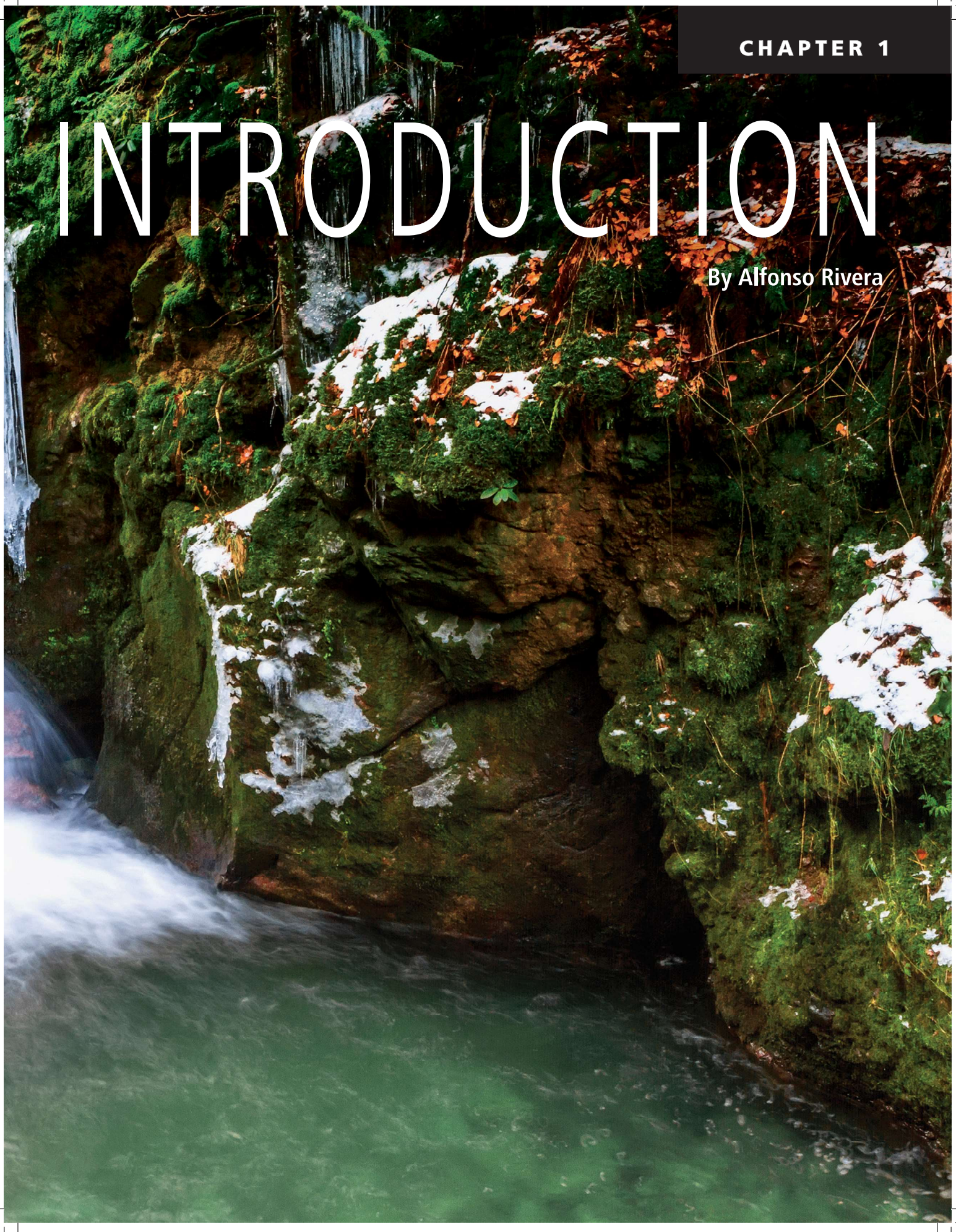


CHAPTER 1

INTRODUCTION

By Alfonso Rivera

1.1 BACKGROUND AND HISTORICAL PERSPECTIVES

1.1.1 A review of the literature

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

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

Groundwater in Canada (1967)

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

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

Groundwater (1979)

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

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

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

Hydrogeology (1988)

