The Sustainable Management of Groundwater in Canada

The Expert Panel on Groundwater

Council of Canadian Academies
Conseil des académies canadiennes

Science Advice in the Public Interest

THE SUSTAINABLE MANAGEMENT OF GROUNDWATER IN CANADA

Report of the Expert Panel on Groundwater

THE COUNCIL OF CANADIAN ACADEMIES
180 Elgin Street, Ottawa, ON Canada K2P 2K3

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The Expert Panel on Groundwater

James P. Bruce, O.C., FRSC, Chair, Environmental Consultant, Climate and Water (Ottawa, ON)

William Cunningham, Assistant Chief, Office of Ground Water, U.S. Geological Survey (Reston, VA, U.S.A.)

Allan Freeze, FRSC, Former Professor and Director in the Geological Engineering Program, University of British Columbia (Surrey, BC)

Robert Gillham, C.M., FRSC, Distinguished Professor Emeritus, Department of Earth and Environmental Sciences, University of Waterloo (Waterloo, ON)

Sue Gordon, Research Hydrogeologist & Leader, Integrated Water Management Program, Alberta Research Council (Calgary, AB)

Steve Holysh, Senior Hydrogeologist, Conservation Authorities Moraine Coalition (Toronto, ON)

Steve Hrudey, FRSC, Professor Emeritus, Environmental and Analytical Toxicology, University of Alberta (Edmonton, AB)

William Logan, Deputy Director, International Center for Integrated Water Resources Management, US Army Corp. of Engineers (Alexandria, VA, U.S.A.)

Kerry MacQuarrie, Professor & Canada Research Chair in Groundwater-Surface Water Interactions, Department of Civil Engineering & Canadian Rivers Institute, University of New Brunswick (Fredericton, NB)

Paul Muldoon, Environmental Lawyer (Toronto, ON)

Linda Nowlan, Faculty Research Associate, Program on Water Governance, Institute for Resources, the Environment and Sustainability and the Department of Geography, University of British Columbia (Vancouver, BC)

John Pomeroy, Canada Research Chair in Water Resources and Climate Change; Director, Centre for Hydrology; Professor, Department of Geography and Planning, University of Saskatchewan (Saskatoon, SK)

Steven Renzetti, Professor, Department of Economics, Brock University (St. Catharines, ON)

Barbara Sherwood Lollar, FRSC, Professor and Director, Stable Isotope Laboratory, Department of Geology, University of Toronto (Toronto, ON)

René Therrien, Professor, Department of Geology and Geological Engineering, Université Laval (Québec City, QC)

Project Staff of the Council of Canadian Academies

PROGRAM DIRECTORS:

Katherine Levitt

Trina Foster

Maria Trainer

WITH ASSISTANCE FROM (IN ALPHABETICAL ORDER):

Michelle Campbell (Consultant)

David Cashaback (Senior Analyst)

Jennifer Chandler (Consultant)

Alison Crone (Program Assistant)

Laurence Davidson (Consultant)

Marc Saner (Director of Assessments)

Christina Stachulak (Program Director)

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James P. Bruce
Chair, Expert Panel on Groundwater

Report Review

This report was reviewed in draft form by the individuals listed below — a group of reviewers selected by the Council of Canadian Academies for their diverse perspectives, areas of expertise and broad representation of academic, industrial, policy and non-governmental organizations.

The reviewers assessed the objectivity and quality of the report. Their submissions — which will remain confidential — were considered fully by the panel, and most of their suggestions were incorporated into the report. They were not asked to endorse the conclusions nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring panel and the Council.

The Council wishes to thank the following individuals for their review of this report:

Diana Allen, Professor, Department of Earth Sciences, Simon Fraser University (Burnaby, BC)

William Alley, Chief, Office of Ground Water, US Geological Survey (San Diego, CA, USA)

R.N. Betcher, Manager, Groundwater Management Section, Manitoba Water Stewardship (Winnipeg, MB)

François Bregha, Senior Associate, Stratos Inc. (Ottawa, ON)

John Cherry, FRSC, Distinguished Professor Emeritus, Department of Earth Sciences, University of Waterloo and Adjunct Professor, School of Engineering, University of Guelph (Waterloo & Guelph, ON)

Rob de Loë, Professor and University Research Chair in Water Policy and Governance, Department of Environment and Resource Studies, University of Waterloo (Waterloo, ON)

Mary Griffiths, Former Senior Policy Analyst, the Pembina Institute (Edmonton, AB)

Terry W. Hennigar, President, Water Consulting (Wolfville, NS)

R. Anthony Hodge, President, International Council on Mining and Metals and Professor of Mining and Sustainability, Queen's University (Victoria, BC)

Theodore Horbulyk, Associate Professor, Department of Economics, University of Calgary (Calgary, AB)

Charles Lamontagne, Hydrogeological Engineer, Water Policy Directorate of the Ministry of Sustainable Development, Environment and Parks, Government of Quebéc (Québec City, QC)

René Lefebvre, Professor, Institut national de la recherche scientifique, Centre - Eau Terre Environnement (Québec City, QC)

Harm Maathuis, Hydrogeologist (Saskatoon, SK)

Ralph Pentland, President, Ralbet Enterprises Inc. (Ottawa, ON)

David Rudolph, Professor, Department of Earth Sciences and Member, Waterloo Institute for Groundwater Research, University of Waterloo (Waterloo, ON)

J. Owen Saunders, Executive Director, Canadian Institute of Resources Law, University of Calgary Faculty of Law (Calgary, AB)

Marios Sophocleous, Senior Scientist, Geohydrology Section, Kansas Geological Survey, The University of Kansas (Lawrence, KS, U.S.A.)

Harry Swain, Senior Research Associate, Centre for Global Studies, University of Victoria (Victoria, BC)

The report review procedure was monitored on behalf of the Council's Board and Scientific Advisory Committee (SAC) by **Ms. Elizabeth Dowdeswell**. The role of the report review monitor is to ensure that the panel gives full and fair consideration to the submissions of the report reviewers. The Board of the Council authorizes public release of an expert panel report only after the report review monitor confirms that the Council's report review requirements have been satisfied. The Council thanks Ms. Dowdeswell for her diligent contribution as review monitor.

Peter J. Nicholson, President
Council of Canadian Academies

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Preface

In September 2006, the federal government, through Natural Resources Canada, asked the Council of Canadian Academies to appoint an expert panel to answer the question "What is needed to achieve sustainable management of Canada's groundwater resources, from a science perspective?" The charge to the panel was further specified in a series of sub-questions:

- *What current knowledge gaps limit our ability to evaluate the quantity of the resource, its locations and the uncertainties associated with these evaluations?*
- *What do we need to understand in order to protect the quality of groundwater supply – for health protection and safeguarding other uses?*
- *For groundwater supply and quality monitoring purposes, what techniques and information are needed? What is the current state of the art and state of practice, and what needs to be developed in Canada?*
- *What other scientific and socio-economic knowledge is needed to sustainably manage aquifers in Canada and aquifers shared with the United States?*

The Council assembled a diverse group of leaders in the science of groundwater, as well as experts in the sociological, economic and legal aspects surrounding sustainable groundwater management. The panel met numerous times over the past seventeen months to consider the existing body of literature in order to answer the above questions. In addition, the panel initiated a call for evidence in July 2007 that solicited the input of a wide variety of stakeholder groups. The panel reviewed the results of this consultation and incorporated that information into its deliberations and conclusions. A compilation of these responses is presented in Appendix 2 of this report.

The report is organised as follows. Chapter 1 provides context, beginning with some highlights of the importance and value of groundwater in Canada, as well as some basic facts about groundwater, presented from the perspective of the charge to the panel. Chapter 2 examines the concept of sustainable management of groundwater based on the five goals identified by the panel. These goals lay out sustainability considerations relative to quantity, quality, ecosystem support, socio-economic benefit, and good governance. Chapter 3 highlights a number of trends and emerging critical issues for groundwater, and thus establishes an agenda of challenges that are urgently in need of management based on sustainability principles. In Chapter 4, the goals presented in Chapter 2 are used as an analytical construct to identify the science and engineering needed to underpin sustainable groundwater management. Particular emphasis is placed on the data and knowledge required for effective decision-making. Chapter 5 then addresses groundwater management and decision-making in Canada — encompassing

jurisdiction, policy and regulation, and economic instruments — in order to assess the degree to which the current governance of groundwater reflects principles of sustainability. Chapter 6 presents a number of case studies to test and illustrate the goals of sustainable groundwater management in concrete, practical circumstances. The report concludes, in Chapter 7, with an overview of the key findings from this report and a summary response to the questions posed in the original charge to the panel. Supplementary material is provided in three appendices. Appendix 1 provides the reader with a primer on the basics of groundwater science; Appendix 2 documents the highlights from the Public Call for Evidence; and Appendix 3 is a compilation of excerpts of recommendations from major reports in Canada on the subject of groundwater.

1 Introduction

1.1 OVERLOOKED AND UNDERVALUED: GROUNDWATER SUSTAINABILITY IN CANADA

Canadians and their industries use enormous quantities of water, second only to the United States in *per capita* terms and more than double the European average (OECD, 1999). Groundwater is a key component of this overall consumption. Nearly 30 per cent of Canada's population (almost 10 million Canadians) depends on groundwater to supply its drinking water, and more than 80 per cent of the country's rural population relies on groundwater for its entire water supply (Environment Canada, 2004b; Nowlan, 2005). Groundwater, a critical resource that Canadians often treat as 'out of sight, out of mind,' is now gaining visibility due to contamination, over-use and conflicts. Groundwater quality and quantity problems incur enormous costs for society.

Headlines from the past year alone illustrate some of groundwater's effects on Canadians' health, environment and economy (Box 1.1). The most tragic groundwater news stories date back to the Walkerton, Ontario, contamination in May of 2000. It was the worst documented outbreak of pathogenic *E. coli* poisoning caused by municipal tap water and led to seven deaths and sickened more than 2,300 with severe gastrointestinal illness (O'Connor, 2002a; O'Connor, 2002b).

Box 1.1: Groundwater in the Headlines

February 17, 2008. Walkerton *E. coli* payout tops $65M but angry businesses feel shut out: More than $65 million has been paid so far to the victims of Canada's worst-ever *E. coli* tragedy, but businesses hit hard by the crisis say they have seen little of the promised compensation — and some blame crass politics for their plight (*Western Star*).

April 7, 2008. More than 1,700 Canadian boil-water advisories in effect: There were 1,766 boil-water advisories in place across Canada as of the end of February 2008, not including an additional 93 advisories in First Nations communities, according to an investigative report published in the Canadian Medical Association Journal (*Globe and Mail*).

April 18, 2008. Ontario renews Nestlé permit to extract groundwater for sale: Application for the permit prompted thousands of letters of complaint (*Globe and Mail*).

May 23, 2008. Cameco testing for uranium leak in Lake Ontario: World's largest uranium producer says computer modelling shows that "small amounts of contaminated groundwater" may be coming from its Port Hope processing plant (*Globe and Mail*).

June 24, 2008. PCBs, fuel leaking into St. Lawrence River, pollution watchdog says: North America's environmental watchdog says up to eight million litres of diesel fuel and up to two tonnes of dangerous PCBs have contaminated Montréal's Technoparc and are leaking into the nearby St. Lawrence River. The watchdog, the Commission for Environmental Cooperation, released its five-year investigation into the site yesterday (CBC).

July 1, 2008. Water expert raises alarm about coal-bed mining in salmon rivers: Dr. Stockner is now raising alarms about the threat coal-bed methane mining holds for salmon rivers in northern B.C.… Effluents once in the ground then entering groundwater and eventually, surface flows, can severely impact the physico-chemical balances of rivers and streams for several decades... Shell's project is in the early exploratory stages, but the plans call for more than 1,000 wells to be dug to extract methane (*Globe and Mail*).

July 9, 2008. Québec towns near border fear tainting of water supply: Elgin Mayor Jean-Pierre Proulx said he's concerned the dump will contaminate the groundwater that ends up in wells used by his 480 residents (Montreal's *The Gazette*).

July 27, 2008. Oilsands threaten groundwater: Conservation specialist warns steam blowout could contaminate massive Athabasca aquifer near Fort McMurray (*Edmonton Journal*).

July 31, 2008. Nitrates killed thousands of PEI fish, officials say: Environment officials are blaming nitrates for recent fish kills in several Prince Edward Island waterways. Thousands of dead fish were discovered late last week along the Wheatley and Cardigan rivers. The nitrates that have leached into streams and rivers from agricultural applications encourage the growth of underwater plant material and algae (*Globe and Mail*).

Despite the economic and ecological value of groundwater, Canada's legislative framework and institutional capacity for groundwater management have yet to fully mature. The application of the scientific knowledge required for a sustainable management of groundwater remains, with some notable exceptions, under-developed (Mitchell, 2004). This is not an acceptable state of affairs, particularly in view of current or emerging stresses on Canada's groundwater resources due to:

- Population growth and its increasing concentration in urban areas, with major implications for land-use planning and watershed protection;
- Intensification of agriculture, resulting in greater demands on groundwater and the ever-present risk of contamination by nitrates and other residues and pathogens;
- Increased exploitation of hydrocarbons and other mineral resources in response to global demand, creating new and growing pressures on the quantity and quality of adjacent water resources — both surface water and groundwater;
- The presence of contaminated sites and the continuing need for remediation;
- The growing concern for groundwater source protection as a consequence of some or all of the foregoing;
- Threats to aquatic ecosystems and fish due to the low flow of streams that are fed by groundwater during dry periods;
- Transboundary water challenges and the ongoing need for cooperative management of water resources that straddle or cross the Canada-US border; and
- The impact of climate change and its resultant changes in the demands placed on, and availability of, our linked groundwater and surface-water resources. The ultimate effects of climate change on the distribution of water in Canada are highly uncertain, but are potentially of great significance for some regions and for economic activity.

Many of these stresses are already established; others are emerging and demand our foresight and pre-emptive action. All point to the need for Canadians to pay greater heed to this country's precious water resources, both above and below the ground. Water is "the driver of nature"[1] and it is therefore imperative that Canada's hydrosphere be managed sustainably.

While there are no widespread cases as yet of Canadian "water follies," such as the catastrophic over-pumping documented in the United States (Glennon, 2005), individual examples of unsustainable groundwater management are on the rise across Canada. Because many surface-water bodies such as rivers and lakes are already heavily used, groundwater sources are likely to be relied on increasingly for water supply by an expanding population that already uses far greater *per capita* amounts of water than citizens in most other countries. The coming conflicts are foreshadowed in recent journal articles such as, for example, "A Gathering Storm: Water Conflict in Alberta" (Block and Forrest, 2005) and "The Processes, Patterns and Impacts of Low Flows Across Canada" (Burn *et al.*, 2008).

An evaluation of the current situation in Canada reveals that we have not yet experienced a catastrophic over-usage of our groundwater resources.

1 Leonardo da Vinci, quoted in World Bank Doc. 456, Groundwater, Legal and Policy Perspectives.

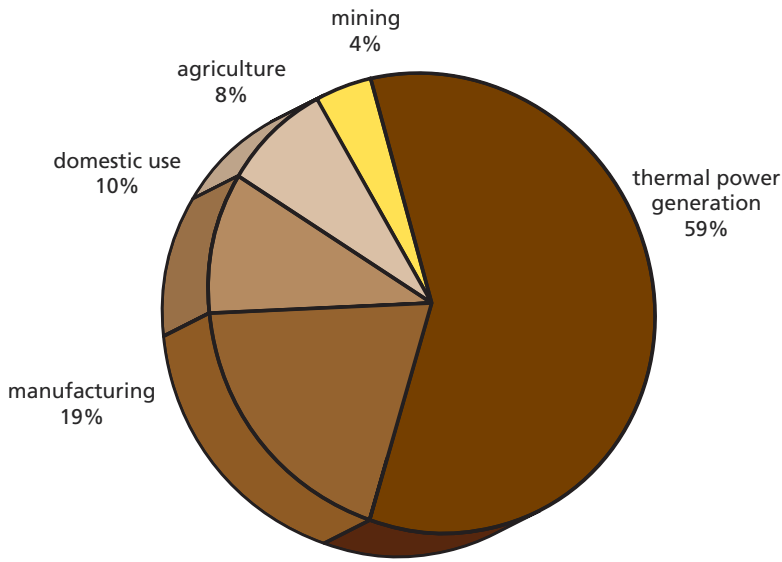
While there have been individual cases where local problems have arisen, nothing could be viewed as a national crisis. This begs the question: why worry about Canada's groundwater? And why now? The answer is that Canada is in the enviable position of being able to put in place proactively, the policies and management practices that can prevent potential calamities in the future — calamities that have been experienced all too often in other parts of the world.

Quantity and Usage

Canada is fortunate to have enormous resources of freshwater; almost 900 000 km^2 or 8 per cent of the nation's total area is covered with fresh surface water (Environment Canada, 2004b). In most of the ways that people and ecosystems are affected, it is the spatial distribution of water flow that matters, not the overall store of water. From this perspective, the North and much of the Prairies are quite arid, with near-desert conditions in the high Arctic; the southern coastal areas, particularly along the Pacific Ocean, are very wet; while the regions bordering the St. Lawrence River and Great Lakes, much of the Atlantic Provinces, and the Rockies enjoy ample, but not excessive, precipitation. Consequently, any consideration of water resources in Canada will have a prominent regional dimension.

The first sub-question of the charge asks: *"What current knowledge gaps limit our ability to evaluate the quantity of the resource, its locations and the uncertainties associated with these evaluations?"* The panel was not able to identify any accurate estimate of the volume of groundwater in Canada — a deficiency acknowledged by the Geological Survey of Canada (GSC) in their statement that "the amount of groundwater stored in Canadian aquifers and their sustainable yield and role in ecosystem functioning are virtually unknown" (Nowlan, 2005; Rivera, 2005). Chapter 4 will consider the scientific and engineering methods and data needed to quantify groundwater resources in Canada.

Total annual freshwater use in Canada for all purposes (industrial, agricultural, domestic, and in connection with thermal power generation) is estimated to be about 45 cubic kilometres (km^3) or very roughly 1,500 cubic metres (m^3) *per capita*, distributed as illustrated in Figure 1.1; this includes both surface water and groundwater. Normal household use, at about 330 litres per person per day (or 120 m^3 per person per year on average) accounts for less than 10 per cent of total use (Environment Canada, 2007). Thermal electric generating industries use approximately 60 per cent of the total as cooling water, virtually all of which is returned to its source without degradation, other than a small increase in temperature (Shinnan, 2008).



(Data Source: Environment Canada, 2007)

Figure 1.1
Average freshwater use in Canada.

Data on the uses of groundwater, within the use of freshwater overall, are limited and dated. Based on estimates for 1995 (OECD, 1995), groundwater accounted for only a little more than four per cent of total freshwater use in Canada, but this was roughly double the amount of annual groundwater use estimated between 1980 and 1990. The United States uses vastly more groundwater than Canada, even on a population-adjusted basis. Groundwater use in the United States in 1995 was 106 km^3, accounting for about 22 per cent of its total freshwater abstraction in that year (OECD, 2004).

The primary use of groundwater in Canada varies regionally, from municipal purposes in Ontario, Prince Edward Island, New Brunswick and the Yukon, to livestock watering in Alberta, Saskatchewan and Manitoba, to largely industrial purposes in British Columbia, Québec and the Northwest Territories, and to domestic wells in Newfoundland and Nova Scotia. Within each province there is variability in the spatial distribution of groundwater use, depending on local aquifer properties and surface-water availability (Environment Canada, 2007). The dependence of provincial populations on groundwater for domestic needs ranges from 100 per cent in Prince Edward Island to about 23 per cent in Alberta. This wide variation illustrates the highly regional nature of dependence on groundwater.

In developing policies regarding groundwater management, regulators will need to know both the current and the projected consumption of the resource.

Record-keeping with respect to groundwater withdrawals varies across the country. All provinces except Québec and British Columbia report having databases of the allocations made to larger groundwater users; however, only Alberta and Saskatchewan record the amount of water actually taken by these users. Ontario and Manitoba are in transition, moving from a system where only allocations are recorded to a system where measurement of actual takings must be reported by users. Record-keeping of extractions is one area where Canadians could and should have certainty. If decisions for additional allocations from a basin are to be in the best interest of the basin's socio-economy and ecosystems, there should be no uncertainty about the volumes that permitted users are already removing, how the water is being used, and the extent and location of the return flows.

Obtaining data on groundwater use is surprisingly difficult. Environment Canada operates a national voluntary survey to collect data from over 2,500 municipalities encompassing over 90 per cent of the Canadian population. The Municipal Water and Wastewater Survey[2] (Environment Canada, 2007) compiles water-use data, including how much groundwater is extracted and the number of residents supplied by domestic wells. It is currently the best source of national data on groundwater extraction for domestic and municipal purposes, but due to a poor response rate from many small municipalities (more than half of municipalities fail to respond), it is incomplete over large sections of the country. To better document groundwater use in Canada, initiatives are necessary to improve the response rate by assisting municipalities with the survey and supporting the collected data with available provincial information on municipal waterworks.

It is apparent from the foregoing that there is a critical lack of data on groundwater allocations, including municipal, industrial and agricultural allocations; on actual withdrawals of groundwater; and on volumes discharged or reused. Groundwater cannot be managed effectively, at any scale, without these data, and the agencies responsible should assign a high priority to securing it.

Quality and Monitoring

Groundwater management in Canada will require more than just the assurance of sufficient quantity. It will also require that the available resources meet the necessary quality standards for human and ecosystem protection. In order to answer the second sub-question, *"What do we need to understand in order to protect the quality of groundwater supply and, thereby, protect public health and generally ensure groundwater is safe to use?"* regulators will need to be able to analyse the existing level of groundwater quality as well as monitor and predict changes. While the provinces currently collect

2 The survey used to be known as the Municipal Water Use and Pricing survey (MUD/MUP); it has been conducted once every two or three years, starting in 1983.

some groundwater quality data, there is no national assessment of trends in groundwater quality, though the National Water Research Institute (NWRI) and the Geological Survey of Canada (GSC) are now collaborating on collecting this information. The research priorities of the NWRI include a national synthesis of groundwater-quality data and the GSC's priorities include a synthesis of physical aquifer data, including aquifer mapping, recharge and vulnerability (Lawrence, 2007). Chapter 3 describes specific instances of the groundwater quality issue while later chapters seek to outline the science that is required to protect the quality of groundwater resources in Canada.

The third sub-question of the charge to the panel asks: *"For groundwater supply and quality monitoring purposes, what techniques and information are needed? What is the current state of the art and state of practice, and what needs to be developed in Canada?"* The scales at which groundwater is monitored include regional monitoring of background water quality and site-specific monitoring of known or suspected groundwater contamination. Regional monitoring focuses on naturally occurring compounds such as arsenic, fluoride and, possibly, dispersed agricultural pollutants, such as nitrate, that have health implications. Regional monitoring is largely the responsibility of provincial agencies. Site-specific monitoring programs focus on anthropogenic contaminants, such as solvents or hydrocarbons from leaking waste-disposal facilities, and are designed to quantify the presence and extent of contamination and aid in the selection of appropriate remedial action. They are usually undertaken by private contractors, hired by site owners, and operated under the scrutiny of provincial regulators.

Value

The fourth sub-question of the charge asks: *"What other scientific and socio-economic knowledge is needed to sustainably manage aquifers in Canada and aquifers shared with the United States?"* While numerous factors will enter into the socio-economic equation for the management of groundwater in Canada, a significant consideration for regulators when developing groundwater policies will be the "value" that groundwater represents to the country. The value of groundwater has both an indirect component (e.g., ecosystem protection, quality of life) as well as a direct component in the form of economic impact. Despite the availability of empirical estimation techniques and the efforts undertaken in other countries to value their water resources (Kondouri, 2004; Young, 2005), relatively little research has been carried out in Canada regarding the value of water (Renzetti and Dupont, 2007). There is consequently very limited information regarding the valuation by Canadian users of water and effectively no current information on valuation by users of groundwater. Chapter 5 of the report addresses the knowledge required to understand the interconnected socio-economic factors and their role in groundwater management.

1.2 THE BASICS OF GROUNDWATER SCIENCE

Water exists as a solid (ice), liquid, or gas (water vapour). Oceans, rivers, clouds, and rain all contain water, and all are in a continuous state of change. Surface water evaporates, cloud water precipitates, and rainfall infiltrates the ground. Despite its various dynamic states, the total volume of water on earth has remained virtually unchanged for the last three billion years, at roughly 1.4 billion km^3 (Powell, 1997; Shiklomanov, 2000). Of course, the distribution of water on earth varies; some locations have an abundance while others have very little. Of the total volume of water, about 97.5 per cent is saline; of the remaining 2.5 per cent, about two-thirds is isolated in polar ice and glaciers, and almost all of the remaining one-third is buried underground. The remaining surface-water fraction, which is our traditional source of freshwater, amounts to only about 0.3 per cent of the planet's freshwater (Gleick, 1996). The circulation and conservation of the Earth's water is called the 'hydrological cycle' (Box 1.2).

The basic concepts and terminology of groundwater science, as used in this report, are summarised in Appendix 1. They include: hydrogeological environments, porosity, hydraulic head, groundwater flow, aquifers and aquitards, groundwater-flow systems, groundwater-surface-water interactions, well yield, aquifer yield and basin yield, groundwater quality and groundwater-related hazards

Box 1.2: The Hydrological Cycle

Solar energy continuously transfers water among the hydrosphere, biosphere, lithosphere, cryosphere and atmosphere in a process that is governed by a water balance (see Figure 1.2). The water balance is an accounting of the water flowing in and out of a defined area in a given time. The area could be an urban garden or the St. Lawrence River watershed.

