 2

Original Version: July 2022, Version 2: March 2023

Specific changes:

page numbers refer to page numbers in the original pdf

page iv, updated Table of Contents to reflect revisions

page 31, deleted citation of LeCompa, 2010

page 69, line 6, capitalized 'Section'

page 72, link "Click for solution to Exercise 1" corrected to go to the solution Exercise 1

page 73, l link "Click for solution to Exercise 6" corrected to go to the solution Exercise 6

page 79, Dolgikh, A., 2019, hyperlink corrected

page 82, Hanot et al., 2011, hyperlink corrected

page 84, LeCompa, 2010, citation deleted

page 86, Molle, et al., 2017, hyperlink corrected

page 87, Rateb et al., 2020, hyperlink corrected

page 100, deleted link to "Return to Solution Exercise 14"

page 105, line 2, changed reference to "Nash and Korzun" to "Nace (1969) and Korzun (1978)"