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

1.1.2 Historical progression on groundwater research

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

Also during the 1960s, distinguished Canadian scientists (Tóth, 1962; Freeze and Witherspoon, 1967), following previous works on *gravity-driven* groundwater flow, developed breakthrough theories of what became known as "hierarchically-nested flow systems." Scientists as early as the end of the 19th century had perceived the relationship

between topography and groundwater flow patterns in unconfined aquifers. King (1899) and Hubbert (1940) noticed that a water table tends to be a subdued replica of its topography, and Hubbert (1940) suggested that topography could control groundwater flow patterns as high elevations become recharge areas and low elevations become discharge areas. Later, during the 1960s, Tóth (1963), and Freeze and Witherspoon (1967) developed mathematical models simulating the effects of topography on groundwater flow systems. Both models supported King and Hubbert's conclusions. These models also indicated that hilly topography could result in the formation of smaller local flow systems, with local recharge and discharge areas, within larger regional systems.

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

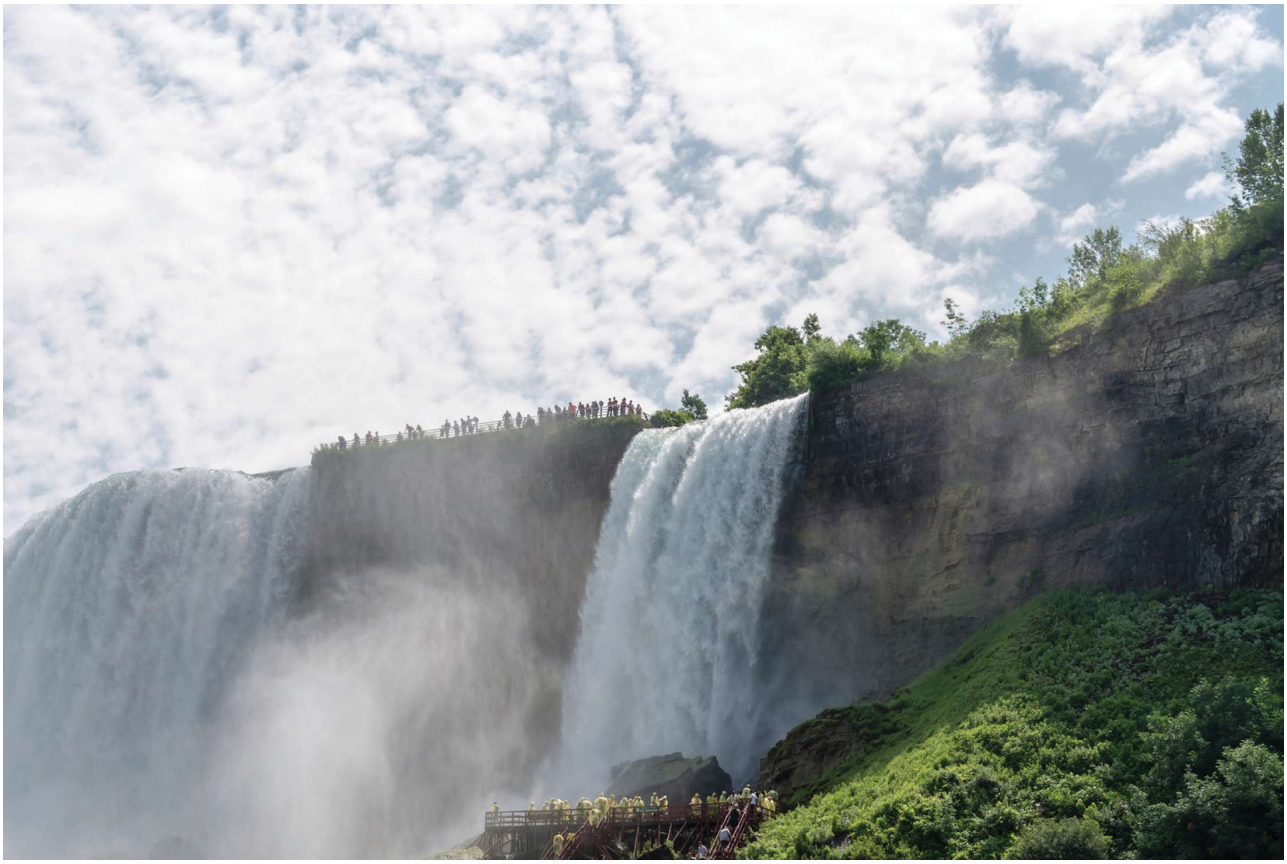
During 1980s, the focus of hydrogeology shifted from flow analysis to transport analysis, and from regional-scale to local, site-specific scale. By the end of the 1980s, several new scientific issues had arisen in response to the discovery of widespread groundwater supply contamination. Remediation efforts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

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

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

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

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



more about the physics and chemistry of groundwater flow.