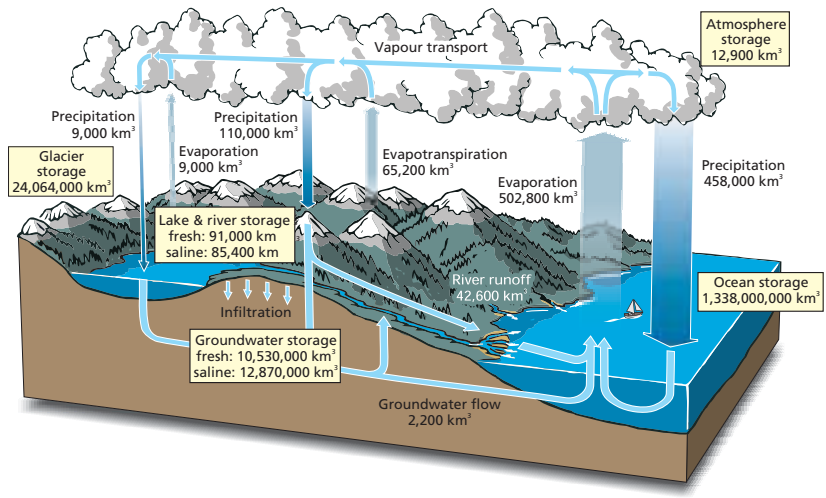
Although at any given moment all the water in the global water balance must add up to the 1.4 billion km^3 total, some segments of the cycle are moving very slowly, specifically deeper groundwater and glaciers. They are considered 'stored water' as their volumes are replaced only over very long time frames. Other segments of the cycle, precipitation and rivers for example, are considered 'flowing water' because they are replenished almost on a daily basis.

Evaporation of surface water by the warmth of the sun drives the cycle. Surface-water features such as oceans, lakes, and rivers provide approximately 90 per cent of the moisture in the atmosphere via solar evaporation; the remaining 10 per cent is evaporated by plants through transpiration. Evaporation is controlled by the energy supply

of the environment and is expected to increase with climate change where water supply permits. At any given time, it is estimated that almost 13,000 km^3 of water is present in the atmosphere, or roughly 0.001 per cent of the earth's total volume of water. Precipitation occurs as water vapour cools and eventually condenses, usually on tiny particles of dust in the atmosphere. It is estimated that approximately 45,000 km^3 of precipitation falls on the global landmass each year.

Rainfall or snowmelt in excess of evapotranspiration and infiltration produces runoff to wetlands, streams and lakes. A fraction of the precipitation water infiltrates into the ground. The rate of infiltration depends on soil type, soil moisture content, slope steepness and the presence of cracks or fractures in the ground. The rate of infiltration and the runoff and evaporation patterns determine, on a local basis, the fraction of water applied to the surface that moves through the soil to become groundwater. Thus groundwater is the residual from precipitation, after evapotranspiration and runoff have been accounted for.

Groundwater represents the largest stock of freshwater in the global water cycle, although it is estimated that somewhat less than half of this volume is freshwater, the rest being in deeper saline aquifers. Only about three per cent of total groundwater is active in the hydrological cycle on an annual basis (Gleick, 1996).



(Adapted and reproduced with permission from United Nations Environment Programme, 2002)

Figure 1.2
The hydrological cycle.

REVIEW OF KEY POINTS

- Nearly 30 per cent of Canada's population (almost 10 million Canadians) depends on groundwater to supply drinking water, and more than 80 per cent of the country's rural population relies on groundwater for its entire water supply.
- Groundwater and surface water are inextricably interconnected within the hydrological cycle. There is really just one store of available freshwater.
- There are very significant current and emerging stresses on Canada's groundwater including population growth and urbanisation; agricultural intensification; impacts related to hydrocarbon production; and the growing impact of climate change.
- In most of the ways that people and ecosystems are affected, it is the local-scale flow of water that matters; the store of water is secondary. This is particularly relevant to groundwater, which flows very slowly. Consequently, any consideration of water in Canada will have a strong regional dimension.
- Canada has not yet experienced widespread over-usage of groundwater. There have been individual cases where severe local problems have arisen, but this has not yet occurred on a national scale.
- Canada is in the enviable position of being able to put in place proactively, the policies and management practices that can prevent such crises from occurring.
- Despite the economic and ecological value of groundwater, Canada's legislative framework and institutional capacity for groundwater management have yet to evolve sufficiently to respond to groundwater challenges.
- There is very limited information regarding the valuation of water in Canada and effectively no current information on valuation by users of groundwater.
- There is a critical lack of data on: groundwater allocations, actual withdrawals of groundwater, and volumes discharged or reused. Groundwater cannot be managed effectively without these data, and the agencies responsible should assign a high priority to their collection.

2 Sustainability in the Groundwater Context

The preceding chapter identified a set of key issues to be considered when developing strategies regarding the management of groundwater: quantity, quality, monitoring, usage and value. This chapter addresses what is meant by sustainable management and proposes a set of goals for the sustainable management of groundwater.

2.1 INTERNATIONAL DEVELOPMENT OF THE SUSTAINABILITY CONCEPT IN RELATION TO WATER

The concept of environmental sustainability was first broached at the Stockholm Conference on the Human Environment, sponsored by the United Nations in 1972. Since then, numerous international conferences have been held to develop definitions of sustainability for a variety of circumstances (Table 2.1), including international meetings devoted solely to water. The first major water conference was at Mar del Plata, Argentina, in 1977, and in the 1990s international water meetings began to proliferate. The first of the triennial World Water Forums happened in Marrakech in 1997, followed by The Hague in 2000, Kyoto in 2003, Mexico City in 2006, and Istanbul in 2009. World Water Week also occurs annually in Stockholm; it focuses on the implementation of international processes and programs in water and development. Despite the prevalence of such meetings, critics continue to point out that they have not measurably advanced water sustainability (Gleick, 2007).

At the World Summit on Sustainable Development in Johannesburg in 2002, participating nations agreed to a number of water actions focused first on halving, by the year 2015, both the proportion of people who are unable to reach or afford safe drinking water and the proportion without access to basic sanitation. This Plan of Action also committed the nations to, among other measures, mitigate the effects of groundwater contamination and develop and implement strategies with regard to integrated drainage basin and groundwater management (WSSD, 2002).

Various international agencies have looked at ways to promote groundwater sustainability. The United Nations Environment Programme produced "Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management," which documented how over-exploited aquifers, falling water tables, and seawater contamination threaten the world's natural underground reservoirs, upon which two billion people depend for drinking water and irrigation (UNEP, 2003). UNESCO has a large groundwater

program, including the Internationally Shared Aquifer Resources Management Initiative, and has also compiled a global report on indicators used to measure groundwater sustainability (UNESCO, 2006). The Food and Agriculture Organisation of the United Nations (FAO) has reported on groundwater and international law (Burchi and Mechlem, 2005). The World Bank's Groundwater Management Advisory Team program assists developing nations with groundwater management and has produced a useful series of Groundwater Briefing Notes (GW MATE, 2006).

Table 2.1
International Initiatives to Define 'Sustainability'

Year	Event	Sustainability Definition
1987	Brundtland Commission (World Commission on Environment and Development)	"…development which meets the needs and aspirations of the present generation without compromising the ability of future generations to meet their own needs." It also stated: "…at a minimum…must not endanger the natural systems that support life: the atmosphere, the waters, the soils and living beings."
1992	United Nations Conference on Environment and Development (also known as the Rio Earth Summit)	"The general objective is to make certain that adequate supplies of water of good quality are maintained for the entire population of this planet, while preserving the hydrological, biological and chemical functions of ecosystems."
1992	Dublin Water Principles Affirm Principle 1 in Lead Follow-up to the Rio Earth Summit	"Since water sustains life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems. Effective management links land and water uses across the whole of a catchment area or groundwater aquifer."

2.2 CANADIAN DEVELOPMENT OF THE SUSTAINABILITY CONCEPT IN RELATION TO WATER

There are many examples in Canada of increased emphasis on sustainability in water management. Recent Canadian legislation contains sustainability commitments, such as the *Auditor General Act* (Government of Canada, 1985a), which requires 25 federal departments to develop and update sustainability strategies, and the *Canadian Environmental Protection Act* (Government of Canada, 1999), whose primary purpose is to "contribute to sustainable development through pollution prevention".

No Canadian law at the federal level refers specifically to groundwater sustainability; however, two federal policies on water do make this link. The 1987 Federal

Water Policy states that its overall objective "…is to encourage the use of freshwater in an efficient and equitable manner consistent with the social, economic and environmental needs of present and future generations" (Environment Canada, 1987). The Federal Water Framework, put together in 2004 by a committee representing 19 departments, established the federal goal of "Clean, safe, and secure water for people and ecosystems". This goal is to be achieved by "sustainable development through integrated water-resources management within the federal government and within national and international contexts" (Government of Canada, 2004). The vision of the Canadian Framework for Collaboration on Groundwater is "To ensure a healthy and sustained groundwater resource for all Canadians" (Rivera *et al.*, 2003).

Provincial water laws and policies are increasingly based on sustainability principles. For example, the *Ontario Water Resources Act* states that: "The purpose of this Act is to provide for the conservation, protection and management of Ontario's waters and for their efficient and sustainable use, in order to promote Ontario's long-term environmental, social, and economic well-being" (Government of Ontario, 1990). Similarly, the *Preamble to Québec's Water Preservation Act* states that "Québec's water resources are essential to the economic, social and environmental well-being of Québec; and whereas it is necessary to provide for the sustainable use of water resources..." (Parliament of Québec, 1999). Other provincial water laws are also guided by sustainability principles.

Non-government bodies have also focused on water and sustainability. The Canadian Water Resources Association produced "Sustainability Principles for Water Management in Canada" (CWRA, 1994), and NGOs lead public education, awareness building, and policy programs across the country.

2.3 THE PANEL'S GROUNDWATER SUSTAINABILITY GOALS

Bearing in mind the foregoing, the panel sought to develop a conceptual framework to help identify what science is needed to underpin sustainable management of groundwater in Canada. The panel recognises that in the context of assessing the scientific requirements for the sustainable management of groundwater in Canada, science should be interpreted broadly to include not only the physical sciences and engineering but also social science and law. While this report focuses primarily on the physical sciences, it also considers the economic, social and legal aspects of a sustainable groundwater management regime.

The panel believes that groundwater management must be a shared undertaking among all orders of government in Canada, and that all governments (federal,

provincial, territorial, and local) therefore have important roles to play in developing the physical science basis for the management of the resource. It is envisaged that a framework for the synchronised, cooperative, and coordinated application of physical science in all regions of the nation would be a substantial step towards a cooperative framework that would extend into the long-term management of Canada's groundwater resources.

Based on the sub-questions in the charge, the panel considered the following:

- *Quantity and Usage:* What is required to ensure sufficient groundwater resources on an ongoing basis in Canada and what science is needed to be able to monitor and evaluate the supply of groundwater?
- *Quality and Monitoring:* What is required to ensure groundwater quality from human-health and ecosystem points of view and what science is needed to be able to monitor and evaluate the quality of groundwater?
- *Value:* What socio-economic factors need to be considered in the decision-making processes surrounding groundwater management?

Having regard for these questions, as well as for the various definitions of sustainability used in international and national documents, the panel believes that the concept of groundwater sustainability should encompass five interrelated goals: three that involve primarily the physical sciences and engineering domain, and two that are mainly socio-economic in nature (Figure 2.1). The five sustainability goals are the following:

(1) *Protection of groundwater supplies from depletion:* Sustainability requires that withdrawals can be maintained indefinitely without creating significant long-term declines in regional water levels.

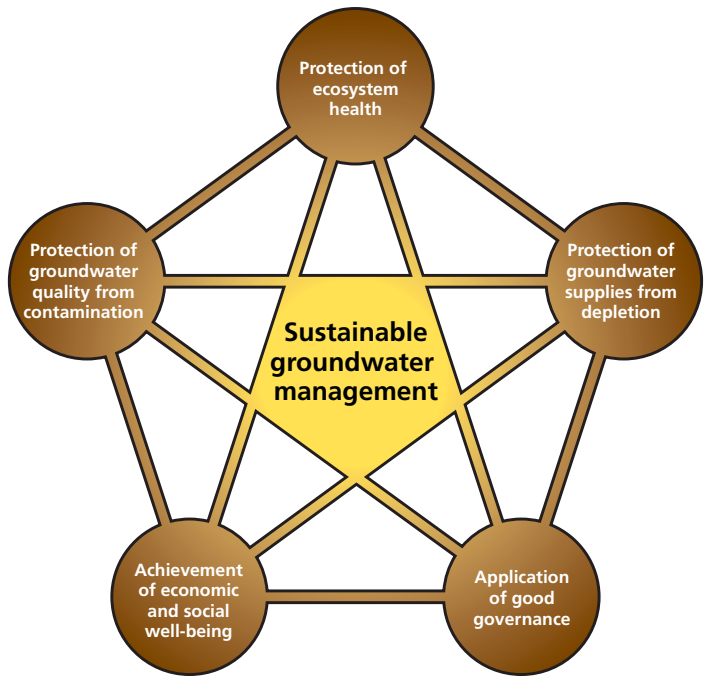
(2) *Protection of groundwater quality from contamination:* Sustainability requires that groundwater quality is not compromised by significant degradation of its chemical or biological character.

(3) *Protection of ecosystem viability:* Sustainability requires that withdrawals do not significantly impinge on the contribution of groundwater to surface water supplies and the support of ecosystems. Human users will inevitably have some impact on pristine ecosystems.

The use of the term 'significant' in the three foregoing goals implies a notion of what may be acceptable to society in terms of permissible degradation or depletion of the resource. The mechanisms by which society determines what is acceptable are encompassed in the following two goals:

(4) *Achievement of economic and social well-being:* Sustainability requires that allocation of groundwater maximises its potential contribution to social well-being (interpreted to reflect both economic and non-economic values).

(5) *Application of good governance:* Sustainability requires that decisions as to groundwater use are made transparently through informed public participation and with full account taken of ecosystem needs, intergenerational equity, and the precautionary principle.[4]



(Council of Canadian Academies, 2009)

Figure 2.1
Groundwater sustainability pentagon.

4 The precautionary principle seeks to encourage those undertaking projects to consider and address harm to the public or the environment even if the scientific consensus that harm will occur is unclear. The precautionary approach is innovative in that it changes the role of scientific data. It requires that once environmental damage is threatened, action should be taken to control or abate possible environmental interference even though there may still be scientific uncertainty as to the effects of the activity (Birnie and Boyle, 2002). The basic elements are the need for a decision, a risk of serious or irreversible harm, and a lack of full scientific certainty. In the past 10 years, the precautionary approach has become an integrated part of both environmental and health-based Canadian regulatory measures (Government of Canada, 1992; Government of Canada, 1999).

Most previous attempts to define sustainable groundwater use (Alley *et al.*, 1999; Devlin and Sophocleous, 2005; Sophocleous, 1997; Sophocleous, 2007) acknowledge that the question of what constitutes sustainability involves judgment and is ultimately a societal decision that should be informed by scientific knowledge and sustainability principles, including the precautionary principle. This is reflected explicitly in the fifth goal, application of good governance. The panel sees the goals as interrelated (Figure 2.1). For example, decisions regarding volumes withdrawn from groundwater resources may also have an important impact on the viability of ecosystems (Box 2.1). More generally, sustainability requires that groundwater and surface water be characterised and managed as an integrated system within a drainage basin or groundwater basin. Groundwater and surface water are both inherent components of basin-wide water budgets, and they are inextricably interconnected as components of the hydrological cycle. Furthermore, withdrawal limits set by groundwater management policies need to consider the societal and economic impact on the surrounding area. In other words, each of these five goals is necessary and no one in itself is sufficient. The overall achievement of sustainability will rely on a careful analysis and balancing of the five goals.

The implementation of policies that are jointly beneficial to the environment and to social and economic well-being requires interdisciplinary understanding and cooperation that challenges our traditional administrative systems at all levels. The systems approach to assessing the sustainability of water-resource development requires consideration of all the components of the hydrological cycle and not of any one component in isolation.

It appears that no authority in Canada at any level (local, provincial, or national) has assessed the sustainability of groundwater use under its jurisdiction or established a sustainable-management strategy in a way that fully meets the above-stated goals. It is not the intent of the panel that these goals should be adopted as writ for the purposes of decision-making. Rather, they are an interpretive tool that was used to guide panel deliberations. Furthermore, since each of these goals addresses the various aspects of the original charge (quantity, quality, monitoring, usage, and value), they can be used to guide data gathering, groundwater modelling, groundwater management, and economic decision-making. The following section serves to elaborate on the role of each of the five goals.

Box 2.1: Water Budgets and Sustainability

Water-budget calculations that attempt to estimate the rates and volumes of groundwater recharge and discharge for a groundwater basin and relate them to precipitation, surface runoff, and the other components of the hydrological cycle are a useful and informative component of many basin-wide groundwater studies. Several of the case histories in Chapter 6 utilise such calculations in their assessments of groundwater conditions in various parts of Canada. However, naïve usage of the recharge calculation from a water budget (or some percentage of it) as a direct estimate of sustainable groundwater yield is not recommended.

An early and simplistic approach to water-resource engineering set the maximum sustainable yield of an aquifer equal to the amount of water that recharges the aquifer under natural, predevelopment conditions. This is widely dubbed "the water budget myth" (Alley *et al.*, 1999; Bredehoeft *et al.*, 1982; Devlin and Sophocleous, 2005). The use of this concept could lead to calculations of sustainable yield that are too high or too low, depending on the hydrogeological circumstances.

The water that is withdrawn has only three possible sources: groundwater storage, induced recharge, and captured discharge. Pumping produces a transient change in the aquifer's water budget, initially taking water from storage, but eventually leading to a new equilibrium with either increased recharge or decreased discharge (Alley *et al.*, 1999; Freeze and Cherry, 1979). In either case, groundwater pumpage takes water from the surface water component of the hydrological cycle, even though the time-lags might be considerable. Induced increases in groundwater recharge rates reduce the amounts of overland flow to streams from upland recharge areas, while decreases in groundwater discharge rates reduce the baseflow to valley streams.

If the positioning of wells in an aquifer increases the recharge, and if the resulting reduction in water available for overland flow is acceptable, then estimates of sustainable groundwater yields based on predevelopment recharge rates may be too low. If the positioning of the wells captures water that would otherwise leave the aquifer as discharge to streams and wetlands, and if this reduction in discharge is not acceptable, then estimates of sustainable yield based on predevelopment recharge rates may be too high. The latter case is more common than the former.

Furthermore, not all the water that is pumped from groundwater is necessarily consumed. Some portion of applied irrigation water, for example, ends up back in the subsurface as so-called 'return flow,' although the 'return flow' might be to an aquifer other than the one from which it was extracted. In the case of domestic and industrial water use, some of it becomes wastewater that is treated and returned to the groundwater or surface water bodies of the hydrological system.

2.4 INTERPRETING THE PANEL'S GROUNDWATER SUSTAINABILITY GOALS

Protection of Groundwater Supplies from Depletion

Sustainable groundwater management must seek to prevent continuous, long-term declines in groundwater levels (Box 2.2). Water-table elevations that reach a new equilibrium position are generally acceptable, provided the third goal, namely protecting ecosystem viability, has been adequately respected. However, if pumping leads to declining water tables that never equilibrate, then the use is unsustainable because the groundwater in storage eventually becomes depleted to a degree that does not allow continued use. (An example of a long-term decline in groundwater levels is provided in the case study of the Denver Basin in Chapter 6.)

Box 2.2: Water-Level Declines in the United States

Groundwater is the principal source of drinking water for about 50 per cent of the United States population, providing approximately 98 per cent of the water used for rural domestic supplies and 37 per cent of the water used for public supplies. In addition, more than 42 per cent of the water used for irrigation is withdrawn from wells. The total groundwater use in the United States was 315 million m^3 per day in 2000 (Hutson *et al.*, 2004).

Because of this reliance on pumped groundwater, the volume of groundwater in storage has declined in many areas of the United States. Among the consequences of groundwater-level declines are increased pumping costs, deterioration of water quality, reduced discharge of water to streams and lakes, and land subsidence. Such negative effects, while variable, happen to some degree with any groundwater use. As with other natural resources, society must weigh the benefits gained by the use of this natural resource against the consequences of such use.

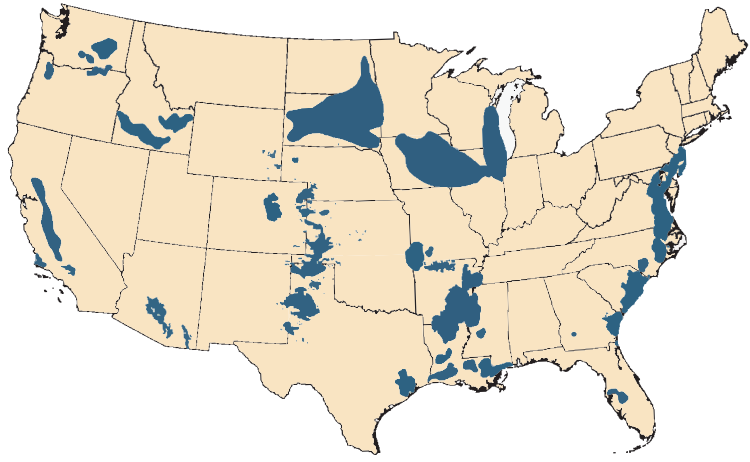
The United States Geological Survey (USGS) compiled a map (see Figure 2.2) depicting areas of water-level decline in excess of about 12.2 metres in at least one confined aquifer since predevelopment, and areas of water-level decline in excess of 7.6 metres in an unconfined aquifer since predevelopment. The areal extent of the water-level decline must be approximately 1,300 km^2 or larger to be included on the compilation map (Reilly *et al.*, 2008). As shown in the figure below, water-level declines may occur over large geographic areas as a result of groundwater pumping.

Although the USGS database contains groundwater information from every state, it is not a comprehensive database of all groundwater monitoring activity across the United States. Thus the map is not a comprehensive evaluation of water-level declines in all areas. United States knowledge is incomplete, in some cases because there are not enough water-level data, and in other cases because data have not been compiled nationally. A national effort is ongoing in the United States to organise available federal, state, and local information on changes in groundwater levels.

Groundwater systems change in response to development and should be monitored and evaluated on a regular basis to quantify the amount of water available for use and the ramifications of using the resource. Each regional groundwater system is unique in terms of climate, hydrogeological framework, and boundary conditions (both type and location), and each system responds differently to stresses from human development and climate.

The USGS is undertaking a broad-scale assessment of the nation's groundwater resources that is adaptable over time and that provides quantitative regional analyses of major areas of groundwater use. The program builds on past federal efforts and a long history of partnerships among the USGS and other federal agencies, states, tribes, and local governments to collect groundwater data and undertake investigative studies of groundwater systems. Products of the program include current estimates and historic trends in groundwater use, storage, recharge, and discharge (water-budget analysis); computer models of regional groundwater systems; region-wide estimates of aquifer properties for major aquifers; evaluation of existing networks for monitoring groundwater availability; and testing and evaluation of new approaches for analysis of regional aquifers.

The program is designed to allow both 'scaling up' to a national synthesis and 'scaling down' to provide information relevant to issues of more local concern. Groundwater management decisions in the United States are made by states, municipalities, and special districts formed for groundwater management. Thus, regional studies are partnered, where possible, with interested agencies and organisations to enhance their relevance to local concerns, and information and models provided at the regional scale are designed to provide a regional framework for more detailed studies and models by individuals who make management decisions at the local level (Reilly *et al.*, 2008).



(Adapted and reproduced with permission from Reilly *et al.*, 2008)

Figure 2.2

Areas of water-level decline in the United States.

To date, there are few examples of excessive groundwater depletion on a large scale in Canada, though localised examples do exist. The Estevan Valley aquifer in southern Saskatchewan saw a substantial decline due to extraction for electricity generation. Pumping was halted in 1994, and estimates suggest the water level in the aquifer will take up to 20 years to recover (Rivera, 2005).

There can be serious economic consequences from excessive depletion. For example, greater costs are expected for pumping and possibly for treatment if groundwater has to be extracted from ever-deeper aquifers because of increasing water-level declines. Alternative water sources via pipelines, tanker water and bottled water (Township of Langley, 2008; Region of Waterloo, 2007b) are often far costlier than local groundwater use. Furthermore, the costs of addressing issues such as land subsidence caused by groundwater over-pumping can be huge. Several instances of costly land subsidence have occurred in the United States (Galloway *et al.*, 1999). Declining storage levels also reduce the buffer provided to municipal and agricultural users during droughts.

Protection of Groundwater Quality from Contamination

Sustainability requires that groundwater quality is not compromised by a significant degradation of its chemical or biological character. The effects of reduced quality in groundwater supplies can affect both human health and ecosystem health. For illustrative purposes, the following discussion is restricted primarily to the protection of drinking-water quality.

While poor groundwater quality may stem from naturally occurring constituents in the aquifer matrix, it is commonly human-induced and a reflection of the local land use. In rural and agricultural settings, groundwater contamination may come from a variety of sources, including manure storage and application, septic systems, accidental spills and pesticide application (CEC and Government of Canada, 2006). In urban settings, large-scale industrial activities, transportation networks, and small-scale commercial operations may contribute. In coastal settings, groundwater management must account for the protection of aquifers from seawater intrusion.

Water-borne disease is a potentially serious problem associated with degraded water quality. The recent tragic example of groundwater contamination in Walkerton, Ontario, claimed seven lives, caused many hundreds of illnesses, and led to the Walkerton Commission of Inquiry, which resulted in a complete overhaul of Ontario's drinking-water management system. Other provinces followed suit in examining the adequacy of their drinking-water protection systems. While nationwide figures for waterborne disease outbreaks are not

readily available, the numbers appear to be significant. For example, between 1980 and 2004, British Columbia had 29 confirmed outbreaks of water-borne disease that affected tens of thousands of people (Government of BC, 2007). At Walkerton, the costs of investigating the problem and putting a new system in place were very high. For example, the Commission itself had a budget of approximately $10 million, and $65 million was paid in compensation to victims and their families (WCWC, 2007).

The Walkerton case is an extreme example of contamination, but it is not an isolated one. As of March 31, 2008, there were 1,859 boil-water advisories in effect in Canada as reported by the Canadian Medical Association. Ontario led the country with 679 orders, and British Columbia was next with 530. These alarmingly high numbers were not segregated by water source, so the number of advisories attributable to groundwater is unknown.

In addition to human health impacts and costs, groundwater quality problems have other substantial costs to society. Agricultural and industrial contamination is far costlier to clean up than to prevent in the first place. For example, the Ontario Ministry of the Environment spent approximately $22 million between 1984 and 1993 remediating surficial soils at a polychlorinated biphenyls (PCB) storage facility near Smithville, plus an additional $3 million to replace the town's water-supply well with a pipeline from Grimsby, about 10 kilometres to the north. It is estimated that up to 40,000 litres of PCB still remain in the fractured bedrock aquifer, and the recovery of PCB and remediation of the aquifer are deemed too complex and expensive. The Ministry therefore spends $0.5 million annually to maintain a pump and treat system to control the off-site movement of contaminants (Government of Ontario, 2002a).

Sustainable groundwater management must seek to prevent groundwater contamination caused by human activities and remediate and restore contaminated groundwater. Protecting municipal users of groundwater from the health risks associated with contaminated water can be met (i) by preventing pollution through effective wellhead and source-water protection programs and effective regulation and enforcement systems, (ii) by ensuring that pumped wells do not have the potential to draw in contaminated groundwater that cannot be readily treated, (iii) by installing peripheral monitoring wells for early detection of potential contaminants, and (iv) by installing appropriate wellhead or water distribution treatment systems (users of private wells rely primarily on pollution prevention measures, although wellhead treatment for naturally occurring chemical and biological constituents is increasingly common in some areas).

It is emphasised that impacts on groundwater from risky land-use practices or over-exploitation may take many years or even decades to appear. Once the impact is observed, it may take an extremely long time or be impossible to repair. This is a unique aspect of groundwater that requires management techniques different from those used for surface water.

Protection of Ecosystem Viability

Groundwater discharge to streams is responsible for maintaining stream baseflow and thus plays a key role in supporting essential ecosystem functions, such as providing habitat for aquatic plants and animals, moderating the impact of cycles of drought, sustaining wetlands, assimilating waste, and transporting nutrients. To illustrate, for brook trout (and, to a lesser extent, rainbow and brown trout), it is not only the flow of groundwater into headwater streams that is important, but also a stable temperature and the dissolved oxygen necessary for egg survival and development (Meisner *et al.*, 1988). How much change can these fish tolerate before their reproduction is unsuccessful? This question continues to be a field of research. No figures exist to show exactly how freshwater species depend on groundwater or how to calculate the amount of groundwater that can be removed from a discharge zone before affecting the health of the river to which it is linked (Gartner Lee Ltd., 2002; Rivera, 2005). Therefore, the water requirements of groundwater-dependent ecosystems and aquatic ecosystems are not yet easily quantified, although these topics are receiving an increasing amount of attention from scientists (IAH, 2007), regulators (USDA, 2007), the European Union in implementing its Water Framework Directive (see Box 5.1), and NGOs and research institutes (WDGF, 2005; Program on Water Governance, 2008; Nature Conservancy, 2008).

Both the quantity and quality of groundwater influence ecosystem viability. One of the most egregious examples of impact on quality comes from Prince Edward Island, where a recent independent commission found that the discharge of nitrate-contaminated groundwater resulted in the degradation of environmental conditions in watercourses and estuaries with the 'costs' including: fish kills, economic losses to commercial and recreational fishing and shellfish harvesting, and reduced real-estate values for shoreline properties (Government of PEI, 2008). This issue is more thoroughly addressed in the Prince Edward Island case study in Chapter 6.

Groundwater extraction will alter, to varying degrees, the natural predevelopment water budget. There is invariably a trade-off between the socio-economic benefits of increased water supply for consumption and the ecological benefits of stable outflow to groundwater discharge areas. Determining the trade-offs is a central goal of sustainable groundwater management. Adequate discharge from the flow system must be maintained to keep major springs viable, to maintain the health of

wetlands, to provide sufficient baseflow to streams, to maintain lake levels at acceptable elevations, and to provide the necessary freshwater contributions to estuarial shorelines. Groundwater withdrawals should not lead to a reduction in the diversity of flora and fauna that populate such habitats.

Understanding the temporal variability of a groundwater-flow system and its interaction with surface water is important. An assessment of groundwater discharge requirements for ecosystem viability must ensure that relevant surface-water features are incorporated into the groundwater understanding when estimating the discharge of groundwater to surface-water bodies, and that the needs and vulnerabilities of the aquatic ecosystem are understood. Both of these tasks are technically difficult, making the determination of an acceptable change in groundwater level a major conceptual and measurement challenge (Farber, 2002).

Governance processes, discussed below in the context of the fifth goal of sustainable management, seek to balance the human benefits of groundwater extraction with the ecosystem benefits incurred by maintaining adequate stream baseflow and wetland habitats. However, while methods to value the human benefits are readily available and well understood, the mechanisms to assign value to the ecosystem benefits are poorly understood and incomplete. Governance is therefore at risk of favouring human benefits.

Achievement of Economic and Social Well-being

Canadians use groundwater for drinking water and for many other purposes. Managing groundwater according to sustainability principles would ensure that residents have stable and good quality supplies. Furthermore, sustainable management policies that maintain water levels, stream baseflow rates, and wetland habitats provide direct economic benefit to tourism, small-craft navigation, the hunting and fishing community, and many others. Groundwater also has value far beyond dollars. Water has spiritual, cultural and aesthetic value. Springs, for example, are often places of scenic and spiritual significance. The panel recognises the importance of sustainably managing groundwater to respect these important values.

From an economic viewpoint, one would ideally seek to maximise the net benefit society derives from using groundwater, including the benefits incurred simply by leaving the groundwater in place. The benefit incurred due to withdrawal of groundwater at any particular time must be considered in the context of two associated costs imposed on society: (i) the sum of the current-period costs experienced by the user, plus costs to any neighbouring users affected by the withdrawal, together with the cost of ecological impacts, and (ii) the cost associated with foregone potential net benefits that might have been enjoyed by future users. Inclusion of this second cost is necessary to ensure that groundwater use is allocated across users

and across time periods so as to maximise its sustained value to society, consistent with the notion of intergenerational equity as a premise of sustainability (NRC, 1997).[5]

This reasoning can have important implications. In the case of a deep aquifer, for example, where head drawdowns due to pumping might not impact surface water supplies for a very long time, the objective of maximum value to society, which involves some discounting of costs and benefits in the future, could validate a program of extensive pumping. Any plan to use such an aquifer in this way is inherently unsustainable according to the first goal — the protection of groundwater from depletion. But the fourth goal, promotion of economic and social well-being, might nevertheless justify such a decision. This could be argued if the loss in value associated with the drawdown in the aquifer were offset with a related increase in value arising from an expansion of human-created capital such as infrastructure, businesses, or investment in alternative water supply technologies. The practical application of such a rationale is illustrated in the Denver Basin case study in Chapter 6. This position is not without its critics, and it illustrates the challenge of defining and operationalising a concept of strict 'quantity' sustainability while taking into account the goal of maximising social and economic well-being over an extended time (Schiffler, 1998; UNESCO, 2006).

The economic and social benefits from the industries that rely on groundwater are enormous but virtually impossible to quantify with the available data. Current industries directly reliant on groundwater include the oil and gas industry and agriculture, especially livestock operations. Failure to manage groundwater sustainably could eventually harm these sectors. The lack of empirically based knowledge about the value of water to the health and well-being of Canadians and their ecosystems may impede the ability of governments to manage groundwater sustainably. Reliable estimates of economic value could promote more efficient decision-making regarding water allocations, water-related infrastructure, expenditures for source water protection, and remediation of contaminated waters.

Regardless of society's best intentions for the long term, there will always be pressure to use groundwater to maintain current socio-economic prosperity. That is why a

5 In technical terms, a value-maximising plan for groundwater use must be such that (i) the marginal benefit of the last unit of groundwater should be equal to the sum of the marginal costs of extraction and the marginal user-cost in each time period. The last term measures the foregone net benefit arising from current-period withdrawals; and (ii) the present value of the net marginal benefit (marginal benefit minus marginal cost) in each time period must be equal across the planning horizon. This second condition must be met if groundwater use is to be allocated across time periods in a way that maximises society's benefit from groundwater use. It is also important to note that the definition of marginal cost here is more complex than that found in static (i.e., one time period) economic optimisation problems.

proper governance process is necessary to establish groundwater allocations and achieve, over the long-term, the five goals of sustainability. Lasting frameworks that identify and protect aquifers and groundwater flows vital to both humans and ecosystems (now and in the near future) are thus needed. These frameworks will require a risk-management approach that seeks to direct potentially unsustainable uses of groundwater to aquifers with reduced ecological value. Arguably, this logic is already being applied informally in many parts of Canada as managers seek to accommodate new demands within the allowances of their drainage basin's ecosystems. In Alberta, for example, petroleum companies are required to look for a saline water source before applying for a licence to remove non-saline water for enhanced oil recovery.

Application of Good Governance

Water governance is the range of political, organisational and administrative processes through which interests are articulated, input is received, decisions are made and implemented, and decision-makers are held accountable. It is distinct from water management, which is the operational, on-the-ground activity of regulating water and imposing conditions on its use. Governance involves more than the activities of any particular 'government,' and extends to public, private, and civil-society actors.

Different groups define different criteria for good water governance (Bakker and Cameron, 2002), but common criteria include: inclusiveness, participation, transparency, predictability, accountability, and the rule of law. Providing relevant information in a form that is accessible to the public is a prerequisite for a fair and transparent decision-making process. Most jurisdictions provide access to some information about groundwater. For example, some provinces make available maps of relevant geology and wellhead-protection areas. Most provinces also maintain public databases of water-use permits and licences, although they are sometimes difficult to interpret.

Inclusiveness is a key component of drainage-basin planning processes in which governments seek to improve management by involving a wide range of government, public, and private stakeholders in the decision-making process. Providing opportunities for conflict resolution is another important part of governance. Opportunities to participate in groundwater licensing decisions vary from province to province. Ontario's Environmental Bill of Rights and associated public registry is one example of a legal public notice and comment opportunity. Another crucial element of good governance is the rule of law. In terms of groundwater management, respecting the rule of law refers to topics such as compliance with licence conditions, enforcement of reporting requirements, respecting and accounting for First Nations' title rights, treaty rights, and ultimate access to the legal system in the

event of unresolved conflicts. Indeed, weak governance structures may lead to greater conflicts over groundwater use:

- Opposition to new proposed legislation in Manitoba designed to better protect groundwater and regulate the hog industry is so strong that hog producers have joined together to create an 'Unfriendly Manitoba' website expressing their opposition to the government's activities. The issue of intensive livestock operations is particularly divisive in a number of provinces.
- Opposition to water-bottling plants withdrawing from groundwater sources has also sprung up across the country, and can involve long and costly disputes (Nowlan, 2005). Uncertainties about how groundwater regulations affect water-bottling operations are a common concern (for example, see the case study in Chapter 6 on Basses-Laurentides).
- Conflicts over groundwater management and use arise in numerous other settings such as land development, golf courses and pipelines.
- Failure to include all affected groups in decision-making procedures can lead to litigation, such as several lawsuits involving First Nations now underway in Alberta.[6]
- Litigation can also arise over failure to assess the cumulative impact of projects, with costly delays for industry, as the recent court case involving the revocation of a water permit for the Kearl oil sands project demonstrates.

Participatory decision-making at the early stages of groundwater development can sometimes, but not always, help to avoid later conflicts. When citizens have access to information and rights to participate in decision-making, they may be less likely to resort to lawsuits (Nowlan and Bakker, 2007). Groundwater laws will be more effective if developed and implemented with a high degree of user participation (Tuinhof, 2001).

Groundwater sustainability can be enhanced when multiple government agencies, citizens groups and scientific researchers work together. For example, H_2O Chelsea — a collaborative project involving a Québec municipality, a research institute, and a citizen-based NGO — works to protect groundwater resources in this small low-density development built on the Canadian Shield in the Gatineau Hills. The municipality now has a policy requiring developers to conduct pumping tests to demonstrate that

6 A number of lawsuits are underway related to First Nations rights and resource and water management. A claim by the Beaver Lake Cree in Alberta seeks to invalidate authorisations for thousands of petroleum projects on the band's core territory (Sandborn, 2008). The Chipewyan Prairie First Nation has made a similar claim (Lillebuen, 2005). The Tsuu T'ina Nation and Samson Cree Nation are asking the Court of Queen's Bench to overturn the Alberta government's decision to close nearly every river, lake and stream in southern Alberta, arguing that the plan doesn't effectively protect the environment (D'Aliesio, 2008).

there is an adequate water supply to support proposed new developments (Nowlan and Bakker, 2007). The consistent application of good governance criteria is likely not only to increase legitimacy but also to improve the quality of decision-making and thus avoid the need to resort to formal conflict-resolution mechanisms such as environmental appeal boards and the courts.

Finally, to ensure that the governance process equitably balances ecosystem needs with socio-economic needs, comparable accounting procedures are necessary in both domains to quantify the value of water. Failure to use economic criteria in decision-making regarding groundwater allocation and groundwater quality means that these decisions are likely to be economically inefficient in the long term, and failure to fully account for the value of ecosystem functions means that the governance process will likely favour socio-economic interests over ecosystem interests.

2.5 REPORTING ON SUSTAINABILITY TARGETS

Performance monitoring is an integral part of implementing sustainable resource management. The data so obtained are best interpreted in terms of clearly defined targets that indicate success or failure with respect to stated goals. Owing to the multiple goals outlined above, and to the complexity of groundwater behaviour, the assessment of sustainability will usually require several independent indicators. Ideally, they must be measurable and representative and should be easily retrievable from program databases. They should be directly related to the sustainability goals and readily compared with sustainability targets, reference values, ranges or thresholds and therefore be able to serve as triggers for action when indicated (Hodge *et al.*, 1995). Representative indicators might include water levels in select water-table wells and deeper piezometer nests, water-quality determinations from potentially vulnerable contaminant locations, spring flow rates, wetland health, streamflow measurements, and estimates of stream baseflow rates. In more complex cases, indicators might be needed to assess the extent of seawater intrusion, land subsidence, or the potential for transboundary impacts. Socio-economic indicators could be based on identified costs and benefits of the approved groundwater development program and on more qualitative measures of social well-being.

It is apparent that techniques for acquiring and applying sustainability indicators to improve management need further development. To provide focus for this ongoing task, the federal government, in cooperation with the provinces, should be encouraged to report on the current state of groundwater quantity and quality in Canada and on progress towards sustainable management. Such a report should be updated at regular intervals, possibly every five years.

REVIEW OF KEY POINTS

- The rising worldwide attention being paid to 'sustainability' reflects a change in human attitudes — one that tempers the traditional focus on the short term and seeks to take fully into account how the actions of today might affect the future.
- The panel formulated five interrelated goals to help address the sustainability dimension of groundwater science and management:
  - Protection of groundwater supplies from depletion
  - Protection of groundwater quality from contamination
  - Protection of ecosystem viability
  - Achievement of economic and social well-being
  - Application of good governance
- It appears that no authority at any level in Canada has assessed the sustainability of groundwater use under its jurisdiction or established a sustainable-management strategy in a way that fully meets these five goals.
- Sustainability requires that groundwater and surface water be characterised and managed as an integrated system within the context of the hydrological cycle in a drainage basin or groundwater basin.
- Impacts on groundwater from land-use practices or over-exploitation may take many years or even decades to appear. Likewise, repair may take an extremely long time, is generally very expensive, and may even be impossible.
- Mechanisms to assign value to groundwater uses and, in particular, the ecosystem benefits of groundwater are poorly understood and incomplete. Governance is therefore at risk of favouring human benefits.
- The assessment of sustainability will usually require several independent indicators. It is evident that techniques for defining and applying sustainability indicators need further development.

3 Current and Emerging Issues for Groundwater Sustainability

New stresses on Canada's groundwater, together with the intensification of several existing pressures, will challenge the sustainable management of groundwater. The trends and emerging issues outlined below form the context within which sustainable groundwater management must go forward and, taken together, constitute an agenda of priorities for groundwater managers and for the science needed to inform their decisions.

3.1 POPULATION GROWTH AND URBANISATION

Canada's population of 33 million is projected to be between 36 and 42 million in 2031 and between 36 and 50 million in 2056 (Statistics Canada, 2005). Meanwhile, the concentration of population in urban areas is forecast to increase from 80 per cent of Canadians today (Statistics Canada, 2007) to 87 per cent of a larger population by 2030 (Globalis Canada, 2005). What are the implications for groundwater resources? The question involves many variables, including the proximity and availability of groundwater resources, the natural vulnerability of groundwater systems, the coherence and comprehensiveness of current governance regimes, the nature of existing stresses, and climate change impacts, all weighted according to the local setting of each basin. In general though, we can expect increased demand for groundwater.

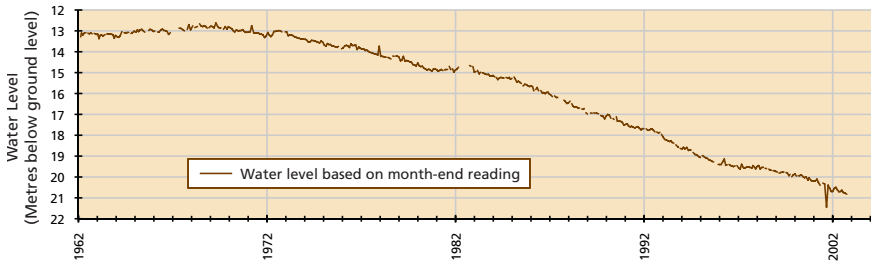
Increased Demand for Groundwater

Increased demand for groundwater will be especially strong where surface water is unavailable due to, for example, poorer quality or higher cost. Intensive and increased groundwater withdrawals may require drilling into deeper aquifers with the risks of lower water tables, decline in well yield, greater lift costs and, in isolated cases, saline intrusion or land subsidence.

The Township of Langley, near Vancouver, British Columbia, is an example of a rapidly urbanising agricultural community (its 2008 population of 100,000 is forecast to reach 165,000 by 2023) that has experienced substantial groundwater declines and is taking steps to reverse them. Ongoing monitoring indicates declining water levels in the more intensively used aquifers (Figure 3.1). In some cases, this trend has occurred for nearly 40 years. An analysis of the data indicates that the declines are not due to changes in precipitation but are the result of groundwater overuse (Township of Langley, 2008). Instituting water-demand management to conserve groundwater can result in

significant savings. The Township estimates that meeting the goals of its proposed water management plans would result in a 30 per cent reduction in overall water use with a savings of approximately $800,000 in 2007 (Township of Langley, 2007).

Population growth and urbanisation usually lead to encroachment of residential, commercial and industrial development on rural and semi-rural areas. The combination of extensive hardened surfaces and increased groundwater withdrawals may reduce the potential for groundwater recharge and diminish the ability to sustain current streamflow rates in low-flow periods. Meanwhile, an increased demand for groundwater may drive efforts to recharge aquifers artificially.



(Data Source: British Columbia Ministry of Environment, 2007)

Figure 3.1

Hydrograph showing water level in Langley municipal water supply well no. 7.

Groundwater Contamination from Pollutants

Growing local populations and urban concentration increase the risk of contamination of groundwater, including:

- Threat of chemical contamination from urban wastewater (via sanitary-sewer leaks), industrial chemicals (spillage, ground disposal) and solid waste disposal (landfills); road de-icing chemicals and dust suppressants; fertilisers and pesticides; leaking underground storage tanks; and leachate from operating and decommissioned landfills, among others.
- Threat of microbial contamination from surface sources since upper-aquifer and shallow groundwater supplies in urban areas are particularly vulnerable to such contamination.
- As urban boundaries expand, potable water may still be supplied through private wells, and homes and businesses may remain on septic systems. The intensity of use would thus amplify any issues pertaining to groundwater quality.

Trend Away from Groundwater to Piped or Treated Surface Water

As water demands increase with population growth, often compounded by greater regulatory scrutiny of water supplies, areas with limited groundwater resources (or, in some cases, limited understanding of their groundwater resources) will seek supplemental water, often in the form of surface water piped from larger lakes. This is increasingly the case in southern Ontario, where the Great Lakes provide an adjacent alternative to groundwater. These responses create other challenges related to sewage assimilation and the regulatory implications of inter-basin water transfers, not to mention that the pipeline-related costs (environmental assessments, public consultation, construction, etc.) are quite often much greater than those associated with local groundwater supplies.

Failure to Enhance Regulatory and Governance Regimes

A key challenge in any environmental issue is the ability of public authorities to respond effectively and in a timely manner. Laws and policies governing land use, agricultural activities, chemical use and spill prevention, waste management and the like, have historically been extremely complex and difficult to strengthen. Some provincial water laws, such as New Brunswick's, provide for the protection of groundwater recharge zones. If the provincial water law does not address protection of recharge zones, it is left to local governments to protect these zones through land-use plans. Coordination between provincial and local governments is vital because the stresses from urban growth and the associated infrastructure needs are felt directly at the local level, while regulatory authority is shared between both levels of government.

3.2 IMPACT OF AGRICULTURE

Agriculture is a major user of water in Canada, with an approximate annual consumption of 3.6 billion m^3 (Environment Canada, 2007). Supplementary irrigation is by far the largest component, accounting for about 85 per cent of the total, while water for raising livestock accounts for approximately 10 per cent. Water use for irrigated agriculture is greatest in the southern regions of western Canada. Although the study of Kulshreshtha and Grant (2007) could not differentiate between the water sources (groundwater or surface water), a major resource in this region is the large rivers that are fed by mountain snowpack, rainfall and groundwater. These rivers are experiencing the impact of climate change (e.g., Demuth and Pietroniro, 2003), like those in the western United States, where it has been suggested that the reduced reliability of surface water supplies because of climate change may result in a growing reliance on groundwater (Scanlon *et al.*, 2005). This may foreshadow a significantly increased demand in western Canada for groundwater for irrigation. Indeed Kassem *et al.*, (2005) have noted that, for the South Saskatchewan River Basin, better representation of groundwater resources

in integrated water-supply and planning models will be required in the future because the demands on groundwater resources are expected to increase due to the limited surface-water supplies. Going forward, it will also be critical to closely monitor the allocated and actual groundwater use by all sectors.

There has been a general intensification and industrialisation of Canadian agriculture resulting in greater farm size and specialisation to capture economies of scale. Interest in the environmental sustainability of agriculture has prompted Agriculture and Agri-Food Canada (AAFC) to develop a set of agri-environmental indicators to track the sector's progress toward meeting environmental objectives (Lefebvre *et al.*, 2005). Within the framework of these indicators, the importance of groundwater is recognised in the context of irrigation, soil salinity, and water contamination by nitrogen compounds and pathogens.

Nitrate Contamination

Although several indicators relevant to groundwater are still under development, the risk of water contamination by nitrogen compounds has already been assessed by Agriculture and Agri-Food Canada. Lefebvre *et al.* (2005) found that, nationally, the nitrate concentration in water leaching from agricultural land (as determined at the Soil Landscape of Canada scale), from residual soil nitrogen and from water-balance estimates, was 24 per cent higher in 2001 (7.3 mg of nitrate per litre) than in 1981. The risk of water contamination by nitrate is likely to have increased due to several factors, including regional increases in fertiliser use, livestock numbers, and legume crop acreages. Low precipitation in 2001 was also cited by Lefebvre *et al.* (2005) as potentially reducing crop yields and nitrogen uptake by crops. While the risk of nitrate contamination of groundwater has increased during the past two decades, there are mature federal-provincial programs in place, such as the National Farm Stewardship Program, that are intended to minimise contamination of water. Best Management Practices for minimising contamination of groundwater are not yet as widely adopted by agricultural producers as they could be. Additional monitoring, research and enforcement are required to ensure agricultural practices achieve desired goals (see case studies on Prince Edward Island and Abbotsford-Sumas aquifer in Chapter 6).