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

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

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

Historically, Canadian scientists' research efforts have been dedicated to the cleanup and remediation

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

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

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

1.2 GROUNDWATER RESOURCES IN THE WORLD AND CANADA

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

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

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

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

1.2.1 Groundwater in the hydrologic cycle

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

Much of the precipitation that falls on the ground's surface is redirected back into the atmosphere as direct evaporation, or

as transpiration from vegetation. The sum of both fluxes is called evapotranspiration and represents by far the most important flux of the cycle, some 63% of annual precipitation on average.

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

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

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

1.2.2 Water quantities

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

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

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

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

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

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

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

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

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

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

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

1.2.3 Water availability

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

Groundwater availability is a function not only of the quantity and quality of the water within an aquifer system, but also of the physical structures, laws, regulations, and socioeconomic factors that control its demand and use. Physical and chemical characteristics of any given aquifer may be used as indicators of groundwater availability; however, at the local level, where most decisions are made,

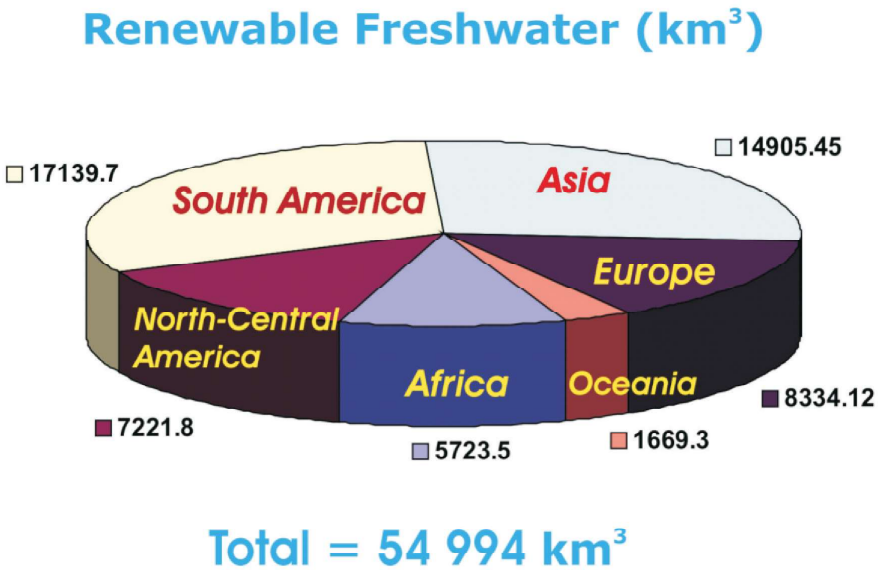


Figure 1.1 Total renewable freshwater supplies by continent, as reported by Gleick (2004).

these characteristics must be considered in conjunction with those societal factors which determine actual groundwater availability, and society's tolerance of the consequences of its use. Societal perspectives and constraints change and evolve with time, just as the groundwater resource does (Alley and Leaky, 2004).