Biofuel Production

A second trend in the agricultural sector is the growing use of feedstocks such as grain and cellulose for the production of biofuels. In the United States there has already been a dramatic expansion in corn-ethanol production. This is forecast to continue for at least another decade (NRC, 2008). Recent assessments of water-quality impacts point to the fact that, compared with soybeans and mixed-species grasses,

corn production has the largest application rates of fertilisers and pesticides. Thus, all else being equal, corn-based ethanol production will likely lead to an increase in application rates of nitrogen-based fertilisers, especially if corn is produced on a continuous basis instead of being grown in rotation with other crops (NRC, 2008). This could be an important consideration in corn-growing regions of Canada (e.g., southern Ontario). The groundwater resources that would be most at risk would be those contained in shallow aquifers that receive relatively high recharge. The net assessment of how biofuel production may affect groundwater availability and quality is dependent on a number of factors, including what crop type is replaced by biofuel corn, regional differences in climate, and whether previously uncropped areas are developed for biofuel production (NRC, 2008).

3.3 RURAL GROUNDWATER QUALITY

It is estimated that more than four million Canadians, mostly in rural or suburban areas, rely on private water supplies that are mostly sourced from groundwater (Corkal *et al.*, 2004). Unlike municipalities, private water users usually do not have the economic ability or geographic opportunities to choose their water-supply source.

Groundwater contamination in rural areas may come from a variety of sources, including manure storage and application, septic systems, accidental spills, and pesticide application. Testing of water quality from private wells in Canada, which is mandatory only for new or re-drilled wells in Québec and New Brunswick, typically reveals a situation that would be unacceptable for a regulated municipal water supply.

There is no national program for tracking how many private wells have water treatment or disinfection systems and how many are subject to contamination. However, according to various surveys, nitrates and bacteria represent by far the most common well-water contaminants in Canada. It is estimated that 20 per cent to 40 per cent of all rural wells have nitrate concentrations or coliform bacteria occurrences in excess of drinking-water guidelines (Van der Kamp and Grove, 2001). Specifically, studies in Saskatchewan and Ontario have found that roughly 30 per cent to 35 per cent of surveyed wells exceeded drinking-water guidelines for bacteria, while approximately eight per cent of wells in Alberta exceeded the guidelines (Fitzgerald *et al.*, 1997; Rudolph and Goss, 1993; Sketchell and Shaheen, 2000). Ninety-two per cent of private wells in Alberta and 99 per cent in Saskatchewan exceeded Canadian guidelines for one or more health and aesthetic parameters (i.e., qualities that affect taste or odour, stain clothes, or encrust or damage plumbing) (Corkal *et al.*, 2004; CEC Government of Canada, 2006).

A 1991–1992 survey in Ontario (Goss *et al.*, 1998) found that of 1,292 farm wells sampled and compared with Ontario drinking-water quality objectives, 14 per cent exceeded the nitrate guideline, 34 per cent exceeded the fecal coliform guideline, and six wells exceeded guidelines for pesticides. A recent expert review of water wells in Ontario (Novokowski *et al.*, 2006) recommended that a comprehensive province-wide water quality survey of all types of private wells should be undertaken immediately and that such surveys should be repeated at least every 10 years to track water quality changes.

A recent study on nitrate contamination of water wells in central Saskatchewan (Hilliard, 2007) found that 25 per cent of the 109 wells identified exceeded the health guideline for nitrate. Of these, two-thirds had at least one of the following characteristics: close proximity to land receiving nitrogen fertiliser application; near a corral; or within 100 metres of a septic field. Most were shallow wells. Other examples of localised contamination from natural sources exist in Canada. For example, in Halifax County, Nova Scotia, Meranger *et al.* (1984) reported that 66 of 94 private residential wells exceeded the Canadian drinking-water guideline for arsenic.

Table 3.1 provides another relatively recent summary of well-water quality studies in Canada. The lower values adopted recently for arsenic, trichloroethylene (TCE) and total coliforms mean that the fraction of tested wells that failed to satisfy the Canadian Drinking Water Guidelines (CDWG) at the time of the above studies will now be larger.

Table 3.1
Summary of Well-water Quality in Canada

Contaminant	Canadian Drinking Water Guideline (CDWG)	Well Coverage	Percentage of wells exceeding CDWG	Estimated population using wells
Arsenic[7]	25 µg/l	all	3 to 8	300,000
TCE and PCE[8]	30 to 50 µg/l	municipal	0.2 to 0.6	70,000
Pesticides	2 to 200 µg/l	rural	0.0 to 0.5	10,000
Nitrate	45 mg/l	rural	5 to 17	400,000
Bacteria[9]	0 *E. coli* / 100 ml < 5 or 10 coliform/100 ml	rural	10 to 36	1,000,000

(Data Source: Canada Council for Ministers of the Environment, 2002)

7 CDWG for arsenic is 10 µg/l effective 2006.
8 CDWG for TCE is 5 µg/l effective 2006.
9 CDWG for total coliforms is 0/100 ml effective 2006.

Considering the currently poor situation of many rural wells, the fact that most source-water protection initiatives are focused on municipal supply wells, and the prospect of further intensification of agriculture, it is apparent that rural groundwater quality requires increased attention. Mandatory testing of new wells and public education initiatives should be expanded and strongly supported. Examples of such initiatives are New Brunswick's Know Your H_2O program, which offered free microbiological testing to private well owners during 2006–2007; the "Mon puits, ma responsabilité" initiative from the Union des Producteurs Agricoles in Québec, which included public-awareness talks on groundwater, the distribution of signs used by farmers to visually identify more than 6,000 rural wells and promote awareness among farmers to keep minimum distances between their operations and wells; and, in Alberta, the recently established Working Well program held 19 workshops that reached more than 900 well owners in 2008, with plans to provide web access to fact sheets on groundwater.

3.4 IMPACT OF ENERGY AND MINING ACTIVITY

Canada is the world leader in the production of uranium and potash and is among the five leading countries for the production of about a dozen other minerals and metals. Canada is also likely to remain among the world's largest producers and exporters of energy, based largely on reserves in the oil sands. The rapid modernisation of China and India, among other countries, will greatly increase world demand for energy, metals and minerals, and thus production in Canada is very likely to increase. This will put greater demands on water and is likely to generate increasing volumes of extraction-related wastes.

The Energy Connection

Energy sustainability and security are closely linked to both surface water and groundwater. This is especially evident in the case study on oil sands development in Chapter 6. However, water from either surface or groundwater sources is also essential for other energy-extraction activities, for hydroelectric power development, for refining, for growing of crops and processing for biofuels, and for cooling purposes in thermal and nuclear electricity production. Indeed, the United States Department of Energy is beginning to link energy security to water security.

Oil Sands and Coalbed Methane: The potential environmental impacts of extraction of bitumen from the oil sands in Alberta will likely remain a controversial issue because of the extremely large area affected, the large volumes of groundwater and surface water being pumped, and the plans to continue extraction for several decades. While some oil sands are accessed through mining operations, much of the resource will be obtained through *in situ* operations. The long-term impact on groundwater is still insufficiently understood, given the likely magnitude of the

impact, but it is likely to be greatest for *in situ* operations, since they cover a much larger area and, at a majority of sites, use non-saline and saline groundwater to provide steam for their operations (Griffiths *et al.*, 2006). As noted in the oil sands case study (Chapter 6), there is a wide range of water use in various surface-mining oil sands projects, ranging from an average of about three barrels of water per barrel of crude oil for open-pit mining operations, to an average of less than half a barrel for *in situ* operations (Griffiths *et al.*, 2006).

Plans for the large-scale extraction of methane from coal seams (coalbed methane or CBM) in Alberta and British Columbia have been identified as a concern for groundwater resources. Methane is captured by drilling wells in target geological formations and depressurising the formations by extracting the groundwater to release the methane gas. The extracted groundwater and any associated brine would have to be disposed of to avoid contaminating surface water and other groundwater supplies.

Geothermal Energy: The objective of curbing greenhouse gas emissions is focusing attention on the potential of geothermal energy, the production of which is very likely to increase in Canada. Energy derived from heat in the Earth's interior can be exploited to generate electricity, in the case of high-temperature geothermal reservoirs, or to heat and cool buildings, in the case of low-temperature reservoirs. With today's very efficient heat pumps, almost any geological formation in Canada can be used as a low-temperature geothermal reservoir. (High-temperature geothermal reservoirs are generally located in tectonically active zones and are therefore much less common than low-temperature reservoirs.) Geothermal heating and cooling requires drilling boreholes in geological formations in one of two configurations: (i) a closed loop, where a cooling fluid is circulated in the tubing installed in the borehole, but where there is no groundwater extraction or injection; and (ii) an open loop, where groundwater is pumped from the geological formation via a well and injected back into the formation via another well after having travelled through a heat exchanger located at ground surface. There is some concern that geothermal systems can potentially degrade groundwater quality as a result of coolant fluid leaking underground from a closed-loop system or as a result of the water injected back into the geological formations from an open-loop system.

Mine Impacts

The main environmental problem associated with mining operations is the generation of effluents from waste rock and tailings which, if allowed to migrate freely, degrade the quality of surface water and groundwater. Current legislation ensures that acid mine drainage is controlled at active mines, but it is not always controlled at abandoned or orphaned mines. These sites will likely remain an issue for several

decades. Additional problems arise from chemical-leach operations, by which effluent waters are often contaminated with metals such as arsenic and require long-term retention in tailings ponds. Water table declines can also occur due to dewatering operations.

Impacts in the North

The increase of energy and mining production will affect northern communities, as exploration and exploitation of natural resources continue to migrate further north. Northern communities are already often faced with groundwater quality and quantity problems, and the impact on groundwater of increased energy and mining production in northern regions is largely unknown.

3.5 CLIMATE CHANGE

Observations of the warming climate and the results of predictive climate models concur that there will be continued warming of the lower atmosphere due to the increased net energy build-up (IPCC, 2007). "Consideration of climate can be a key, but under-emphasised, factor in ensuring the sustainability and proper management of groundwater resources"(Alley *et al.*, 1999).

The most recent report of the Intergovernmental Panel on Climate Change (IPCC) (Meehl *et al.*, 2007) dealing with global climate projections concludes that the intensity of precipitation events around the globe is likely to increase, and such a trend has already been observed in parts of Canada. High-intensity rainfalls, especially in spring, have been shown to be related to many water-borne infectious disease outbreaks in Canada from 1974 to 2001 (Schuster *et al.*, 2005). These outbreaks stem from surface waters or shallow wells with insecure wellheads, but the proportion of each has not been documented. There is a projected tendency for drying of the mid-continental areas during summers through increased evaporation, indicating a greater risk of droughts in those regions. Projected mean-temperature increases vary by region across Canada, from 2°C to greater than 6°C in the high Arctic, accompanied, in general, by less snow accumulation in winter, seasonal changes in river flow, greater evaporation rates, melting glaciers and thawing permafrost.

Unfortunately, owing to a lack of definitive studies, there are no specific groundwater conclusions in the IPCC report for the north temperate zones. The first linkages of this nature have just been developed but they have not been applied to climate change problems yet. The IPCC conclusions on surface hydrology nevertheless have important implications for groundwater recharge and withdrawal and are consistent with observations in some regions of Canada. The longer snow-free season

will produce greater seasonal evaporation, leaving less water to replenish the groundwater systems. This situation may be problematic for ecosystems dependent on the baseflow discharge of groundwater, and it may deplete groundwater supplies with strong surface water connections.

Implications of Climate Change for the Groundwater Cycle

Impact on Recharge: Groundwater recharge can occur from water stored in lakes, ponds, and wetlands or from soil water in porous materials. Both soil water and surface water storage are sensitive to a changing climate; indeed, surface storage is very sensitive to snowmelt and intense rainfall events. Larger snowmelt or intensive rainfall events will have greater likelihood of forming runoff from the catchment to surface water storage areas and thus likely result in less recharge. The March snowpack that feeds the spring melt in most of southern Canada has declined in recent decades (NRCan, 2008). Models project this to continue in future decades with more rain and less snow in winter months (NRCan, 2008). This often results in more river flow in winter, but lower flows in the critical summer and autumn months. Thus, contributions to low flows from groundwater will become increasingly important to protect watercourses and ecosystems in seasons of greatest demand. However, during periods of severe drought in the western Prairies (e.g., 2001–2002), which are expected to become more frequent, even deep groundwater levels have been observed to decline (e.g., SWA, 2008).

While snowmelt runoff is expected to decline, intense rainfall events may increase in many regions. Rising temperatures will have important implications for surface and ground temperature. Evaporation, which depletes both surface water and soil water storage, is expected to increase over Canada as climate change progresses. In all areas of Canada except the Prairies, evaporation has already increased since 1960 (Fernandes *et al.*, 2007). On the other hand, increases in ground temperature may lead to a decline in the occurrence of frozen soils in spring, which may lead to greater infiltration of snowmelt water.

In summary, a number of processes suggest that the spring recharge of groundwater from snowmelt might decline, except where frozen soils thaw due to warmer winters. Episodic summer recharges from intense rainfall events are likely to compensate only partially for this since such events contribute mainly to runoff. There is strong evidence that evaporation will increase further where water supplies are sufficient to support it. The combination of the changes in these hydrological processes will likely mean reduced groundwater recharge across Canada under climate change. This is consistent with observed trends, such as those examined by Rivard *et al.* (2003), who suggested decreasing groundwater recharge in eastern Canada. Furthermore, rising sea levels will pose an increasing threat of salt water intrusion into groundwater along coastal areas. A complete analysis of the potential effects

of climate change on groundwater recharge has not been accomplished for Canada.

Impact on Withdrawals: Groundwater withdrawals for watering gardens, irrigating crops and supplying water for ethanol plants from which biofuels are produced are likely to increase under climate change. Withdrawals will be largest in periods of drought, which may increase in length and spatial extent. Only a few studies "have focused on water supply and allocation schemes under climate change scenarios on regional and provincial scales" (de Loë *et al.*, 2007).

Impact on Baseflow: Since groundwater discharge to streams is generally considered proportional to recharge rates, it is expected that this discharge will decline as water tables drop. This discharge is important for maintaining low flows in many rivers and streams. A recent analysis by Ehsanzadeh and Adamowski (2007) suggests that climate change will bring declining low flows in many rivers across Canada, with modified trends from the Ottawa Valley eastward, in southern British Columbia and in southwest Alberta, and upward trends in the northwest, with little change on the Prairies and in southern Ontario.

Impact of Climate Change on Permafrost

Thawing of permafrost is having increasingly profound effects on watercourses, groundwater, land subsidence, and water infrastructure (Cohen, 1997). Areas most susceptible to landslides include ice-rich, fine-grain sediments on slopes close to bodies of water. Peat bogs are subsiding in the Mackenzie Basin as the underlying frozen soils thaw. While there is evidence from comparative aerial photographs of the decline in the peat plateau in the southern Northwest Territories (Bill Quinton, personal communication), the full impact of recent warming on thermokarst[10] development, as the permafrost degrades and ablates, has not been assessed. Rising groundwater temperatures in the discontinuous permafrost zone in northern parts of the western provinces indicate greater warming than the 1-to-2°C rise in air temperature since 1970 (Cohen, 1997). Thawing, and the accompanying land deformation, can disrupt surface and groundwater-flow systems. In some cases, water pipelines and fuel storage facilities can be disturbed (Cohen, 1997).

Warming at high northern latitudes in climate-model simulations is also associated with large increases in simulated thaw depth over much of the permafrost regions. A poleward movement of the southern extent of permafrost and a 30 per cent to 40 per cent increase in active-layer thickness is projected for most of the permafrost area in Canada, with the largest relative increases concentrated in the northernmost locations. Initially, soil moisture would increase during the summer (NRCan, 2008).

10 Thermokarst refers to a land surface that forms as ice-rich permafrost melts.

By late this century, when the thaw depth will have increased substantially, a reduction in summer soil moisture will likely occur.

In conclusion, both reduced recharge in much of southern Canada and increased water demand in a warming climate will affect groundwater levels in the coming decades. Much more research on this issue is urgently needed to ensure sustainability of supplies and to assess impacts on ecosystems. It is therefore appreciated that a recent report from Natural Resources Canada examines the preliminary scientific data on the likely impacts of climate change on water and other resources in Canada (NRCan, 2008).

3.6 SOURCE-WATER PROTECTION

Over the past two decades there has been a considerable effort, both in research and policy-making, to develop and implement preventative methods for limiting contaminants in groundwater. Although wellhead protection practices evolved earlier in the United States (typically through the 1990s), most Canadian provinces, with New Brunswick being a key exception, were less active (Nowlan, 2005). In Canada, groundwater management activities were being carried out sporadically at a local level, generally by municipalities that were interested in maintaining high-quality groundwater supplies so as to avoid the costly expenditures of addressing contaminated municipal supply wells, such as those incurred at Smithville and Elmira in Ontario. The situation changed in 2000 following the tragedy in Walkerton, Ontario, which led to a report calling for a revamping of water management in Ontario, with considerable focus on groundwater (O'Connor, 2002b). This prompted Ontario to develop a comprehensive *Clean Water Act*. Other provinces implemented similar programs, such as Alberta's Water for Life program, Québec's Water Policy update, Manitoba's Water Stewardship program, British Columbia's new water strategy program, and Saskatchewan's Watershed Authority.

Our technical ability to map capture zones and time-of-travel zones necessary for source water protection plans is still developing, and there is a tendency to err on the conservative side when delineating these zones. There have been remarkably few tests worldwide of the ability to accurately predict capture zones, and few predictions would claim accuracy greater than a factor of two, even in relatively simple hydrogeological environments. Because corrective action, including land purchases, may be required in protection zones where significant threats are identified, the size of capture zones can have major economic implications for municipalities and landowners. Since land-use decisions are contentious, often with large financial implications, methods to minimise the uncertainty in delineating municipal wellhead protection zones will be a priority (Box 3.1). Basin managers must decide on the right balance between, on the one hand, additional expenditures to acquire new data to better confirm subsurface conditions and, on the other, coping with the risk associated with using uncertain modelling analysis results.

Box 3.1: Transference of Technical Information to Decision-Making

A key outcome of effective groundwater management is land-use decisions that adequately consider impacts on the groundwater system.

A present-day concern in Ontario is that municipalities continue to spend significant funds in modelling groundwater systems only to have the final consultant reports stress the uncertainties associated with the understanding of the groundwater-flow system. This is, of course, appropriate from the consultant's perspective, since they wish to ensure that the uncertainty is properly conveyed so that decisions are taken with full knowledge of the limitations of the analysis. However, from the municipality's perspective, there is a desire for reliable knowledge subject to few, if any, technical caveats that are hard for non-experts to evaluate. The solution lies in the clear need for technical expertise at the municipal level to take the information derived from such studies and to translate it into an effective risk management framework so that the municipality's decisions benefit from the scientific analysis, including the inevitable uncertainty, that has been undertaken.

Consider the following situation that was submitted from Don MacIver, Mayor of the Township of Amaranth, Ontario:

"In our municipality, we have three groundwater studies by eminent hydrogeologists, all using exactly the same wellhead data sources from the Province of Ontario and the same models. After hundreds of thousands of dollars were spent for each study, three radically different maps were generated for various hydrogeological issues, especially the mapping of areas of contamination related to recharge areas."

"We intended to use these maps to restrict the spreading of biosolids and other developments on sensitive agricultural land. With three different sets of maps produced by experts, it was clearly apparent that the hydrogeology mapping of groundwater that we intended to select would not withstand the challenges to our proposed bylaws in court. Obviously the developers or biosolid spreaders would use the other sets of groundwater maps to support their case."

"Legal challenges would, as is the case in subdivision disputes, become nothing more than two hydrogeologists arguing in court at public expense. Therefore, we turned to the Conservation Authority and their hydrogeologists to resolve the three different studies and produce one set of values and maps that would withstand legal challenges, with their hydrogeology expert defending their analysis. The Municipality needs this type of technical and expert support that will withstand legal challenges in court."

(Source: Personal Communication, January 2008)

Groundwater presents a particular challenge as source water for First Nations communities because it is not clear, in the current absence of any regulatory structure addressing the safety of drinking water for First Nations (Swain *et al.*, 2006), who is responsible for assessing the quality of drinking water from wells that are used as individual water supplies on First Nations reserves. In addition, as is also the case for surface water, First Nations reserves generally lack the capability to influence source water protection in up-gradient areas located off-reserve. The practice of on-reserve source-water protection is only beginning to receive attention.

3.7 ECOSYSTEM PROTECTION

The intricate linkage between groundwater systems and surface streams requires further study. Many cold water streams receive at least half of their total flow from groundwater (Winter *et al.*, 1998). The research and work needed to ascertain groundwater contributions to the instream-flow needs of aquatic species are in their infancy. Hydrogeologists will need to work in partnership with fisheries biologists and other aquatic scientists to better understand the role of groundwater resources in maintaining aquatic ecosystem viability and integrity. The definition of instream-flow needs requires intensive research and agreement on procedures.

Since aquatic species have diverse requirements for cool water and other aspects of habitat, and require a sufficient streamflow during groundwater-fed low-flow periods, determining the groundwater contributions required to protect ecosystems is complex. There is often an attempt to express these requirements as instream-flow needs (IFNs). Several jurisdictions across Canada have different ways of calculating IFNs. Indeed, it has been estimated that there are currently more than 200 methodologies in use (Tharme, 2003). A concerted effort needs to be made to narrow the range of approaches to the problem if useful guidance is to be provided to groundwater managers to address this aspect of groundwater sustainability (Sophocleous, 2007). The provinces, notably Alberta and Ontario, have undertaken studies of this issue, but for the sake of developing nationally agreed-upon procedures, it would be desirable for the federal Department of Fisheries and Oceans to work with the provinces.

3.8 TRANSBOUNDARY WATER CHALLENGES

Disputes about water bodies that span or cross the Canada-US border can challenge sustainable groundwater management. Recent disputes involving surface water illustrate the variety of issues that might arise, such as the introduction of alien species in the Garrison Diversion project and the Devils Lake disputes between Manitoba and North Dakota; the transboundary pollution in the Flathead River originating from a proposed coal mine in British Columbia and flowing into

Montana; the mine and energy development proposals that threaten wilderness areas in the Taku and Iskut-Stikine watersheds in British Columbia and Alaska; and the continuing pollution and water-level problems in the Great Lakes (IJC, 2008).

To date, transboundary groundwater tensions have been rarer than surface water disputes in Canada-US relations. This is in sharp contrast with the complex and pressing issues of groundwater sharing along the more populous and arid United States-Mexico border, involving at least 17 shared groundwater basins (Hall, 2004). The case study on the Abbotsford-Sumas aquifer (Chapter 6) is one example of a groundwater issue that has generated considerable attention but has so far not abated the nitrate contamination that migrates from Canadian sources to American wells. Pressure on aquifers in the Great Lakes basin will also gain prominence in the coming years as climate change affects lake levels and recharge patterns (see also Chapter 6).

Institutional Mechanisms

The existing institutions involved in transboundary water management have not historically focused on groundwater, although there are signs that groundwater is gaining prominence as an issue that needs attention. The International Joint Commission (IJC) is expected to issue a comprehensive report on groundwater in the Great Lakes region in 2009. The Great Lakes Charter Annex and accompanying set of agreements between two Canadian provinces and eight American states addresses groundwater extraction through its general prohibition on large-scale diversions from the Great Lakes basin.

In most cases, transboundary Canada-US water disputes are resolved through cooperative mechanisms and information sharing through action bodies such as the Abbotsford-Sumas International Aquifer Task Force, the Great Lakes Council of Governors, and the extensive bi-national cooperative framework of the IJC. However, unilateral state action has prevailed over a negotiated diplomatic solution in the case of the Devils Lake discharges into the Red River basin. (After initial overtures to Canada were not accepted, the United States refused to allow the dispute to be submitted by a reference to the IJC.[11]) There are other cases in recent years in which provincial and state governments have taken a lead. This trend is illustrated by the Great Lakes Annex Agreement, where the national governments allowed the adjacent states and provinces to negotiate an agreement. For the upcoming renegotiation of the Columbia Basin Treaty, the Government of British

11 The United States and Canada have a practice of referring matters to the IJC only through joint referral, and never through a unilateral reference, though the Boundary Waters Treaty provides that disputes over transborder water pollution may be referred to the IJC either unilaterally (Article IX) or jointly (Article X).

Columbia, rather than the Government of Canada, has been building public understanding concerning the issues at stake and has established the Columbia Basin Trust to promote the applicable science and public education.

Bulk Exports of Water

There continues to be public uncertainty about the adequacy of Canadian laws to protect water from bulk exports. Although all the provinces, with the exception of New Brunswick, have passed legislation that forbids the bulk export of water, and although federal law prevents exports from boundary waters, laws might nevertheless be changed by a future legislature. Some experts have therefore proposed a new federal 'Model Act' to address the perceived deficiencies in the Canadian legal framework that governs water exports (CWIC, 2008). While the debates and bulk-export proposals usually involve surface sources (e.g., Gisborne Lake in Newfoundland and Labrador), groundwater is, in principle, not immune from diversion and bulk removal.

3.9 CONTAMINATED SITES AND REMEDIATION

Contaminated sites are areas that have been polluted as a result of human activity to a degree that creates a risk to health or the environment. The issue of contaminated site clean-up illustrates the complexity of sustainable groundwater management and the extent of coordination required among different jurisdictions.

It has been estimated that there are over 100,000 sites in the United States contaminated with chlorinated solvents (Box 3.2). In Canada, less effort has been put into identifying contaminated sites, although current estimates indicate that there are approximately 5,000 sites on land owned or controlled by the federal government and 28,000 sites on non-federal properties (ECO Canada, 2008). While national attention has been focused on a few of these, such as the Valcartier military base in Québec and the Elmira and Smithville sites in Ontario, they are only symptoms of a much greater problem. In 2000, the City of Barrie, as a precautionary measure, removed one of 12 supply wells from service because its trichloroethelyne (TCE) concentration had reached 23 μg per litre, approximately half of the maximum allowable levels for drinking water. The source of the TCE remains uncertain (City of Barrie, 2003).

The problem is exacerbated by the fact that drinking-water limits for many industrial chemicals are very low, of the order of five μg per litre for several chlorinated solvents, for example, and thus relatively small discharges can contaminate very large volumes of water. In addition, because of the relatively

low solubility of many of these chemicals, small sources can persist for long periods of time. Thus, a small release by a single dry-cleaning establishment or gas station could result in a major groundwater contamination problem. With the growing awareness of the problem and the potential liability, commercial operations have become much more conscientious in their use of hazardous chemicals, and thus the incidence of releases to the environment has decreased substantially. Nevertheless, the thousands of legacy sites that remain represent a continuing threat to groundwater quality.

Management of contaminated sites in Canada is risk-based, with standards and practices varying from province to province. It is required that wellhead protection zones be mapped, that potential sources of contamination within these zones be identified, and that the level of risk to the water supply be determined. Where significant risk is identified, corrective action is required. The process presents considerable challenges to municipalities. First is the uncertainty associated with the mapping of wellhead protection zones. Second, historical records of chemical use are far from complete and, recognising that small historical sources can still cause major problems, it is likely that attempts to identify potential sources of contamination will also be far from complete. Managing the risk presents a further challenge. The obvious choices are: to select a replacement supply, such as surface water; to move the municipal well to a different aquifer or location; to remediate the source and associated contaminant plume, should one exist; or to treat appropriately at the wellhead the water drawn from the supply wells. Methods for remediating contamination by industrial chemicals, particularly chlorinated solvents, after they have entered the subsurface, are costly. Wellhead treatment can provide an engineered, though often complex, solution, but it is often politically unpopular and is costly in its own right. In some cases, the only cost-effective solution is to find an alternative water supply.

Deterioration of groundwater quality as a consequence of yet-unidentified contaminants is an emerging issue. Over the past few decades, the soluble constituents of petroleum products and chlorinated solvents (and other industrial organic compounds) have been identified as contaminants, followed more recently by MTBE (an additive to gasoline, replacing lead) and perchlorate. While MTBE has been a significant issue in the United States, it has had only minor use in Canada, and a recent survey by Environment Canada indicates that perchlorate is not a significant problem in Canadian groundwater (Environment Canada, in preparation). Based on the record of the past thirty years, it must be anticipated that as-yet-unidentified chemicals will emerge as significant threats to water quality.

Box 3.2: Contaminated Site Clean-up

There is no overall federal law that requires sites with contaminated groundwater and soil to be remediated. Different federal agencies and coordinating bodies work on the issue of contaminated sites. The chief regulatory requirements are found in provincial laws. The main qualification for including a site in the federal inventory of contaminated sites is that there is a concentration of a substance in the soil or groundwater (usually a petroleum product or a metal) that is higher than 'expected' for that region of Canada. In 1996, the federal Office of the Auditor General estimated that there were approximately 5,000 contaminated federal sites in Canada, and the 2004 federal budget updated this number to approximately 6,000 sites, with an associated clean-up cost in excess of $3.5 billion.

Provincial laws require the clean-up of contaminated sites that are not on federal land. Usually the statute provides that provincial environmental officials may order investigation and clean-up of contaminated sites where statutory triggers occur, such as discovery of an adverse effect or off-site migration of contaminants. These laws vary significantly, as noted in a report on federal, provincial, and territorial standards, guidelines, and regulations used to establish remediation limits for key contaminants (NB DoE, 2005).

One consequence of the lack of national coordination is that records of contaminated sites and remediation activities across Canada are not easily accessible. One common practice is to extrapolate statistics on these issues from United States sources to create estimates of the Canadian situation. It is estimated, for example, that over 100,000 sites in the United States are contaminated with chlorinated solvents (USEPA, 1999). Furthermore, considering all hazardous-waste sites, the United States National Academy of Sciences (NRC, 1994) estimated that there could be between 200,000 and 300,000 hazardous-waste sites in the United States and that costs of remediation could be of the order of $750 billion. There are likely thousands of chlorinated-solvent sites in Canada as well, but records are not readily available, and specific breakdowns for nuclear, military, and landfill sites are also lacking.

There are several key differences in the regulatory and remediation situation in Canada, compared with the United States. Large American environmental restoration programs such as Superfund, and remediation research and technology development programs on the scale of, for instance, the Strategic Environmental Research and Development Program, do not have equivalents in Canada. Regulatory powers, as well as the consequences of non-compliance, are significantly greater in the United States. Finally, the approach in Canada can be broadly described as a risk-based approach, rather than an approach based on prescribed numerical standards for groundwater contaminants. While standards and practices vary from province to province, the key feature of the Canadian risk-based approach is that remediation or treatment is triggered only if

there is an identifiable on-site or off-site risk. In this context, risk refers to the likelihood of exposure of a hypothetical human or ecological receptor to specific contaminants at levels exceeding maximum acceptable concentrations. Sites are typically assessed in a phased approach with an initial option of remediation to generic criteria based on projected land use or to site-specific criteria that are based on a more detailed site-specific risk assessment. In short, even if contamination at a given site exceeds a specific standard level, if there is no risk to a receptor or end-user and no migration off-site, resources are focused instead on sites that pose more significant risks. Furthermore, site remediation in Canada is typically triggered by a change in use, such as the offer of a property for sale or an application for rezoning.

Pharmaceuticals and personal care products have lately become an issue of concern, particularly in surface water (Kolpin *et al.*, 2002). The primary source of pharmaceuticals in the environment appears to be treated sewage effluent discharged to surface water. Potential pathways to groundwater could include recharge from surface water bodies, artificial recharge and septic systems. Though still in the early stages of investigation, the only reported occurrences of pharmaceuticals in Canadian groundwater have been associated with septic system effluents (Carrara *et al.*, 2008). Currently, little is known concerning the fate and transport of these chemicals in subsurface environments.

Waste Management Practices

Recognising that contaminated sites represent the consequences of past waste management practices, current disposal procedures are relevant to long-term groundwater sustainability. There is an increased awareness about the health and ecosystem impacts of municipal and industrial wastes, and the provincial, federal, and international legislation controlling the procurement, ownership, transportation, and disposal of these substances has been effective in reducing releases to the environment. Continuing efforts are nevertheless required to ensure that contaminants remain well-regulated, that emerging contaminants are identified, and that disposal sites are judiciously located to minimise damage to groundwater regimes and constructed and maintained in compliance with a high standard.

Emerging waste streams include carbon sequestration and radioactive waste. Carbon sequestration captures carbon dioxide and pumps it underground for long-term storage as a measure to mitigate the atmospheric build-up of greenhouse gases. Potential groundwater risks include the gradual migration of carbon dioxide into shallow aquifers and resulting changes in the groundwater chemistry and overall water quality, as well as the displacement of deeper native brine and the triggering of changes in shallow groundwater-flow regimes (IPCC, 2005). Groundwater-flow

patterns are important to siting and designing radioactive-waste disposal facilities in a way that ensures the longest possible travel time for potential radionuclide emissions from containment structures to possible receptors.

3.10 CHANGING PUBLIC ATTITUDES

Management policies that ensure long-term sustainable groundwater use in Canada will have to be robust, not only with respect to the emerging issues that have been highlighted in this chapter, but also in the face of possible changes in public attitudes that may accompany future developments. The following is a brief enumeration of relevant issues where public attitudes are particularly important and which, if attitudes were to change significantly, could enhance or undermine future political support for more sustainable groundwater management.

The Sustainability Ethic: The current public discourse on sustainable development is taking place during a period of increasing political support for careful stewardship of our natural resources. However, the continued prevalence of a strong environmental ethic cannot be taken for granted. There have been many swings of the pendulum in the past, and there will likely be more in the future. Support for environmental protection tends to wax and wane, being stronger in good economic times than in bad, and during periods of social activism rather than more laissez-faire periods. The boom and bust of the economic cycle has a very significant impact on public psychology and therefore makes it difficult to maintain stable long-term policies in support of sustainable development (Homer-Dixon, 2001).

Public Funding Priorities: Attitudes toward public spending are particularly important, whether driven by the economic cycle or not. One of the clearest messages the panel received from individuals who responded to the call for evidence was a demand for more funding for hydrogeological studies. Respondents from both the public and private sectors thought that government support for research, regulation, and public education on groundwater sustainability matters was inadequate. Of course, more funding for sustainability-oriented environmental policies would ultimately lead to one of two outcomes: either less funding for other government programs or higher levels of taxation. Increased taxation is never popular with either taxpayers or legislators; therefore, policies designed to ensure sustainable use of groundwater will always be at risk of fluctuations in the level of financial support from the public sector.

Evidence-informed Decision Making: Policies designed to encourage sustainable use of groundwater ought to be based on sound scientific principles and should foster the use of the most up-to-date and innovative technical and socio-economic instruments to meet policy goals. Therefore, any erosion of public trust in the methods of science and evidence-based policy analysis could undermine sustainable-use objectives.

The Security Imperative: The rise of international terrorism has led many to fear for the safety of drinking-water systems and other vulnerable infrastructure such as dams and levies. These fears could lead to huge public expenditures to improve system security, a priority that would far eclipse attention to the studies needed to assess groundwater sustainability. At the same time, lack of faith in public water systems could lead to greater reliance on personal supply systems based on locally controlled groundwater pumpage, thus increasing withdrawals that are hardest to assess and control.

Management of Conflict: It is possible that groundwater sustainability policies could lead to limitations on use that cause conflicts between competing water consumers, or between consumers divided on the issue of ensuring the maintenance of groundwater discharges for the protection of the ecosphere. It is likely that there will be considerable political pressure from all sides on this front in future years, and managing such conflict is one of the most difficult challenges facing resource-use decision-makers. The key to successful management of conflict is creating dispute-resolution mechanisms that come into play before conflicts erupt.

REVIEW OF KEY POINTS

Population Growth and Urbanisation

- Coordination between provincial and local governments is vital because the stresses from urban growth and associated infrastructure needs are felt directly at the local level, while regulatory authority is shared between both levels of government.

Impact of Agriculture

- While best management practices for minimising contamination of groundwater could be more widely adopted by agricultural producers, there are grounds for optimism that the risk of nitrate contamination could be reduced, although success to date has been limited.

Rural Groundwater Quality

- Considering the currently poor quality of the water in many rural wells, the inadequate monitoring programs and inconsistent educational programs that promote and assure rural well-water quality, the fact that most source-water protection initiatives are focused on municipal wells, and the prospect for further intensification of agriculture, it is apparent that rural groundwater quality requires increased attention, including community-based outreach programs on water wells and aquifers.

Impact of Energy and Mining Activity

- Energy sustainability and security are closely linked to both surface water and groundwater. More specifically, the long-term cumulative impact on groundwater of oil sands development is still insufficiently understood, given the likely magnitude of the impact, but it is likely to be greatest for *in situ* operations, since they cover a much larger area and, at most sites, use groundwater (either saline or non-saline) to provide steam for their operations.

Climate Change

- Climate change will affect groundwater levels in coming decades through reduced recharge in much of southern Canada, increased water demand in a warming climate, decreased synchronicity of recharge and withdrawal timings, and increased decadal variability of recharge and withdrawal as drought cycles intensify. Much more research is urgently needed to ensure sustainability of supplies and to assess impacts on ecosystems.

Source Water Protection

- The technical ability to map capture zones and time-of-travel zones necessary for source water protection plans is still developing. The tendency to err on the conservative side when delineating capture zones increases their size, and this can have major economic implications for municipalities and landowners.

Ecosystem Protection

- The research needed to ascertain the groundwater discharge requirements for aquatic species is in its infancy. The definition of instream-flow needs from groundwater requires intensive research and agreement on the procedures for establishing these needs.

Transboundary Water Challenges

- The existing institutions involved in Canada-US transboundary water management have traditionally not focused on groundwater, although there are signs that groundwater is gaining prominence as an issue that needs attention (e.g., the pending report of the IJC on groundwater in the Great Lakes region).

Contaminated Sites and Remediation

- Commercial operations have become much more conscientious in their use of hazardous chemicals, and thus the incidence of releases to the environment has decreased substantially. Nevertheless, the thousands of contaminated legacy sites that remain pose a continuing threat to groundwater quality.
- Deterioration of groundwater quality due to unidentified contaminants is an emerging issue. For example, little is known concerning the fate and transport of pharmaceuticals from treated sewage effluent into subsurface environments. It must be anticipated that as-yet-unidentified chemicals will emerge as significant threats to water quality.

Changing Public Attitudes

- Long-term management of groundwater resources may have to take into consideration possible changes in public funding priorities, waxing and waning of the sustainability ethic, swings in the level of public trust in science and government, and public concerns over water security and the management of water-based conflicts.

4 Scientific Knowledge for the Sustainable Management of Groundwater

This chapter addresses the fundamental understanding needed to inform the management of groundwater for sustainability. The focus here is on the behaviour of the groundwater system in response to natural and human-induced influences. This knowledge is required for any science-based approach to sustainable management that has the goals of protecting the quantity and quality of groundwater as well as its contribution to the viability of ecosystems.

4.1 THE ANALYSIS OF GROUNDWATER-FLOW SYSTEMS

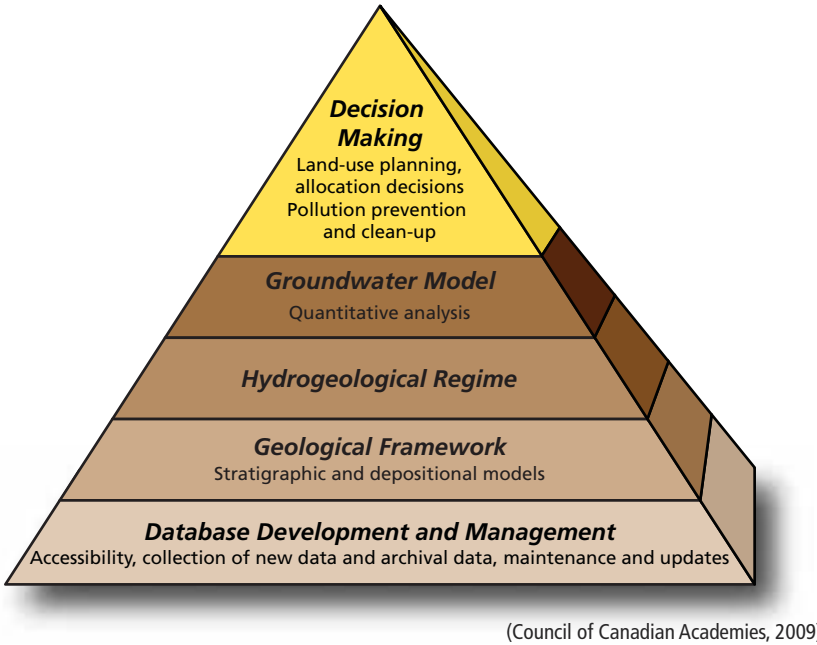
Groundwater studies can occur at many scales, ranging from site-specific to regional; therefore, it is necessary to establish the appropriate scale for sustainable management and to tailor the science to that scale. While it is convenient to suggest that studies be conducted at the watershed scale, boundaries of watersheds and groundwater-flow systems may not fully coincide. Groundwater studies must therefore aim to address the flow system, from area of recharge to area of discharge. This flow-system scale, which is often referred to as the groundwater catchment scale or groundwatershed, forms the backdrop to this discussion.

Flow-system analysis is based on the effective use of a suite of conceptual and quantitative tools and methods, with the forecasting of long-term impacts generally being the goal. There are four investigative components that, when managed in an integrated manner, should lead to credible and defensible interpretations of groundwater-flow systems. This, in turn, will enable decision-making on issues pertaining to groundwater and land use that contribute to the sustainable utilisation of the resource. The four components listed below form a scientific framework for the sustainable management of groundwater. The Oak Ridges Moraine, Region of Waterloo, and Big River case studies in Chapter 6 illustrate the application of this four-component framework:

- A comprehensive geological, hydrogeological, and hydrological database that supports the following components of the framework;
- An understanding of the geological framework through which the groundwater flows;
- A quantitative description of the hydrogeological regime; and
- An appropriate groundwater model.

The components of the framework are illustrated in Figure 4.1, shown as a pyramid to emphasise their connection to the decision-making process (Kassenaar and Wexler, 2006; Sharpe and Russell, 2006). The foundation of this framework is a comprehensive base of data that describes the relevant geological environment, as

well as the hydrogeological parameters and dynamic elements (e.g., precipitation and evaporation; surface water measurement; withdrawals; and land-use changes) that determine groundwater behaviour. A discussion of data collection and management issues is deferred to Section 4.4. The following discussion focuses on the other three components of the framework. Particular emphasis is placed on the fourth component, groundwater modelling, of which the other three components constitute integral parts.



(Council of Canadian Academies, 2009)

Figure 4.1
Science requirements for groundwater sustainability.

The Geological Framework

The development of a sound understanding of the subsurface geology is one of the most critical steps in managing groundwater (Sharpe and Russell, 2006). This involves understanding the geological processes responsible for the original deposition of the rock or sediment framework. Secondary processes that can influence groundwater movement through this framework — such as tectonic activity and metamorphism that might, for example, fracture the geological framework or reduce the permeability — must also be considered. This understanding of the geology enables groundwater managers to estimate aquifer configuration and extents, thereby providing guidance for more effective characterisation efforts and enabling improved input to groundwater models

and improved predictions of groundwater flow-system dynamics. Since drilling is expensive and information cannot be collected everywhere, and because parameters that control groundwater movement can vary considerably over short distances, an understanding of the geological setting provides a defensible and cost-effective means of interpolating hydrogeological measurements across broad areas. Geophysical methods (e.g., seismic reflection, electromagnetic ground-penetrating radar, etc.) are increasingly being used to assist in characterising the subsurface geological framework and, where conditions are suitable, have proven to be a cost-effective alternative to more costly drilling programs.

The Hydrogeological Regime

The next requirement is to develop an understanding of the groundwater-flow system through analyses of hydraulic head measurements, pumping test results, and other relevant hydrogeological data. These types of studies allow for the quantification of the hydrogeological environment and enable hydrogeologists to define, for example, aquifer extents and thicknesses, confining-layer extents and thicknesses, porosity and hydraulic conductivity distributions, and other elements of the hydrogeological regime. With these quantitative estimates in hand, calculations can be made of hydrogeologically important entities such as flow velocities, bulk-flow rates, water budget components, and discharge rate to streams.

Groundwater Models

The final element of the four-component framework is the construction and use of an appropriate hydrogeological model. Groundwater flow and transport models are useful tools for supporting decision-making because they allow hydrogeologists to probe the potential impacts of land-use and pumping changes on the overall groundwater-flow system. Furthermore, the very development of these models necessitates the systematic interpretation of information from a variety of sources in order to develop an integrated understanding of groundwater systems. Within this framework, groundwater-flow modelling plays an integrative role; when model predictions are tested, the results frequently lead to re-evaluation, reconsideration, and quantitative adjustments of the understanding of the hydrogeological regime. Through an interactive process among the four components of the study framework, a calibrated model is developed in which results, such as hydraulic head patterns and subsurface flow rates, are consistent with measured values in both space and time. Once calibrated, the model can then used to forecast the effect of imposed, cumulative stresses, such as increased pumping from wells, on the overall groundwater-flow system.

Groundwater models have benefits that extend beyond simply predicting groundwater movement and contaminant transport. Properly calibrated models help to prioritise

data-collection activities and provide a method for forecasting future conditions under alternative development scenarios. They provide the most sophisticated available method to evaluate the cumulative impacts that arise when there are many pumping sites or land developments.

Hydrogeological models are mathematical solutions to the equations that describe groundwater flow and contaminant transport. Several types of models exist, ranging from very simple to very complex. Some simple models are based on analytical solutions that require many simplifying assumptions. Another type of simplified model involves drawing a flownet for an aquifer, which is a graphical solution to the groundwater-flow equation. Simple models can be useful, but the most commonly used models for prediction are based on numerical solutions of the flow or transport equation, and it is this type of model that is under discussion here.

Depending on the scope of the investigation, the model may consider only the groundwater-flow system, or it may attempt to predict a more comprehensive response that integrates groundwater and surface water, or even atmospheric conditions. These latter approaches can be particularly important in ecological studies where there is a strong connection between groundwater and surface water, or where the goal is to assess the effects of climate variability and long-term change. Once a reasonable understanding of the physical hydrogeological system has been achieved, it is also possible to superimpose quality issues, with concentration and transport parameters as input to contaminant-transport models.

Contaminant Transport Models

Contaminant transport modelling is frequently undertaken to determine the time of arrival of known contaminants at sensitive receptors; to assist in the design and management of groundwater remediation activities; to help anticipate quality changes that could result from proposed changes in land use; and, increasingly, to delineate capture zones and time-of-travel zones around pumping wells.

While groundwater-flow models are the basis for both regional flow modelling and contaminant-transport modelling, there are major differences in their approaches. In regional flow modelling, the important output is usually quantity, with only minor regard for the source or the path followed. In this case, parameters such as hydraulic conductivity, averaged over a substantial volume of the subsurface, may be sufficient. For example, although a particular aquifer may be known to be heterogeneous with hydraulic conductivity values varying over two or three orders of magnitude, it may well be sufficient to assign a single ‘average’ hydraulic conductivity to the entire aquifer, such as that which might be determined from a large-scale pumping test.

On the other hand, for the purpose of contaminant transport modelling, the primary output from flow modelling is the velocity field, from which estimates of time-of-travel can be derived. From the foregoing example, and assuming that the velocity is roughly proportional to the hydraulic conductivity, velocities within the aquifer could vary by a factor of 100 to 1,000 and locally could be orders of magnitude different from the velocity that one would be calculated on the basis of a spatially uniform hydraulic conductivity. Thus, for contaminant-transport modelling, very detailed stratigraphic information is required, paying particular attention to the high-permeability zones and their interconnectedness.

Transport models superimpose various processes on the velocity field, depending upon the contaminant of concern. For non-reactive contaminants such as chloride, this would be limited to hydrodynamic dispersion; however, for reactive or biodegradable solutes, reactive processes of increasing and considerable complexity have been incorporated. It is important to recognise that for each process included in the transport model, the geologic materials must be characterised with respect to at least one additional transport parameter. This can add substantially to the efforts required for site characterisation, to the computational requirements, and ultimately to the level of uncertainty in the results.

Verification and calibration can present further difficulties in contaminant-transport models. In regional flow models, there are various measurable quantities against which simulated results can be compared; water levels and groundwater discharges to streams are the most common. The normal outputs from contaminant-transport models are concentration distributions. Should contaminants or contaminant plumes already be present, there is a basis for testing model results. In many applications however (particularly models of the future effects of changing land use or delineation of capture zones and time-of-travel zones), contaminants are not present initially and thus there is no reasonable basis for model calibration; this leads to considerable uncertainty in predicted results, or to a cautiously large delineation of the capture zones.

We turn now to a more thorough discussion of the role of models in groundwater management and decision-making. This will be followed by an extensive assessment of the data inputs that exist and the data still required to enable more effective groundwater management.

4.2 THE ROLE OF MODELS IN GROUNDWATER MANAGEMENT

Models are important tools for groundwater management, but are generally under-utilised in Canadian jurisdictions; however, it must be recognised that not all hydrogeological issues require a complex modelling solution. The first question

to be considered in any hydrogeological investigation is whether a model is appropriate to address the issues under consideration, and whether there is sufficient understanding of the system to justify the use of a model. Model complexity should be scaled to the demands of the catchment. In simple situations, a conceptual model coupled with reliable data may be sufficient for managing groundwater sustainably. In larger or more-complex basins, numerical modelling will undoubtedly be necessary. Numerical models are almost always needed to fully quantify the cumulative impacts of multiple wells or sources of contaminant loading. Proper assessment and accounting of cumulative impacts is a prerequisite to the sustainable use of the resource.

Models don't make decisions, people do. When used appropriately, groundwater models can be useful tools to assist in making decisions in support of sustainable groundwater management. However, both the input and the output from a model must be subject to analysis before a final decision is made. In addition, it is essential that groundwater modellers have a suitable level of training and experience in order to effectively develop and run the model and interpret its results in the context of the particular catchment and the issues being analysed (Gerber and Holysh, 2007).

Model-Use in Management Decision-Making

As noted in Section 3.6, jurisdictions in Canada now clearly recognise the need for source water protection as the first barrier to protecting drinking-water quality. More generally, the land-use planning process must consider the long-term availability and vulnerability of local groundwater resources and the potential for cumulative impacts. Where they are available and in use, the products of hydrogeological studies — including aquifer mapping, characterisation, and modelling — have been effective in integrating groundwater concerns into the land-use management process, provided that the groundwater investigations precede the land-use development. The groundwater studies necessary to provide this knowledge are best undertaken on a catchment-scale and with a flow-systems approach that requires detailed knowledge of recharge, sustainable yield and discharge conditions. Wellhead and source-water protection plans are common applications of this approach.

Where conflicts over water use develop, modelling of alternative allocations can often help to clarify the future scenario that optimises social well-being and ecological health. An example of this approach is provided in the Big River basin case study in Chapter 6. This case study demonstrates how the existence of a well-defined model, built on clear assumptions and fully documented hydrogeological interpretations, can aid in creating a trustworthy and transparent base of evidence for conflict resolution.