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

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

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

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

1.2.4 Water supply and use

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

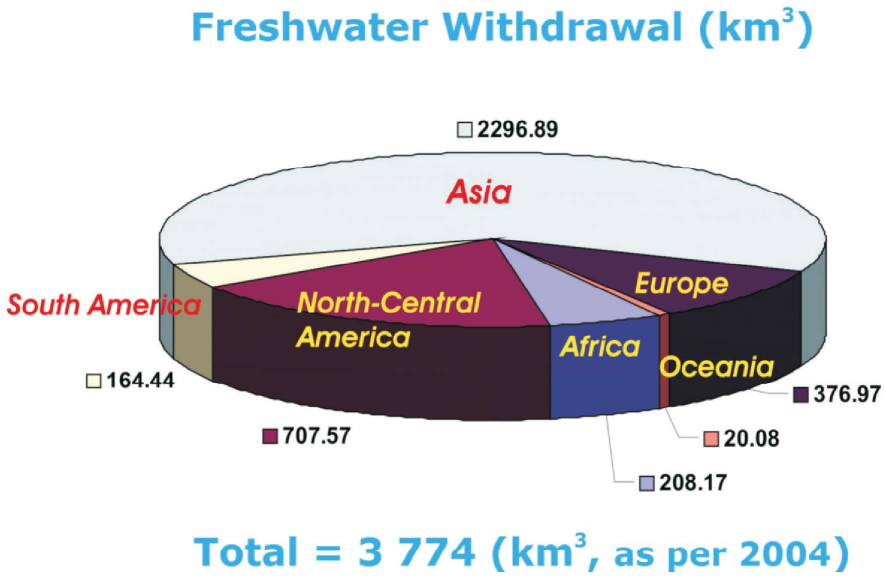


Figure 1.2 Total freshwater withdrawals by continent (Gleick, 2004).

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

TABLE 1.4 WATER CONSUMPTION IN THE WORLD DURING THE 20TH CENTURY, BY SECTORS IN KM³/YR (DE MARSILY, 2000)

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

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

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

When these numbers are compared with those of the global water cycle in Table 2.2 of Chapter 2, we find some 40,000 km³ of "available" freshwater, of which 27,000 km³ comes from river flow and 10,500 km³ from groundwater baseflow. If the 27,000 km³ cannot be contained by the current capacity of the world's dams (Canadian dams have a capacity of 846 km³), then only 10,500 km³ of baseflow is left. This means that the total fresh water withdrawn in the world in the year 2000 (5,191 km³ in Table 1.4) was about half of the baseflow volume. Thus, the "problem" is not lack of water, but the disparity between population needs and water source location. The Earth's freshwater sources are not evenly distributed, so there are very water-rich regions and very water-poor regions.

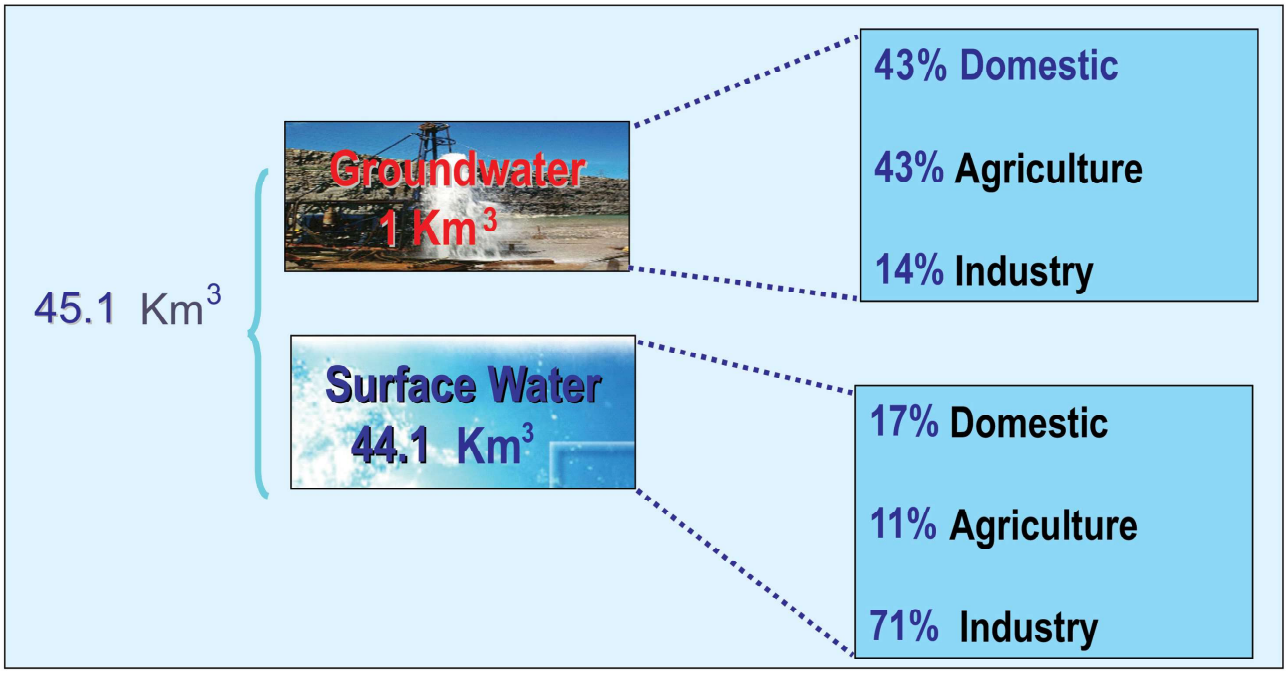


Figure 1.3 Freshwater withdrawals in Canada as per 1996 (Source data from Statistics Canada, 2003)