Models in the Public Sector

Looking forward, as provincial authorities increasingly seek sustainable groundwater allocation strategies, their modelling capacity must improve in order to develop, understand and operate authoritative catchment-scale groundwater management models. These catchment-scale models should ideally integrate and support ongoing local-scale private sector groundwater studies.

The use of models by provincial regulatory agencies varies from province to province; in most provinces it lags behind state-of-the-art application. In Ontario, under the new *Clean Water Act*, the use of groundwater models is progressing very rapidly, and frequently seems to take place without the time necessary to fully develop and use the critical thinking that must be an inherent part of hydrogeological modelling analysis. It is important in such cases, where tight timelines are a key factor, that the documentation of the uncertainties in the modelling results be at the forefront so that decision-makers can weigh all the evidence.

The panel strongly endorses the development of effective modelling platforms by government agencies to aid in their assessments of groundwater sustainability. Situations that lead to the most effective uses of numerical groundwater models are situations in which the requirement of the model to provide sound hydrogeological input to decision-makers is successfully balanced with the need to provide transparent documentation of details of the model that highlight both its strengths and its weaknesses.

In reviewing the responses from public agencies to the Call for Evidence, it is clear that jurisdictions vary widely in their scientific approach to groundwater sustainability assessment. In jurisdictions where the appropriate agencies have apparently not instituted the four-component approach recommended here, or its equivalent, the roadblocks appear to fall into four categories: (i) lack of a mandate from above, (ii) lack of sufficient funding to carry out such a program, (iii) lack of people or expertise to design and carry out the necessary field measurement programs, hydrogeological interpretations, and computer modelling exercises, and (iv) lack of sufficient available data.

Documentation

Given the amount of data and geological understanding that typically are used to develop a groundwater-flow model, rigorous documentation of the model development process is critical. Such documentation should include the data used to populate the key parameters across the model domain, as well as any changes made to these parameters as the model evolves. Transparency in the modelling process is needed to allow different practitioners to readily run the model. Documentation of the lessons learned in the model journey also needs to be carefully

set down so that future modellers can build on any insight developed. This also allows for a prioritisation of the key datasets needed to improve the overall hydrogeological understanding.

Uncertainty and Risk Management

Numerical models do not provide unequivocal answers to issues in groundwater management; rather they provide simulated results that must then be further considered in the context of providing practical solutions to the problem at hand. It is therefore imperative that model output uncertainty be carefully explained by modellers to decision-makers.

The routinely used groundwater-flow and contaminant-transport models generally provide theoretically accurate representations of the fundamental physical and chemical processes that are active in most hydrogeological situations. However, the confidence in the geological and hydrogeological understanding on which predictions are based depends on the availability of the data in the area of interest, and on the interpretations of this data. There may be issues with respect to the quality and density of data points, and also with the types of data; for example, data on the geologic material, groundwater levels and precipitation are necessary across the area being modelled, and streamflow data are necessary at key junctures within the study area.

In practice, the accuracy of models can be affected by a number of sources of error and uncertainty, largely stemming from the fact that groundwater is hidden from sight and its behaviour is less observable and more uncertain than is the case for surface water. In particular, the accuracy of modelled predictions is affected by the following:

- Errors, gaps, and uncertainties in the conceptual geological or hydrogeological understanding that is developed for the groundwater system under study. Such uncertainties include, for example, the continuity and effectiveness of aquitards as barriers to flow; the connectivity of multiple aquifers; the influence of facies changes on the extent of aquifers and aquitards; and the hydraulic role of joints and faults in fractured rocks and in solution channels in carbonate rocks. Incomplete data can often be interpreted in a number of equally plausible yet conflicting ways.
- Errors and gaps in the data used to develop a quantitative understanding of the hydrogeology. For example, uncertainty in the three-dimensional configuration of hydrogeological parameters, such as hydraulic conductivity, will be greatest in areas where logged drill holes are sparse, and other types of geological and geophysical mapping have not been carried out.
- Errors in calibrating the groundwater model to the flow system in question, perhaps due to a paucity of hydraulic-head data, spatially, vertically or temporally.

- Uncertainty surrounding the applicability to the study area of the fundamental groundwater-flow and transport equations underpinning the computer models, perhaps due to the presence of fractured or solutioned rocks rather than porous sediments.

As a consequence of uncertainty, modelling needs to be viewed not as a one-time effort but as an ongoing process. As additional field data are collected and as understanding is gained over time about the conceptual and quantitative nature of the hydrogeological regime, the model needs to be periodically adjusted and recalibrated. In all cases where reliable field-based observations are available, these measurements should supersede numerical-model-simulated output and the model must be amended to reflect the field data. As the information base improves, the uncertainty in model predictions will be concomitantly reduced. Furthermore, the model results can be used to highlight the parameters and areas of greatest uncertainty and thus guide the location and details for new drilling and monitoring. This reduction in prediction uncertainties, as data and experience accumulate, gives rise to a 'living model' approach that is well suited to an adaptive management philosophy. Lessened uncertainty in hydrogeological prediction leads to less risk in the making of groundwater management decisions. Early decisions will thus reflect a precautionary approach, but as uncertainty narrows, management decisions can be made with greater levels of confidence. When decisions must be made, the most recent modelling results are used to inform such decisions. If uncertainty is high, it is likely that a risk-averse course of action will be selected. If uncertainty is low, a more cost-effective path forward may be possible. This 'living model' concept is similar to that used for municipal official plans. Such plans are generally reviewed and updated on a five-year cycle, but they can usually be amended at any time if new or additional information merits. However, on any given day the current plan is still used as the basis for making decisions.

There is no general criterion to define how accurate a prediction should be or, equivalently, how small the uncertainty needs to be before it is considered acceptable. From a decision-making standpoint, this is an economic issue. Additional data should be collected until such time as the cost of collecting them exceeds the benefits that could be realised from a better or less-costly decision. For example, the level of uncertainty that is acceptable for a groundwater allocation decision might be unacceptable for a contaminant remediation decision. Defining the acceptable level of uncertainty should therefore relate to the context of sustainability for a given situation, and the uncertainty in science must be captured in all subsequent decisions with a formalised risk-management process. Establishing procedures and standards in this respect may facilitate the contracting and administration of risk-management and modelling expertise by local agencies.

4.3 THE FRONTIERS OF MODEL DEVELOPMENT

The multiple goals of sustainable groundwater management may require sophisticated models that can (i) better capture the interaction between groundwater and surface water; (ii) integrate hydrogeological phenomena with economic variables; or (iii) provide a detailed account of contaminant transport. The development and refinement of such models are active areas of research in which Canadians continue to make significant contributions.

Integrated Groundwater-Surface-Water Models

Numerical models used in hydrogeology have generally focused on groundwater only and neglect or greatly simplify interactions with surface water. Renewed interest in the simulation of all components of the water cycle has recently led to the development of numerical models for integrated surface-water and groundwater flow. These models are more complex than groundwater-only models and they will likely play a bigger role in the future in predicting groundwater availability. In order to take advantage of this developing class of models, agencies undertaking monitoring activities should seek integrated hydrological monitoring systems that capture and integrate climate, surface water, groundwater, and extraction or consumption data.

Contaminant Transport Models

There is ongoing research and development in contaminant-transport modelling. One area of research concerns multispecies contaminant-transport models with reaction networks. These transport models are designed to provide more accurate representations of potentially very complex chemical and biological reactions that occur in groundwater, and that affect a multitude of contaminants. Models are also currently being developed to simulate contaminant transport coupled with other physical processes, such as variations in fluid density or fluid temperature. The simulation of multiphase flow processes and their impact on contaminant migration and remediation also remains an active area of research.

Hydrogeological Land-Economic Model Integration

Much of the discussion in Chapter 5 suggests that the integration of economic models (that incorporate user demand for groundwater) with hydrogeological models (that describe groundwater dynamics) would provide managers with a powerful tool to promote sustainable groundwater use. A number of such integrated computer models have been developed and used to examine the linkages between economic activity and surface water, for example, Environment Canada's Water Use Analysis Model (Kassem *et al.*, 1994).

Models reflecting links between economic activity and groundwater are less common and have tended to be devoted primarily to the use of groundwater by

the agriculture sector. An early example is Kelso (Kelso *et al.*, 1973). More recently, researchers at the University of California have developed CALVIN,[12] an integrated economic-engineering model that links the surface and groundwater supplies of California with the state's major water-using sectors (Jenkins *et al.*, 2004). The application of such models, especially complex, linked, hydrogeological-economic models, if developed with care and caution, could also be valuable in the Canadian milieu.

In addition, the integration of models that address land use and management components with hydrogeological and economic features is an emerging need in Canada. The linking of these models will provide a means by which to compute and analyse a range of indicators relevant to evaluating ecological, social, and economic performance within a groundwater sustainability context. For example, the 5th EU Framework Programme funded the creation of OpenMI[13] as a technology platform for linking different models. As part of the 6th EU Framework Programme, OpenMI has been used and further expanded to encompass models that facilitate integrated analysis of policy questions across land, water, social, and economic outcomes.[14] The existence of such tools in a Canadian context would be of great utility not only for improving groundwater management, but also in managing cumulative impacts across media in cost-effective ways.

Ongoing Research

Canadian researchers have contributed significantly to groundwater modelling methods and software and these developments are reflected in the generally wide usage of models in the domestic consulting industry, although applied primarily at local scales to address issues relating to landfills, contaminated sites, and the capture zones of large supply wells. Box 4.1 provides a short summary of ongoing research directions in Canada.

We now turn to the final element of the four-component framework for sustainable management of groundwater flow-system analysis: the base of data that is needed to support the other three components.

4.4 DATA REQUIREMENTS FOR SUSTAINABLE GROUNDWATER MANAGEMENT

Groundwater data, whether from borehole drilling, geophysical surveying, or larger scale pumping tests, are expensive to obtain. It is therefore surprising to find that these data, once obtained, are commonly not preserved in an efficient or accessible format.

12 For more information on CALVIN, please see: http://cee.engr.ucdavis.edu/faculty/lund/CALVIN.
13 http://www.openmi.org/.
14 http://www.seamless-ip.org/; http://www.sensor-ip.org/.

For example, in current practice in Ontario, especially for larger watershed-management studies, one of the biggest allocations of project funds and time (often well over 50 per cent) is for collecting and managing existing data because no structured, comprehensive, water-related databases are maintained by public agencies. Over the course of many years, groundwater-related data have been lost or over-looked because of the lack of a readily accessible database. A recurring theme with consultant-led projects across the country is that, given the major effort required for collecting and managing existing data, there is insufficient time and budget remaining for the optimal data analyses required to develop innovative solutions to hydrogeological problems. Although budgets may be insufficient to begin with, and should be revised to reflect the work necessary to undertake the project, certainly one of the first steps in remedying this issue should be to optimise the management of data at the appropriate public sector agency and to provide ready consultant access to the data so that the task of amassing the needed data is not repeatedly duplicated over the years.

Box 4.1: Groundwater Research in Canada

Much of the current hydrogeological research in Canada is focused on groundwater quality, although increasing attention is being paid to sustainability, integrated groundwater-surface-water studies and aquifer characterisation. A partial list of current research topics or areas includes:

- Aquifer characterisation and development of improved methods for characterisation;
- Integrated groundwater-surface-water studies (at watershed scale in some cases);
- Fate and transport of a wide range of potential and known contaminants, including both organic and inorganic and emerging contaminants, such as endocrine disruptors and personal care products;
- Behaviour of non-aqueous liquids in the subsurface (industrial solvents and petroleum products in particular);
- Occurrence and mobility of pathogens;
- Industrial contributions to groundwater contamination including agriculture, manufacturing, and the natural resource and energy sectors;
- Remediation of contaminated groundwater; and
- Mathematical models of increasingly complex chemical and physical phenomena.

Comprehensive figures on the amounts and sources of funding for groundwater research in Canada do not exist. In 2006–2007, the Natural Sciences and Engineering Research Council of Canada (NSERC) provided $5 million to support groundwater research undertaken by university faculty (personal communication, March 31, 2008). In addition, the Canadian Water Network (CWN), one of the 21 national Networks of

Centres of Excellence, has annual funding that averages $5 million. The CWN involves 125 researchers from 38 universities across Canada and addresses a broad range of issues affecting both surface water and groundwater. Research is conducted in collaboration with the diverse community of end-users of water research across Canada.

Some data, publicly available from the Department of Earth and Environmental Sciences at the University of Waterloo, provide a snapshot of the support for what is likely the best-funded academically based groundwater research program in Canada. Total water-related research funding in 2005–2006 was about $6.7 million.[15] This includes work on both groundwater and surface water. About 57 per cent consisted of research grants with the remainder primarily from contracts. Approximately one third of the funds ($2.2 million) came from the federal government, about $1.5 million of which was from NSERC programs. Provincial sources accounted for about seven per cent of the total, with the remaining 60 per cent from industry, primarily from the United States and other international sources (personal communication, March 26, 2008). While likely to be of practical relevance and beneficial to Canada, as well as to the sponsoring industry, this latter research will not necessarily be consistent with provincial and national groundwater priorities.

Natural Resources Canada (NRCan) and Environment Canada both have active groundwater science and technology programs, although their financial resources are limited. The primary focus of NRCan is currently directed to the mapping and characterisation of major Canadian aquifers, while the focus of Environment Canada concerns the occurrence, fate and transport of contaminants of national concern. Several provinces also have active aquifer mapping and characterisation programs that have been ongoing for many years. Although there are numerous examples of collaboration among federal, provincial and university researchers, the federal departments have very limited resources in support of extramural research. These departments are consequently constrained in their ability to encourage university researchers to address topics of national priority.

Given the poor record of groundwater data management across the country, it is critical that the collection, maintenance, and management of existing and newly collected groundwater-related data, coupled with ready access to these data, be viewed as a priority for action across the country.

In general, the level of resources dedicated to systematic water-related data collection has failed to keep pace with the demands of land development, and in some cases has declined over the past 20 years, as illustrated by the number of stream gauges in Canada declining from 3,600 to about 2,900 (Statistics Canada, 2003).

15 Based on an assumption that 85 per cent of research funding going to the Department of Earth and Environmental Sciences was water-related.

Some proactive provincial programs have nevertheless emerged, including the 2001 Ontario Provincial Groundwater Monitoring Network (PGMN) and the *Ontario Clean Water Act*. The latter requires watershed-focused water budgets with particular requirements for collecting and interpreting streamflow measurements.

When assessing data needs, a first consideration is the scale of the investigation and the questions that need to be answered. For example, projects to assess the transport of specific contaminants in the groundwater system need localised subsurface data that typically must be obtained from on-site drilling, sampling, and monitoring. On the other hand, projects to assess groundwater availability within a catchment are more regional in scale. While there is a need for similar types of information for both types of studies, in the case of basin-scale studies, the subsurface geological framework is typically conceptualised on a regional scale and local data might not be as significant.

The problem being addressed also influences the type of data needed. For questions of allocation — for example, recharge and discharge rates, as well as climate and streamflow data — would be critical to evaluate the flow of water through the system and make appropriate allocation decisions. In this regard, it is important to have these data collected at the same location, which is generally not the case in Canada. In assessing contaminant plumes and designing treatment programs to minimise impact to groundwater quality, localised data on aquifer hydraulic conductivity and geochemical processes would be more critical.

The data required for effective groundwater management fall under the following general headings:

- Geological data (includes elements such as borehole logs, sediment grain size and compositional analyses, geophysical survey results, and mapping products);
- Hydrogeological data (includes elements such as aquifer or aquitard parameters and water levels);
- Climate data;
- Groundwater quality data;
- Groundwater withdrawal data; and
- Surface water data.

Geological Data

Geological information to support an understanding of groundwater flow can be extracted from various geological mapping programs undertaken by provincial geological surveys, the Geological Survey of Canada, or studies undertaken by university researchers and consultants. Hydrogeologists rely largely on borehole data as the fundamental tool in characterising the subsurface geology and

hydrogeology, although as noted earlier, geophysical methods for subsurface characterisation can be effective in many settings (for example, see Pullan *et al.*, 2004). At a broader scale, information from water well records can also be used to support the conceptualisation of the regional geological setting.

Surface mapping has typically been undertaken throughout Canada at various scales and is used extensively by the hydrogeological community to support the estimation of recharge rates and to further decipher the subsurface geological environment. Many of these provincial maps are not available in a digital format and are therefore of limited value to current Geographic Information System (GIS) methods of analysis. Programs to make available high-definition surface-geology maps should be supported. The raw data used to derive various geological maps consists typically of outcrop descriptions or the geological logging of boreholes and are generally available in hard copy only.

(Courtesy of the Oak Ridges Moraine Groundwater Program)

Figure 4.2
Installing a Groundwater-Monitoring well.

In a similar vein, aquifer maps that are derived from various raw hydrogeological data can also be considered as a data source. In this regard, only British Columbia, Manitoba, and New Brunswick indicate that a systematic delineation of provincial aquifers has been undertaken. Alberta and Saskatchewan have a comprehensive suite of hydrogeological maps that provide information on groundwater availability and quality; these are interpreted by some hydrogeologists to be equivalent to aquifer maps. There have also been many provincial studies that have comprehensively characterised various aquifers in many of the provinces. Several recent studies, led by the Geological Survey of Canada (GSC), of the Oak Ridges Moraine, Châteauguay River Watershed, and Annapolis-Cornwallis Valley Aquifer, among others, have also provided insight into sedimentary geological processes and have considerably advanced the conceptual geological understanding in the areas investigated.

The last comprehensive assessment of Canada's groundwater resources was published in 1967 (Brown, 1967). Currently, efforts are underway to establish a National Groundwater Inventory and, in that regard, the Groundwater Mapping Program managed by the GSC has undertaken to assess 30 key regional aquifers (Rivera, 2005). The collaborative assessments are intended to broaden knowledge on recharge; discharge; estimation of sustainable yield; quantification of aquifer vulnerability at a regional scale; and to provide provincial and local groundwater managers with the data and information needed to make informed land-use and groundwater-allocation decisions. (See, for example, the case studies of Basses-Laurentides and Oak Ridges Moraine in Chapter 6.) With funding of roughly $3 million per year, nine of the 30 aquifers had been assessed by 2006. At current rates, however, it is expected the mapping will not be complete for almost another two decades. In view of the importance of better hydrogeological knowledge as input for models, and for better groundwater management generally, a more rapid pace of aquifer mapping is necessary.

Given the relatively immature status of aquifer mapping across the country, there appears to be a need to develop a method of categorising aquifers at different scales (provincial, regional, or local). This is a difficult task, especially in glaciated terrains where stratigraphy can vary over short distances, or in fractured rock environments where fracture networks create the aquifers. Nevertheless, the development of such a framework would help local studies link to provincial objectives of further understanding groundwater-flow systems. The existing Intergovernmental Geoscience Accord (NGSC, 2007) should be used to guide the respective roles of the GSC and the Provincial surveys with respect to this mapping initiative.

Hydrogeological Data

There are several programs that capture data on aquifer transmissivity, hydraulic conductivity and storage values. Nova Scotia, New Brunswick, and British Columbia

report having a provincial database that includes this information, and Manitoba is in the early stages with paper records currently available. This exemplifies a recurring theme; although many data are collected, there are few systematic efforts to assemble them into a collective database to improve future understanding and management of the resource. In the meantime, hydrogeologists must rely on their knowledge of reports and maps on file with local agencies, or if the data have not been made public, repeat the field investigations to acquire the necessary data.

Well Data: Provincial water-well record datasets are relied upon to provide an important source of data to the groundwater industry and decision-makers across the country. Although there is no systematic national database of wells or groundwater levels across Canada, the datasets provide good spatial coverage across many parts of the country. While the geological data may be rudimentary for many of the wells, a regional understanding of subsurface aquifers can usually be determined. A shortcoming of the datasets is that they typically contain records of water wells and fail to capture the more detailed geological data obtained from boreholes drilled by technical consultants for hydrogeological or geotechnical investigations. Water wells are usually drilled using mud or air rotary techniques that provide only an approximate representation of the subsurface geology (Russell *et al.*, 1998). Depending on the aquifer sequences, water well records can reveal more aquitard information than aquifer information owing to the fact that once a suitable aquifer is encountered, the well is stopped and screened without necessarily defining the base of the aquifer. Shallow dug wells and older drilled wells are also missing from the databases and the position coordinates of many wells are only accurate to several hundred metres at best.

The panel surveyed all provinces to identify current programs and the types of groundwater information collected and to determine whether the data are readily available to the public (Table 4.1).

In Ontario, a new regulation calls for the capture of all consultant-drilled boreholes and the entry of this higher-quality geological data into the database. Saskatchewan and Alberta have, at times, maintained programs to geophysically log wells when they are drilled; Manitoba collects geophysical data from selected wells and has developed an inventory of geophysical data that is being linked to the water well record database (Box 4.2). Integration of digital data facilitates management tasks, including the interpolation of aquifers over large distances, thus reducing the long-term costs of groundwater exploration. British Columbia's water well record management program is currently voluntary, although it is understood that well logs will be mandatory in the future. Many drilled wells in that province are not in the database.

Table 4.1
Summary of Provincial Water Well Databases (August, 2007)

Province	Does the province maintain a database of water well records?	Are the data readily accessible and available to the public?
Newfoundland and Labrador	Yes	Yes — $50 charge for CD of wells drilled between 1950 and 2002 (~15,500 records)
Prince Edward Island	Yes	Yes — no charge for records; planning for web access to records
Nova Scotia	Yes	Yes — $100 charge for entire database of wells drilled between 1940 and 2004 (97,000 records)
New Brunswick	Yes	Yes — no charge for records
Québec	Yes	Yes — well records are searchable on a website at no cost
Ontario	Yes	Yes — $20 charge for individual well records; more data available by request; moving to web access (~550,000 records)
Manitoba	Yes	Yes — data available by request ~110,000 records in database from 1970 onward
Saskatchewan	Yes	Yes — no charge for records
Alberta	Yes	Yes — well records are searchable on a website at no cost
British Columbia	Yes	Yes — no charge for records

(Courtesy of William Cunningham)

Figure 4.3
Monitoring well with satellite telemetry equipment.

Box 4.2: Manitoba's Water Well Monitoring System

The mandate of the Water Stewardship Branch is to manage the province's surface water and groundwater resources to provide for the social, cultural, and economic well-being and the health and safety of present and future generations of Manitobans. The Groundwater Management Section focuses on the evaluation, monitoring and protection of groundwater. The group administers the provincial *Ground Water and Water Well Act*, undertakes studies to map aquifers, collects long-term temporal data and maintains databases of hydrogeological conditions, all with the aim of assessing the sustainability of major aquifers.

Monitoring of groundwater levels was first undertaken in the 1960s in support of the Red River Floodway. The network has grown progressively to approximately 550 monitoring wells. The 2007 program also included 250 water-quality samples and the monitoring of 35 rainfall gauges. These data were added to the database to develop a regional-scale understanding of water levels and quality. From a sustainability perspective, major aquifers have been mapped and their hydraulic properties defined through borehole geophysics and pumping tests to facilitate sustainable yield estimates.

The Province is currently undertaking a well-by-well evaluation of the network to see what value is being derived from each well and to better develop the Province's overall monitoring philosophy. This evaluation will be used to assess whether each monitoring well needs to be maintained in the network or if it is duplicating responses obtained by other wells. The evaluation process involves an analysis of the hydrographs, borehole geophysical logging, conducting a pumping test, and water sampling of all active and inactive wells if that information does not already exist. Eleven wells were decommissioned in 2006–2007 as a result of the program.

In 2006–2007, the groundwater management section operated on a budget of about $1.4 million with a staff of 14 (Government of Manitoba, 2007).

Water-Level Data: Water level information is the other key dataset that is derived from the water well records. It is impractical to develop an understanding of longer-term trends in water levels from water well records because they generally contain only one water level measurement at each well. It is obviously necessary to measure water levels over a longer time period to see trends that can lead to an understanding of how aquifers respond to drought, rainfall or snowmelt. In addition to more general day-to-day monitoring linked to water takings or other land use-changes, the requirements of which vary on a case-by-case basis and from province to province, the provinces all

have active regional ambient groundwater-level monitoring networks with the number of observation wells ranging from fewer than 25 to over 500 (Table 4.2). A recent summary of the provincial groundwater monitoring networks is available from the Saskatchewan Research Council (Maathuis, 2005). In every province, except Newfoundland and Labrador and Ontario, the data are available publicly either by request or via a website. British Columbia has one internet site for real-time data where two to four days of current data are available, and a separate site where all of the data can be accessed.[16] Figure 4.3 illustrates a monitoring well equipped with telemetry equipment to provide real-time data to users. It is important that the water-level data, once collected, also be reviewed and analysed to look for long-term trends and other relevant details about the groundwater system. It is unclear how well the provinces are doing in this regard.

Climate Data

Precipitation and temperature data, in particular, are essential components of regional groundwater investigations, allowing for the estimation of evapotranspiration, groundwater recharge and runoff. Environment Canada maintains a database of climate stations, with some temperature and precipitation data from more than 11,000 stations across the country.[17] A selection of approximately 200 stations have up-to-date weather data posted hourly online while another set of stations has climate normals calculated and available. Many of the 11,000 stations are historical and no current climate information is collected. Unfortunately, it is only once the data are downloaded that one can determine how long the climate station has been active and the extent of missing data. For example, of the approximately 11,000 climate stations, only about 1,500 have climate normals; i.e., sufficient data is available to cover 15 years of activity between 1971 and 2000.[18]

16 The following websites provide data on water level monitoring programs in various provinces. In British Columbia, see http://www.env.gov.bc.ca/rfc/river_forecast/grwater.html for real-time data and http://srmapps.gov.bc.ca/apps/gwl/disclaimerInit.do for long-term data. In Alberta, see http://www.telusgeomatics.com/tgpub/ag_water/; in Saskatchewan, see http://www.swa.ca/WaterManagement/Groundwater.asp?type=ObservationWells#; in Nova Scotia see http://www.gov.ns.ca/enla/water/welldatabase.asp; and in Prince Edward Island see http://web3.gov.pe.ca/waterdata/tool.php3.

17 The complete database is available at the Environment Canada website (http://climate.weatheroffice.ec.gc.ca/Welcome_e.html) and is easily accessible.

18 To improve the service, Environment Canada could, for each climate station, provide the years of record on a map and differentiate, using different colours, the stations that are currently active versus those that are no longer monitored or maintained.

Table 4.2
Summary of Aquifer Mapping and Groundwater Monitoring Programs (August, 2007)

Province	Does the province have an inventory of aquifers?	Does the province have a program to measure groundwater levels in a monitoring network?
Newfoundland and Labrador	No	Yes — up to 25 wells in the network; the data are not accessible to the public.
Prince Edward Island	No (only one main aquifer)[19]	Yes — 13 wells are monitored in a partnership agreement with the federal government; data are accessible over the web.
Nova Scotia	No	Yes — 24 wells are monitored; data are available on a public website.
New Brunswick	Yes	Yes — up to 25 wells are monitored; the data are available by request.
Québec	No	Yes — 25 to 50 wells are currently monitored with plans to expand to between 200 and 500 wells; data are available on a public website.
Ontario	Partially — a series of consultant-led studies were undertaken in the vicinity of the municipal supply wells and the studies contain some aquifer information. There is no systematic program to develop this further.	Yes — about 460 wells are monitored in a partnership with watershed authorities; data are available only to the watershed authorities via a password-protected website.
Manitoba	Yes — at a regional scale since most of the aquifers are bedrock-related. In areas dominated by glacial sediment aquifers, there are maps that address the likelihood of finding a suitable aquifer.	Yes — 550 wells are monitored regularly, mostly in areas of groundwater withdrawals; data are available by request; the intent is to put data on the web.
Saskatchewan	Groundwater maps address the likelihood of finding groundwater supplies.	Yes — 50 to 100 wells are monitored; long-term data are available on a website.
Alberta	Groundwater maps address the likelihood of finding groundwater supplies.	Yes — over 197 Groundwater Observation Wells are monitored; data are available on a website.
British Columbia	Yes — inventory of some 900 aquifers — not necessary to delineate the full extent of the aquifer (e.g., could be delineated on the basis of a number of wells using same unit).	Yes — 163 wells are monitored; data are available on a website.

19 In Prince Edward Island, since there is a single sandstone aquifer covering the province, further aquifer mapping is unnecessary from a geological perspective.

Table 4.3 shows the extent to which each province maintains climate data in addition to the data maintained by Environment Canada. While most provinces tend to rely on Environment Canada, many report data from additional meteorological stations, although these stations are typically operated intermittently as part of a localised research project, or for some other specific purpose. The stations are inadequate for providing a year-round accounting of precipitation or temperature for the purposes of groundwater management. In the case of three provinces (Newfoundland and Labrador, Manitoba and British Columbia), programs to collect some climate data are in place, but only for part of the year. Ontario does not maintain climate stations of its own, but for source-water protection initiatives, the province has regenerated missing data from Environment Canada's stations in order to make the data more useful for ongoing source-water protection work.

Only three provinces, New Brunswick, Québec, and Alberta, have programs to supplement the Environment Canada data. With regard to public access to data, Québec allows for a web-based search of their stations to see what types of data are collected at each station.[20] Specific data requests can be made directly to the province. Alberta allows real-time data (on both precipitation and streamflow) to be viewed through a web portal.[21] Historical data do not appear on the website and access requires a direct inquiry to the province. New Brunswick's website only allows for the searching, by month and year, of a summary of the precipitation, streamflows and groundwater-level data.[22]

Table 4.3
Provincial Climate Data Collection (August, 2007)

Province	Does the province have a program to collect climate data?	If yes, are the data readily accessible and available to the public?
Newfoundland and Labrador	Yes — for winter road conditions	
Prince Edward Island	No	
Nova Scotia	No	
New Brunswick	Yes — no specific information provided	Yes
Québec	Yes — 155 stations run by Province	Yes
Ontario	No	
Manitoba	Yes — but only operated in growing season	Yes
Saskatchewan	No	
Alberta	Yes	Yes
British Columbia	Yes — for snowpack in mountains	

20 For more information on Québec's online climate data, see Surveillance du climat website at: http://www.mddep.gouv.qc.ca/climat/surveillance/index.asp.

21 For more information on Alberta's online climate data, see Alberta's River Basins website at: http://environment.alberta.ca/apps/basins/default.aspx.

22 For more information on New Brunswick's online climate data, see New Brunswick's Water Quantity Information website at: http://www.gnb.ca/0009/0371/0007/0006-e.asp.

Surface Water Data

Streamflow, or the amount of water that flows from a watershed, is an important component of the water budget and can significantly contribute to an understanding of subsurface hydrogeological conditions. In cases where the groundwater-flow system generally reflects the surface-water divide, streamflow data can better constrain estimates of recharge to the groundwater system.

Environment Canada, in cooperation with the provinces, some municipalities and industries, jointly operates a network of streamflow gauges, generally known as the HYDAT network.[23] There are currently 2,844 stations in operation, of which roughly half transmit data in real-time, but data from 5,577 inactive stations remain available in the database (WSC, 2006). The database is available through the Environment Canada website and allows for querying historical data by station and year.

Most provinces rely on the HYDAT network for all of their surface-water flow needs. Table 4.4 summarises the streamflow data collection initiatives of the provinces. Only Québec and Alberta have gauged stream locations above and beyond the HYDAT network. Alberta's River Basins web site, which incorporates more than just the HYDAT stations, is a particularly useful source of real-time data in a tabular format.[24] HYDAT gauging station locations are selected based on the needs of the funding partner and serve a number of specific purposes ranging from flood control to hydroelectric power generation to municipal water supply. From a groundwater perspective, this means that there are numerous watersheds, especially in the northern parts of the country, but also in the south, where no public streamflow measurements have been taken or where gauges are located higher up in a watershed and do not permit determination of how much water is actually leaving the lower reaches of a watershed. Furthermore, it is rare that climate, streamflow and groundwater levels are all measured at the same location within the basin, making correlation of some data difficult.

23 HYDAT stands for Hydroclimatological Data Retrieval Program. Environment Canada has a website (http://www.wsc.ec.gc.ca/index_e.cfm) where the data can be downloaded on an annual basis since 1991 (previous data are available in hard copy) for a fee of $100.

24 For more information on Alberta's online streamflow data, see Alberta's River Basins website at: http://environment.alberta.ca/apps/basins/default.aspx.

Table 4.4
Provincial Streamflow Data Collection (August, 2007)

Province	In addition to Environment Canada's HYDAT data, does the province have a program to collect streamflow data?	If yes, are the data readily accessible and available to the public?
Newfoundland and Labrador	No	
Prince Edward Island	No	
Nova Scotia	No	
New Brunswick	No	
Québec	Yes — 158 stations run by province.	Yes — by request, although an increasing number are online.
Ontario	Partially — Some conservation authorities have programs to collect additional streamflow data but this is not mandated by the province and the data are not collated at a provincial level.	
Manitoba	No	
Saskatchewan	No	
Alberta	Yes	Yes — real-time available on website; historical data by request.
British Columbia	No	

Groundwater Quality

There is considerable disparity in the requirement for, and the thoroughness of, groundwater quality monitoring across the country. In Alberta, for example, water-well drillers are required only to submit the drill logs to Alberta Environment. They may advise that the well owner should have groundwater quality analysed, but there is no requirement for conducting the analysis. The only sample likely to be collected may be for bacteria or coliform. (There are groundwater testing requirements related to the drilling of shallow coalbed-methane (CBM) wells, but they target a specific subset of domestic-water wells within a 0.6-kilometre radius of a CBM well (ERCB, 2006). Requirements vary from province to province with respect to water-quality data for newly drilled domestic wells, but typically only bacteria or coliform testing is required.

Mandatory testing for water quality of all newly constructed or re-drilled water wells in New Brunswick was introduced under the Potable Water Regulation in 1994

(Government of NB, 1989; Government of NB, 1993). Before work begins on a well, a licensed drilling contractor collects the testing fee from the well owner. The well owner must then submit the voucher and a water sample from the well after it has been subject to normal usage. The water sample is tested at a provincially operated laboratory for total coliform and *E. coli*, as well as a range of inorganic parameters such as calcium, chloride, iron, fluoride, and arsenic. The well owner is notified of the results and the Department of Environment maintains the data in a province-wide groundwater database, along with the "Water Well Drillers Report". Under the Potable Water Regulation, the testing results are treated as confidential and may be released only with the permission of the well owner, or in an aggregate format that does not identify the individual well from which the sample was retrieved. During the 2006–2007 fiscal year, the Department of Environment analysed samples from 1,356 new or re-drilled wells, which represented a redemption rate of 66 per cent for the testing vouchers. During the same time period, water-well information, including water quality, was provided in response to over 750 requests from professional consultants conducting a variety of assessments (NB DoE, 2007).

Assessments of groundwater monitoring must distinguish between regional monitoring of background water quality and site-specific monitoring of known or suspected groundwater contamination. Regional background monitoring usually focuses on the potential exceedances of naturally occurring contaminants such as arsenic or fluoride, and possibly, non-point agricultural pollutants such as nitrate. It is often carried out by provincial agencies in their regional monitoring-well networks in concert with water-level measurement programs (although chemical samples do not need to be taken nearly as often as water-level measurements, given the unlikelihood of any rapid changes in regional water quality).

Site-specific monitoring programs are designed to detect the occurrence of anthropogenic contaminants, like solvents or hydrocarbons, arising from point sources such as leaking waste-disposal facilities or industrial spills. They usually require many monitoring wells, perhaps even including some with sophisticated multi-depth sampling points. Such monitoring networks are designed to quantify the presence and extent of contamination and aid in the selection of appropriate remedial action. They are usually installed by private contractors, hired by site owners, and operated under the scrutiny of provincial regulators.

The design of monitoring-well networks that are effective and cost-efficient for either purpose is a difficult task and further research is needed in this area. Furthermore, the design and installation of individual monitoring wells requires great care in order to avoid the introduction of spurious chemicals into the

subsurface environment. Proper protocols have been developed in recent years (Nielsen, 2006), but are time-consuming and expensive. Monitoring groundwater quality is much more difficult than it would appear, and reliable data are not easy to come by.

It is the panel's opinion that while there is a need for improved groundwater-quality data across the country, particularly with respect to benchmarking baseline conditions so that long-term changes can be properly documented, it is recognised that specific monitoring initiatives can be very costly without direct corresponding benefits. Water-quality monitoring programs are probably best developed on a case-by-case basis by individual provinces and local agencies, although coordination of effort at a limited number of sites is needed to permit assessments of national or large-scale regional trends. There may be a need for a sparse monitoring network, coordinated on a national scale, to detect any large-scale trends in groundwater quality due to changes in the chemical composition of global or regional precipitation.

Groundwater Withdrawals

As discussed in Chapter 1, the collection of data on groundwater withdrawals is spotty across the country and many major users of groundwater are not required to regularly report their extractions. This is information that is essential for groundwater management, and the costs of collecting such information could largely be borne by the users with only minor implications for public sector budgets.

4.5 MANAGING THE COLLECTION AND SHARING OF DATA

Managing the collection and sharing of Canada's groundwater monitoring data, including water levels and quality, requires substantial improvements, particularly with respect to ambient background conditions and trends. As documented in the preceding sections, all provinces and local agencies have ongoing water level monitoring programs. But the number of observation points is generally insufficient and water-quality data are not a priority of these programs. Systematic analyses of these data are not done in many cases and no mechanism exists to identify new and emerging potential threats or to evaluate the need for action to monitor or remediate, except in a reactive mode.

An important objective of data acquisition and management is to bridge agency and disciplinary boundaries and to compile an integrated, comprehensive database covering geology, groundwater, surface water and climate-related information across the catchment area. This broad scope recognises that water management cannot stop at municipal boundaries and that a broad range of data sources needs to be tapped to establish the foundation for credible groundwater decision-making and effective long-term resource management. Management of the database

should also seek to capture high-quality data collected by technical consultants that would otherwise be lost in archived paper reports. In Ontario, for example, the same data have been found to be repeatedly collected at the same location, sometimes several decades apart, simply because there is no formal database to house such information.

Water management in Canada, as in many countries, crosses multiple levels of government and several departments within each government. Approaches used in the United States and elsewhere to address this inherent fragmentation contain relevant lessons for groundwater data and information management across Canada. One promising approach would be to provide access to groundwater-related data through a database system similar to the National Water Information System of the United States Geological Survey (Box 4.3). This requires a common database structure, shared among water resource departments, that would facilitate a common portal to publicly disseminate the data, minimise staff support needed to maintain groundwater databases and remove duplication of effort to assemble and maintain the data. Ongoing Canadian initiatives in this regard are outlined in the following paragraphs.

Groundwater Information Network: A group of federal, provincial and watershed agencies is working in partnership with the national GeoConnections[25] program to develop a Groundwater Information Network (GIN). The GIN is developing standards for data management to facilitate sharing of information. Groundwater monitoring at all levels must be more strongly supported and a platform for sharing data, such as the GIN, needs to be developed through federal-provincial cooperation. Universities and technical consultants who undertake data-collection field activities, but generally do not contribute to public groundwater databases, are encouraged to do so.

Water Well Mapping and Analysis System: This project is an initial component of GIN and seeks to add 'depth' to the Canadian Geospatial Data Infrastructure (CGDI) by making well log records available from several major groundwater data providers. The stimulus for this project came from the Canadian Framework for Collaboration on Groundwater (Rivera *et al.*, 2003). Ontario, Manitoba, Alberta, British Columbia and Nova Scotia have agreed to participate with Natural Resources Canada (NRCan) in the project by sharing their well water information.

25 GeoConnections is a federal initiative to leverage the power of the internet to access terrain science data compiled by federal departments, primarily in the form of maps and satellite imagery. The program is founded on the Canadian Geospatial Data Infrastructure that provides for storage and access to virtually any form of location-based information.

By developing a web-based standard data structure for drill logs (called Groundwater Markup Language)[26] and following CGDI data access protocols, the project enables online access to existing well log databases located in the partnering provinces. It is envisaged that, over time, partners to the project will expand beyond the provinces to include other groups and agencies with significant well log holdings. In addition to enabling access to groundwater information, the project will also provide web-based tools to visualise, analyse, and integrate the well log records. This is facilitated by third-party software developers who leverage the common data standards.

Box 4.3: Groundwater Data Management & Access in the US

The United States does not have a comprehensive national groundwater database. Rather, data on groundwater quality and level are collected and stored by federal water agencies, most state agencies, and some local entities. Much of the data collected by states is publicly available on the internet. Extensive amounts of groundwater-related data are also made available online through mission-based national programs led by both the United States Environmental Protection Agency (EPA) and the United States Geological Survey (USGS). In addition, a web portal is under development by the Consortium of Universities for the Advancement of Hydrological Science.

The EPA maintains two data management systems containing water-quality information: the Legacy Data Center and STORET. These are primarily surface-water quality systems, but groundwater quality data from approximately 75,000 wells are also available.[27]

The USGS monitors the quantity and quality of water in the nation's rivers and aquifers, assesses the sources and fate of contaminants in aquatic systems, develops tools to improve the application of hydrological information, and ensures that its information and tools are available to all potential users. This diverse mission cannot be accomplished effectively without the contributions of the Cooperative Water Program (CWP) (USGS, 2008b). For more than 100 years, the CWP has been a highly successful cost-sharing partnership between the USGS and water-resource agencies at the state, local, and tribal levels. The CWP has contributed significantly to meeting USGS mission requirements and keeping the agency focused on real-world problems. The linkage to local and state water-resource needs also ensures that the program responds quickly to emerging issues.

26 Groundwater Markup Language (GWML) is being developed mainly in Canada with the input of international collaborators in the United States, Europe and Australia. It is still in development and not yet in use.

27 For more information on the Legacy Data Center and STORET, see http://www.epa.gov/storet.

The USGS and Cooperators jointly plan the scientific work performed within the CWP. The result is a national program with broad relevance and widespread use of its products. Because rivers and aquifers cross jurisdictional lines, studies and data collected in one county or state have great value in adjacent jurisdictions. Through the CWP, the USGS ensures that the information can be shared and is comparable from one jurisdiction to the next.

Cooperators choose to work with the USGS because of the agency's broad technical expertise, its long-standing record of performing high-quality measurements and assessments, and its commitment to providing public access to data collected under the CWP. Because the USGS is a scientific, non-regulatory body, parties in many types of regulatory and jurisdictional disputes accept its data and analyses as impartial and valid.

Within the Cooperative Water Program, about half of the funds (which totalled $215 million USD in 2004, almost two-thirds of which was provided by the Cooperators) are used to support data-collection activities, the remainder being used for interpretive studies. The USGS compiles and analyses information resulting from these activities into regional and national synthesis products.

The National Water Information System (NWIS) supports the acquisition, processing, and dissemination of information about water quantity and quality collected at over 1.5 million sites around the United States. The NWISWeb system[28] is a publicly accessible, aggregated compilation of data (from 48 local NWIS systems) that contains water levels from about 800,000 wells and water-quality data from more than 300,000 wells. The NWIS is both a work-flow application and a long-term database. It contains not only groundwater quality and levels, but also surface water data (e.g., quality, flow, stage, and discharge). The NWIS provides continuous access to data collected over the last 100 years, as well as telemetered surface water, groundwater, and water quality data. The real-time data processing feature enables data transmitted via satellite or other telemetry to be processed and made publicly available on the web site within 5 to 10 minutes after transmission. Currently, more than 1,000 wells have real-time groundwater level instrumentation. Data from these wells are used to assist with many State and local programs such as drought designation, salinity monitoring and well-field management. To help sift through the data, management tools are made available through web-based systems to provide 'at-a-glance' reporting on the location of wells and the status of the most recent measurements. A variety of national networks have been designed based on data in the NWISWeb system.

There is an effort underway in the United States to create a more comprehensive, national source of water monitoring data. The Advisory Committee on Water Information

28 For more information on the NWISWeb system, see http://waterdata.usgs.gov/nwis/gw.

(ACWI) represents the interests of water information users and professionals in advising the federal government on water-information programs (USGS, 2008a). In January 2007, ACWI established a Subcommittee on Ground Water (SOGW), consisting of federal, state, business and academic volunteers, to encourage implementation of a nationwide, long-term groundwater quantity and quality monitoring framework. The effort is analogous to the recent European groundwater initiative under the European Community Water Framework Directive. A report from the SOGW, released in 2009, provides a framework for a 'network of networks' among state and federal agency groundwater monitoring networks.

The SOGW is reviewing various models for an information portal, including the Hydrological Information System (HIS) of the Consortium of Universities for the Advancement of Hydrological Science (CUAHSI). CUAHSI, which represents more than 100 United States universities, receives funding from the National Science Foundation to develop infrastructure and services for the advancement of hydrological science and education in the United States, and has specifically been funded to develop the HIS.[29] The HIS portal intends to make the nation's water information universally accessible, while also providing access to the original data sources. The portal will transparently access a geographically distributed network of hydrological data sources using web services. The HIS user will be able to see the locations of data sources from various agencies, identify all of the data of interest, and obtain these data with a single request.

National Groundwater Database (NGD): The NGD is an established and growing groundwater database with two roles: (i) it is the database engine and structure behind GIN; and (ii) it is the information management vehicle for the GSC groundwater mapping program. As part of its internal information management strategy, the management of the NGD proposes to establish standard types of data, which will be publicly disseminated, for the various projects of the groundwater mapping program. NRCan projects will be responsible for adding to these standard layers as part of their project activities.

National Land and Water Information Service: Agriculture Canada is investing $100 million over four years to establish a national web-based source of information of agricultural and environmental data on land use, soil, water, climate, and biodiversity to primarily assist agricultural land-use decision-makers (AAFC, 2009).

29 For more information on the CUAHSI Hydrological Information System, see http://www.cuahsi.org/his.html.

National Atlas: The Atlas of Canada intends to integrate groundwater maps from NRCan with other social, environmental and economic themes at national, continental and global scales. This will provide the geographical context to help explain the significance of the science knowledge collected by the groundwater program. A variety of groundwater-related maps will be included, initially at a national scale.

National Water Atlas: The Atlas of Canada is teaming up with Environment Canada, Agriculture and Agri-Food Canada, and Statistics Canada to create a web-based Water Atlas to provide an up-to-date and reliable accounting of Canada's water at a national scale. The maps are intended to provide a scientific and general overview of the state of the quality and quantity of water in Canada. Initial plans suggest it will be hosted by the Atlas of Canada, with a tentative completion date of 2010.

REVIEW OF KEY POINTS

Groundwater Knowledge and Science for Sustainable Management

- Four investigative components, when managed in an integrated manner, can inform decisions as to the sustainable use of groundwater: (i) a comprehensive water database, (ii) an understanding of the geological framework, (iii) a quantitative description of the hydrogeological regime, and (iv) an appropriate groundwater model.
- Hydrogeological studies, including aquifer mapping and characterisation, have been effective in integrating groundwater concerns into the land-use management process, provided, of course, that the groundwater investigations precede the land-use development.

Groundwater Modelling in Practice

- In most provinces, the use of models by regulatory agencies lags behind state-of-the-art application. Thus, as governmental authorities increasingly seek sustainable groundwater allocation strategies, there is a need to improve their capacity to employ catchment-scale groundwater management models.
- To be most effective, numerical groundwater models must provide sound hydrogeological input to decision-makers, together with transparent documentation that highlights both the strengths and weaknesses of the model. In particular, it is imperative that model output uncertainty be explained by modellers to decision-makers.
- Modelling needs to be viewed as an ongoing process. As additional field data are collected, the model needs to be adjusted and recalibrated periodically. This 'living model' approach is well suited to an adaptive management philosophy.

State of Knowledge

- Models that couple atmosphere, land surface, hydrology and groundwater need development to enable better assessment of the impacts of land-use change and of climate change and variability.
- Models reflecting links between economic activity and groundwater are not common and have tended to be devoted primarily to the use of groundwater by the agriculture sector.
- Much of the current hydrogeological research in Canada is focused on groundwater quality, although increasing attention is being paid to sustainability, integrated groundwater-surface-water studies and aquifer characterisation.

Aquifer Mapping and Characterisation

- The last comprehensive assessment of Canada's groundwater resources was published in 1967. The Groundwater Mapping Program managed by the GSC aims to assess 30 key regional aquifers; only nine assessments have been completed.

At current rates, it is expected that the mapping will not be complete for almost two decades. In view of the importance of better hydrogeological knowledge as input for models and for better groundwater management generally, a more rapid pace of aquifer mapping is necessary.

Groundwater Quality Monitoring

- There is considerable disparity in the requirement for, and the thoroughness of, groundwater-quality monitoring across the country. Specific groundwater-quality monitoring can be very costly without direct commensurate benefits. Monitoring programs are best developed on a case-by-case basis by individual provinces and local agencies, although coordination of effort at a limited number of sites is needed to permit assessments of national or large-scale regional trends.

Groundwater Data Collection and Integration

- In general, the level of resources dedicated to systematic water-related data collection has failed to keep pace with the demands of land development and in some cases has declined over the past 20 years. Moreover, systematic efforts to assemble groundwater-related data into a readily accessible pan-Canadian information management system have been limited. The collection, maintenance, and management of existing and newly collected groundwater-related data, and ready access to these data, should be viewed as a priority for action across the country.
- Approaches used in the United States and elsewhere to address the fragmentation of groundwater data and information management contain relevant lessons for Canada (for example, the National Water Information System of the United States Geological Survey).

5 Groundwater Management and Decision-Making

This chapter addresses primarily the remaining goals of sustainable groundwater management, namely the achievement of socio-economic well-being and the application of good governance. A description of the jurisdictional environment in Canada provides context. Issues related to the good governance of groundwater are illustrated in Section 5.2, primarily through examples and a discussion of current provincial and local practices, including the technical and legislative aspects of drinking-water standards. The achievement of socio-economic well-being is addressed in Section 5.3, with particular emphasis on the potential for the broader application of economic instruments to encourage the sustainable use of groundwater in Canada.

5.1 GROUNDWATER JURISDICTION IN CANADA

The Constitution of Canada distributes among the federal and provincial governments the powers to make laws and to own and manage property. Water is not specifically mentioned as a constitutional head of power for either of these orders of government. The provinces have the primary legal jurisdiction through their powers of ownership over public land.

Primary Provincial Role

Legislative powers derived from the Constitution give the provinces the primary role in water management, including jurisdiction to regulate:

- management and sale of public lands;
- property and civil rights;
- local works and undertakings;
- municipal institutions; and
- generally all matters of a local or private nature.