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

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

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

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

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

1.3 BOOK STRUCTURE AND OVERVIEW

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

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

interactions with the environment. Chapter 3 presents the basic steps and current practices of mapping and assessing regional-scale aquifers.

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

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

1.3.1 Objectives of major parts and chapters

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

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

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

data, information, tables, figures, maps, and statistics provided in this section.

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

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

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

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

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

CANADA'S GROUNDWATER RESOURCES

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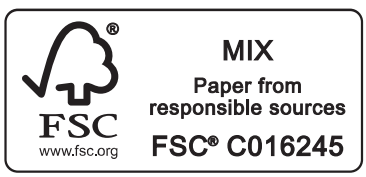

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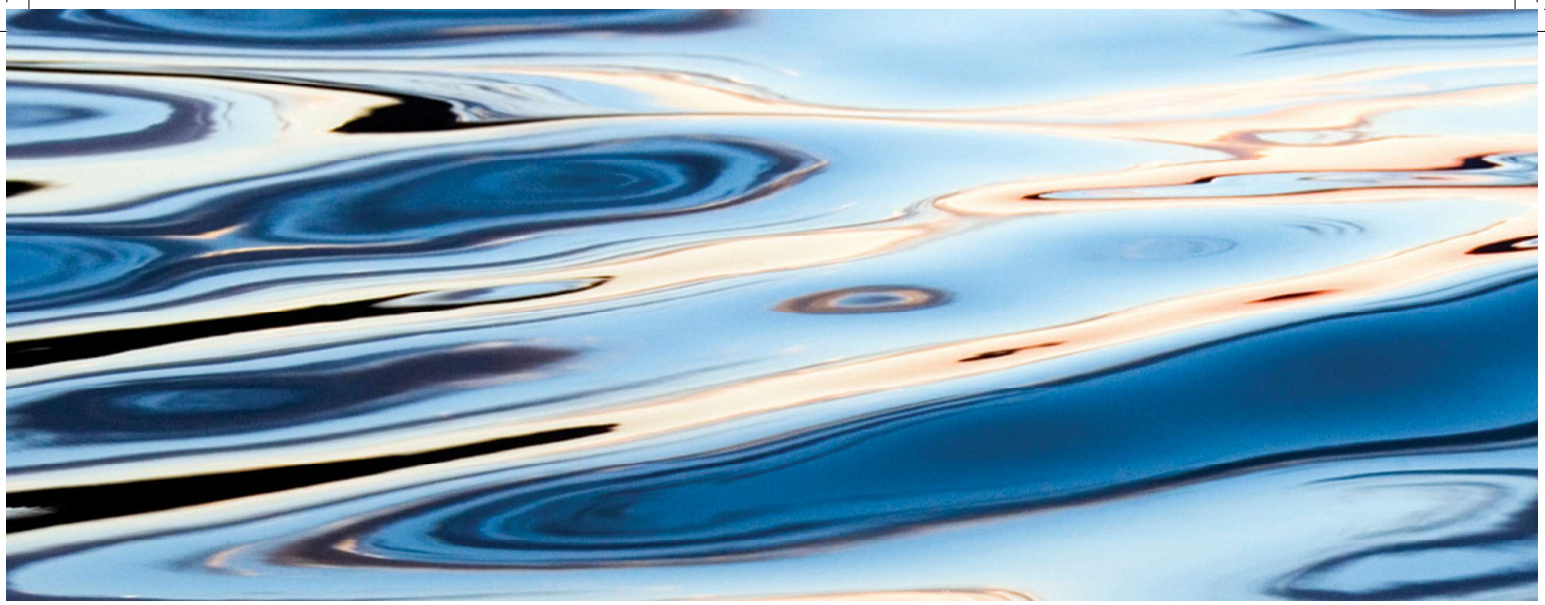

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