The provinces, as the primary regulators of groundwater, map and monitor the resource; assess its recharge and discharge; evaluate sustainable yield; develop and maintain models; assess groundwater extraction impacts on streamflows and groundwater-surface-water interactions; collect and compile groundwater information; and generally manage groundwater resources. Provincial regulations also set well construction and closure standards, establish licensing or registration systems for well drillers, and specify water testing and chemical analysis requirements for new and altered wells.

To carry out these essential roles, each province has staff and resources dedicated to groundwater management. Provinces take different approaches to their

management responsibilities, and the various provincial legal frameworks vary accordingly (Nowlan, 2005). New Brunswick's approach, for example, has generally been viewed as successful. Its Wellfield Protected Area Designation Order gives regulators the authority to identify and protect the entire recharge area associated with and surrounding a wellfield by setting out three subzones. Each subzone has specific restrictions on permitted land uses and activities to account for the differences among contaminants that persist in the environment for different time frames, move at different rates, and pose different health risks. Similar approaches are used in other provinces. Saskatchewan uses aquifer management plans. Since 2006, Ontario requires source-protection plans for drinking-water sources, and Québec protects groundwater catchments under the *Règlement sur le captage des eaux souterraines*.

Significant Federal Role

The federal government also has legislative and proprietary powers to manage groundwater on federal lands, including national parks and military bases. The main constitutional powers of the federal government related to water, though not always relevant to groundwater, include jurisdiction over:

- boundary and transboundary waters shared with the United States;
- sea-coast and inland fisheries (including fish habitat);
- interprovincial watercourses (shared with provinces);
- international or interprovincial 'works and undertakings' (which the courts have interpreted to cover pipelines);
- federal works and undertakings;
- canals, harbours, rivers, and lake improvements;
- national parks; and
- Indians and lands reserved for Indians. (Canada's aboriginal population is much broader than the group covered by the *Indian Act* and includes Inuit, non-status Indians, Métis, and status Indians not resident on reserves — persons for whom the federal government does not have formal water responsibilities.)

The federal Parliament also has wide powers over the environment stemming from the constitutional responsibility for the "peace, order, and good government" of Canada; the criminal law, which may be used to protect public safety or health; the power to negotiate and implement international treaties,[30] but only if the subject matter of the treaty falls within federal jurisdiction; and, perhaps of most relevance to water, spending power.

30 The federal government also has the constitutional authority to implement Empire treaties, i.e., treaties originally concluded by the British Empire on Canada's behalf. The Boundary Waters Treaty is the most important example of this type of treaty with respect to water.

Water Agreements with the United States: Boundary water is the subject of the 1909 International Boundary Waters Treaty (BWT) with the United States, one of Canada's oldest resource treaties.[31] The treaty includes, among several provisions, the obligation not to cause pollution that will injure health or property in the boundary waters of the other party. The scope of the treaty is limited to the lakes and rivers along the Canada-US border and thus excludes groundwater. The institution that implements this treaty is the International Joint Commission (IJC). While traditionally focusing on shared surface waters, it has also had to examine groundwater as part of its mission. The IJC has recommended that the Canadian and United States governments take an ecosystem approach to managing the US-Canadian international watersheds, including the creation of joint watershed boards, which would presumably also affect groundwater management.

Other Canada-US water agreements include the 1961 Columbia River Treaty, the 1972 Great Lakes Water Quality Agreement, and a remarkably large number of additional formal and informal agreements, in place mostly within the framework of the BWT. With respect to the Great Lakes, an agreement was reached in December 2005 among the eight states that border the lakes and the provinces of Ontario and Québec. It has now been approved by all jurisdictions, including the United States Congress.

This agreement aims to limit and regulate transfers of water out of the basin and will affect groundwater in the basin. Ontario recently passed the *Safeguarding and Sustaining Ontario's Water Act* (Government of Ontario, 2007) that also seeks to implement the provisions of the 2005 Agreement. A case study on groundwater in the Great Lakes is presented in Chapter 6.

Multinational Agreements: National rules are influenced by international law. International treaties on biodiversity and climate change, for example, affect Canada's freshwater management responsibilities. Recent rules on transboundary aquifers have been proposed by the Drafting Committee of the United Nations International Law Commission, but are not yet legally binding.[32] Canada has

31 Boundary waters are bodies of water, such as the Great Lakes, that form part of the international boundary. For the purpose of this treaty, boundary waters are defined as the waters from main shore to main shore of the lakes and rivers and connecting waterways, or the portions thereof, along which the international boundary between the United States and the Dominion of Canada passes, including all bays, arms, and inlets thereof, but not including tributary waters which in their natural channels would flow into such lakes, rivers, and waterways, or waters flowing from such lakes, rivers, and waterways, or the waters of rivers flowing across the boundary.

32 The UN International Law Commission's Draft Articles on the *Law of Transboundary Aquifers* were adopted on first reading in 2006 and were submitted to governments for comments and observations on January 1, 2008 (United Nations, 2008).

Box 5.1: The European Union's Water Framework Directive

The European Union's Water Framework Directive (WFD) was adopted in October 2000 to guide national-level action aimed at restoring water quality and managing quantity sustainably (EU, 2000). Key themes of the WFD are action on a basin scale, requiring cooperation among basin states, and a focus on water quality, whereby states are to assess and rank basin-water quality and deliver 'good' water status by 2015.

By focusing on basins, the WFD provides for the integrated management of groundwater and surface water for the first time at a pan-European level. In addition, groundwater quantity is specifically addressed in the directive, with abstraction limited to that portion of the overall recharge not needed by the ecology of the watershed.

From a quality perspective, the directive adopts a 'precautionary approach' and prohibits the outright discharge of contaminants to groundwater and requires monitoring to document possible indirect discharges. The premise of this approach is that, as a stock resource, groundwater should not be polluted at all. It is noted that nitrates and pesticides, as non-point sources, are controlled by chemical quality standards.

Further direction was provided in a 2006 Groundwater Directive which, *inter alia*, requires member states to:

- define and categorise groundwater bodies within basins on the basis of the pressures and impacts of human activity on the quality of groundwater (this was completed in 2004 and 2005);
- establish registers of protected areas within basins for groundwater habitats and species directly dependent on water (the registers must include all bodies of water used for the extraction of drinking water and all protected areas);
- establish groundwater monitoring networks based on the results of the classification analysis so as to provide a comprehensive overview of groundwater chemical and quantitative status;
- set up a river-basin management plan for each basin to include a summary of pressures and impacts of human activity on groundwater status, a monitoring of results, an economic analysis of water use, a protection program and control or remediation measures;
- by 2010, take into account the principle of cost recovery for water services, including environmental and resource costs, in accordance with the 'polluter pays' principle; and
- establish, by the end of 2009, a program of measures for achieving WFD environmental objectives — namely abstraction control and pollution control measures that would be operational by the end of 2012.

entered into significant free-trade agreements that may have implications for water management; however, this remains an unresolved issue.[33]

In some parts of the world, effective management coordination has been achieved in spite of complex jurisdictional issues. A notable example is the European Union Water Framework Directive (Box 5.1).

Shared Responsibility Over Water

The Constitution gives formal, shared, water-management responsibilities to both the federal and provincial governments in relation to agriculture. In practice, these two orders of government also share responsibility for interprovincial water issues and health, among other issues.

The *Canada Water Act* (Government of Canada, 1985b), originally passed in 1970, but seldom used in recent years, enables the federal government to enter into agreements with the provinces and territories to undertake comprehensive river-basin studies; to monitor, collect data and establish inventories; and to designate water quality management agencies. The Act also gives the federal government the power to act unilaterally, a power it has not used. Other federal water laws relevant to groundwater are: the *Fisheries Act* (Government of Canada, 1985c), which prohibits damage to fish habitat and the deposit of deleterious substances in fish-bearing waters and which may be useful to protect groundwater essential to fish habitat; the *Canadian Environmental Protection Act* (Government of Canada, 1999), which controls toxic substances and prevents pollution; the *Canadian Environmental Assessment Act* (Government of Canada, 1992); and the *Species at Risk Act* (Government of Canada, 2002).

In the 1987 Federal Water Policy (Environment Canada, 1987), the Government of Canada committed to a number of actions, such as developing national guidelines for groundwater assessment and protection, and measures to achieve appropriate groundwater quality in transboundary waters. The policy presents the federal government's philosophy and goals as to how water should be managed in Canada in the best interest of Canadians, now and in the future, under a joint and cooperative management approach with the provinces. The policy remains largely unimplemented and remains in the public domain for information purposes only (Box 5.2).

33 See Joseph Cumming, "NAFTA Chapter XI and Canada's environmental sovereignty: investment flows, article 1110 and Alberta's *Water Act*" (Cumming and Forochlich, 2007). This article addresses the potential effect of Chapter XI of the North American Free Trade Agreement (NAFTA) on Canada's ability to effectively protect its natural resources through regulation. Specifically, the article discusses a Case Study involving Alberta's *Water Act* and how its objectives could be undermined by Article 1110 of NAFTA.

Box 5.2: 1987 Federal Water Policy

The Federal Water Policy was formulated in the aftermath of a public inquiry on water management led by University of British Columbia Professor, Peter Pearse. The "Pearse Inquiry" marked a paradigm shift in Canada (which also occurred in many other countries) from water policies employed as vehicles for economic development to water policies for the effective long-term management of the resource itself.

Under a joint and cooperative management approach with the provinces, the policy was based on two goals: (i) to protect and enhance the quality of the resource, and (ii) to promote the wise and efficient management and use of the resource. Five strategies were recommended to aid in the implementation of the goals:

- water pricing to reflect the full value of the resource and to serve as a means of controlling demand;
- science leadership to encourage research into current and emerging issues and further develop the data structures to improve the knowledge base available to decision-makers;
- integrated planning on a watershed basis, recognised as the best scale for water management and also the scale most conducive to joint federal, provincial and municipal cooperation;
- legislation renewal to address water challenges, including inter-jurisdictional issues and the control of toxic chemicals in the water cycle; and
- public awareness programs to communicate to Canadians the pressures on their water resources (and the consequences for themselves) so as to encourage the uptake of policy initiatives.

Individual policy statements addressed the many facets of water use and value, including groundwater contamination, safe drinking water, climate change, and data and information needs, among others.

In 2005, the Report of the Commissioner of the Environment and Sustainable Development criticised the government for its "stagnant federal water policy" (CESD, 2005).

Municipal Regulation

Municipalities derive their powers from the provinces. Areas of delegated municipal jurisdiction typically include the power to make land-use and local environmental bylaws. A Supreme Court of Canada decision in 2001 affirmed the right of municipalities to pass bylaws to protect the health of their citizens and the environment (SCC, 2001). Local governments supply water to users on a central system.

They do not issue permits for water takings or allocations. In fact, local governments require a permit from the province for water takings to supply their own systems. Local governments are directly involved in groundwater management in cases where groundwater is a source of municipal water supply, and indirectly through land-use decisions that have the potential to contaminate groundwater.

There is an increasing trend for provinces to delegate groundwater management responsibilities to local governments and multi-stakeholder bodies. This effort is likely to be most successful where the provinces have ensured that delegation is supported by sufficient financial and human resources and where there is a requirement to take action and report back on progress.

In the view of the panel, management of groundwater and land use should be fully integrated. Some integration is beginning to occur through source-water and wellhead protection plans. At a broader scale, aquifer vulnerability maps are increasingly used as tools to guide municipal land-use decisions. Integration is, however, still often incomplete due to:

- inadequate data for assessing the impact of land-use change on recharge and runoff;
- little capacity of municipal governments to effectively implement provincial policy statements as land-use changes are approved;
- little enforcement of best management practices that are recommended, or even mandated, as part of an approved land-use change or in farm land management; and
- prevalence of local political pressure to ensure that new tax-paying land-use changes are smoothly approved.

Aboriginal and Treaty Rights to Water

Though there has been no specific judicial consideration of an Aboriginal right to the use of water, it is reasonable to assume the existence of a right to use water for traditional purposes such as fishing and transportation (Bartlett, 1988). Both federal and provincial governments have a duty to consult aboriginal groups when resource and land-use decisions may affect their rights. The provision of clean drinking water in aboriginal communities across Canada is an ongoing problem that these communities and the federal government are attempting to resolve. (Exact figures on the number of Aboriginal communities reliant on groundwater for drinking water are not available.)

Although a number of federal laws govern water and wastewater on reserve lands, no one law regulates this issue, and the 2006 report of the Expert Panel on Safe Drinking Water for First Nations noted the ‘considerable disadvantage’ of the

patchwork of federal laws, and the numerous advantages of new federal legislation on this topic, i.e., a bridge to self-government, improving capacity of First Nations to deal with water issues, uniform standards for all First Nations, and greater accountability (Government of Canada, 2006a; Government of Canada, 2006b).

Groundwater jurisdiction is also complicated by unresolved Aboriginal water interests, which include legally recognised rights, such as treaty rights, and unresolved claims of Aboriginal rights and title.[34] Recent Supreme Court of Canada (SCC) cases have affirmed the significant leverage that Aboriginal peoples have on the environmental regulatory process and a new confluence between Aboriginal and environmental law (Cassidy and Findlay, 2007). The Haida (SCC, 2004a) and Taku River (SCC, 2004b) cases both arose in the context of environmental regulations related to forestry, mining and environmental assessment. In decisions jointly released in 2004, the SCC held that the government had a duty to consult and accommodate Aboriginal interests before Aboriginal rights and title were finally determined. A subsequent case involving the Mikisew Cree and Treaty held that the duties of consultation and accommodation also applied in a treaty context (SCC, 2005).

Jurisdictional Fragmentation and Coordinating Mechanisms

The different spheres of responsibility for groundwater management overlap and therefore sometimes conflict. The problem is not so much complexity as fragmentation, often intra-jurisdictional, with a lack of coordination. For example, permit allocations made by provincial regulators may diminish baseflows to streams critical for fish habitat and biodiversity maintenance, two areas of federal responsibility (Saunders and Wenig, 2006). Another example occurs when provincially managed groundwater violates health guidelines for drinking water, affecting a municipality's ability to use that source for municipal supply. This is complicated further where groundwater migrates across the Canada-US border, which impacts on American consumers and farmers, as in the case of the Abbotsford-Sumas aquifer discussed in Chapter 6. Resolving these overlaps and conflicts is an essential prerequisite for sustainable groundwater management.

Coordinating mechanisms that involve the federal, provincial and territorial governments and that are relevant to groundwater include: the Canadian Council of Ministers of the Environment (CCME), which has a forthcoming initiative on groundwater; the Federal-Provincial-Territorial Committee on Drinking Water,

34 Aboriginal rights are rights held by Aboriginal peoples that relate to activities that are an element of a practice, custom or tradition, integral to that Aboriginal group's distinctive culture. Aboriginal title is a separate Aboriginal right to the land.

which establishes the Guidelines for Canadian Drinking Water Quality; and Federal-Provincial/Territorial Environmental Assessment Cooperation Agreements. Coordination is also required with local governments, local water users and community and environmental groups.

Interprovincial coordinating agreements on water involving the federal government include agreements related to the Prairie Provinces Water Board (PPWB, 2006), the Mackenzie River Basin Master Agreement (MRBB, 1997), and the Canada-Ontario agreement on Great Lakes water quality (Canada-Ontario Agreement, 2007). Coordination also involves Aboriginal peoples, as Aboriginal rights to water are complex, contested and an as-yet unresolved issue that affects water governance and water management in a number of ways (Woodward, 1994).

Working groups have emerged in recent years that span the federal, provincial and municipal orders of government in the interest of coordinated groundwater strategies. In 2003, a National Ad-Hoc Committee on Groundwater composed of stakeholders from federal and many, but not all, provincial groundwater agencies, as well as a few representatives of the academic and private sectors, issued the Canadian Framework for Collaboration on Groundwater (NRCan, 2003). The goals of this document were to acquire groundwater information and knowledge, improve collaboration among agencies and organisations, establish linkages among groundwater information systems, and provide a resource base accessible to all levels of government for the development of a groundwater management policy. Some of the collaborations envisioned in the report are ongoing; others have been slow to start. A meeting of Canadian government hydrogeologists in October 2007 under the auspices of the Canadian Chapter of the International Association of Hydrogeologists is further evidence of emerging cooperation at the working level, but there is still a need for a more clear-cut, formally stated division of duties among the various levels of government.

Coordination of groundwater management with local governments is also required, as many provinces are delegating an increasing number of water management responsibilities, such as watershed planning, to municipal governments or to multi-jurisdictional governance bodies. Alberta's Watershed Planning and Advisory Councils, Ontario's source-protection committees to protect sources of drinking water in Ontario's *Clean Water Act*, and Québec's Basin Organisations are three examples (Nowlan and Bakker, 2007).

The amount of decision-making authority delegated to these types of bodies varies. Most perform an advisory, rather than a regulatory, function. Delegation may be justified on the basis of the principle of subsidiarity, which has been endorsed by the Supreme Court of Canada as "the proposition that law-making and

implementation are often best achieved at a level of government that is not only effective, but closest to the citizens affected and thus most responsive to their needs, local distinctiveness and population diversity" (SCC, 2001).

Overlapping jurisdiction may become a greater challenge to both surface-water and groundwater management owing to the growing interest in the watershed planning approach. Implementation of sustainable groundwater initiatives will require even greater coordination in the future to overcome the administrative divisions in Canadian water-resource management institutions. Such divisions are common between those who deal with water quantity and those who deal with water quality; between experts in groundwater and surface water; and between those responsible for water science and for water policy.

5.2 THE GOVERNANCE AND MANAGEMENT OF GROUNDWATER IN CANADA

Certain uses of groundwater are unregulated. For example, private domestic use is usually exempt from provincial licensing requirements, and most provinces do not require a permit to be obtained until a certain threshold amount of water will be used. (The threshold varies substantially from province to province.) Wells on private land are generally not regulated after commissioning. Small septic systems are regulated locally at the time of installation but subject to only limited monitoring after installation. Federally regulated lands (First Nations reserves,[35] national parks, military bases, prisons) and entities (airlines, banks, and railways) have no specific water regulations.

Policy Tools for Achieving Sustainability

A number of policy instruments exist to help achieve the sustainable management of groundwater. Regulations on groundwater allocation and prevention of contamination are one group of tools, but they vary widely from province to province. Economic instruments are also created by regulation, and they seek to shape the economic environment in which users make decisions regarding their water use and discharges. Common law remedies may also be used to protect the environment. Voluntary codes of practice and nonbinding standards, including the Canadian Drinking Water Guidelines, constitute another group of tools. Agricultural waste and well construction may be controlled by either codes of practice or regulations in different parts of Canada.

35 The recent Report of the Expert Panel on Safe Drinking Water for First Nations considered the options for regulating safe drinking water on reserves and recommended three potential options (Government of Canada, 2006a).

Efforts to regulate groundwater allocation and the prevention of contamination are challenged by informational deficiencies. Private groundwater withdrawals are often not measured, and the impacts of these withdrawals on groundwater levels and quality may not be well understood. In the words of one analyst, "very few (if any) commodities possess as many idiosyncratic characteristics as groundwater" (Kondouri, 2004). Perhaps as a result, water-related policies and regulations have typically been concerned with influencing the 'quantity' of water used, or the 'quality' of water, but rarely both together. Unfortunately, much of the research literature reflects this artificial separation. Policies aimed at influencing the allocation of specific quantities of water are considered in isolation from policies aimed at achieving a specified level of water quality or from policies resulting in groundwater quality changes as a consequence of excessive abstraction. Sustainable water management clearly involves both quantity and quality as acknowledged in the framework of the five interrelated goals introduced in Chapter 2. The legal framework nevertheless treats quantity and quality separately. Water laws regulate access, allocation, and water quantity; health, environmental and sector-specific laws regulate water quality.

Overview of Provincial Regulation of Groundwater

All provinces manage groundwater through regulations for well construction, maintenance and abandonment, as well as licensing and registration requirements for well drillers. Many provincial laws envision that groundwater will be included in water or watershed plans, though the degree to which this occurs varies from province to province. Ontario passed a *Clean Water Act* (Government of Ontario, 2006) in October 2006 that is anticipated to have positive implications for groundwater protection. The focus of the legislation is to protect present sources and existing future sources of drinking water through (i) assessment of threats to both surface and groundwater in vulnerable areas; (ii) formation of multi-stakeholder source-water protection committees that develop plans to address source-water threats; and (iii) adoption and implementation of plans by municipalities once approved by the Ontario Minister of Environment. These plans may supersede municipal official plans and zoning bylaws if there is an inconsistency. In contrast, Alberta's South Saskatchewan River Basin water management plan (approved in 2006) excluded from the planning process groundwater that was not hydraulically connected to the relevant surface water (Alberta Environment, 2006).

In addition to explicit water laws, a wide range of provincial laws on health, energy development, and pollution prevention and control serve to regulate groundwater extraction, allocation, protection and use. One British Columbia survey listed 39 provincial statutes relevant to watershed planning (WCEL, 2004). A few provinces have passed specific legislation that prescribes

a separate land management regime for a designated area with a particular groundwater issue or focus, such as the Oak Ridges Moraine in Ontario, discussed in Chapter 6.

Many provinces require an environmental assessment of projects with significant groundwater impacts, and procedures invariably allow public participation. The federal government also requires assessments. For example, a project requires a comprehensive study under the *Canadian Environmental Assessment Act* (Government of Canada, 1992) if it involves "the proposed construction, decommissioning or abandonment of a facility for the extraction of 200,000 m^3 per year or more of groundwater, or an expansion of such a facility that would result in an increase in production capacity of more than 35 per cent," or if a federal proponent is involved. Projects that meet both federal and provincial thresholds will be subject to a joint assessment. Even if a formal environmental assessment process is not triggered, many provinces and territories require permit applicants to notify the public of their application and to conduct a public consultation.[36]

Many provinces have also developed non-regulatory strategies for water, such as Québec's water policy, Our Life, Our Future; Alberta's Water for Life strategy; and British Columbia's Living Water Smart strategy. There are also sectoral policies specific to groundwater, such as Alberta's Groundwater Allocation Policy for Oilfield Injection Purposes. Nevertheless, few provinces have developed a comprehensive groundwater strategy, although Alberta is in the process of developing one (Eckert, 2007).

Regulation of Groundwater Withdrawals

Provincial water laws and regulations prescribe who is entitled to a groundwater-use right, such as a permit or licence; how to allocate water between competing water users; and when to remove or curtail rights. In all the provinces except British Columbia, groundwater and surface water are part of the same licensing regime. British Columbia remains the sole jurisdiction in Canada that has no general licensing requirement for groundwater extraction above a defined threshold level. A submission made by British Columbia to the panel identified the lack of a legal framework as a challenge. This submission noted that there

36 Many provinces have an administrative agency that hears appeals of licences or permits. For example, Ontario has an Environmental Review Tribunal; British Columbia and Alberta have Environmental Appeal Boards; and Québec has the Tribunal administratif du Québec. Other administrative tribunals also make decisions on key groundwater issues. For example, in Alberta, the Energy and Utilities Board plays the pivotal role in approving projects that have an impact on groundwater and surface water, including coal-fired power plants and associated mines, oil sands, oil and gas wells, and the use of water for enhanced hydrocarbon recovery.

is generally a lack of understanding and awareness that other provincial agencies and local governments, who make decisions that potentially impact groundwater, need to manage or protect groundwater as part of their business. In 2008, the Government of British Columbia released its Living Water Smart report (Government of BC, 2008) which promises to correct some of the gaps that exist in the current regulatory framework by 2012–2014. The lack of a province-wide mandate for the implementation of this vision nevertheless remains an issue.

Licensing systems that establish rules for priority of use, based on criteria such as the date the licence was obtained (prior allocation), or on set categories such as municipal supply, agricultural, industrial, and power generation, are used in eight of the thirteen jurisdictions (all but British Columbia, Saskatchewan, Québec, New Brunswick and Prince Edward Island) (Nowlan, 2005). Most provinces and territories recognise essential human needs — usually called 'domestic uses' in the statutes — as the highest of priorities. The criteria for issuing a groundwater permit vary from province to province, though notably, no province uses information on the economic value of the water's proposed use as a criterion for decision. In addition, where there is a price for permits to take water, the charges are used only to defray administrative costs and do not provide an incentive for conservation. Data are summarised in Table 5.1.

A common way for regulators to limit the environmental impact of groundwater withdrawals is through the design of criteria for issuing a groundwater licence or permit. These criteria, however, may reflect only a limited consideration of cumulative impacts and ecosystem protection. The oil sands case study in Chapter 6 illustrates this lack of cumulative impact assessment. Another example relates to the lack of cumulative impact assessment by the province of Ontario (this is being done on a more local basis; see case study in Chapter 6) for a number of golf course developments in the Oak Ridges Moraine area in Ontario (Garfinkel *et al.*, 2008). There is, to date, no standard methodology for incorporating instream-flow protection into laws and regulations, although a number of provinces are examining ways to address this gap (Box 5.3). Environmental assessments and approvals for industrial activities also incorporate ecological requirements, as the oil sands and other case studies in Chapter 6 demonstrate. Provinces may use moratoria to restrict groundwater extraction when conditions such as over-allocation so dictate. For example, Prince Edward Island currently has a moratorium, in effect since 2001, on issuing permits for new irrigation wells, as outlined in the Prince Edward Island case study in Chapter 6.

Table 5.1

Provincial Groundwater Allocation Fee Structures (June 2005)

Question / Jurisdiction	Is groundwater ownership explicitly vested in the public?	Price charged for groundwater use (if so, price variables)	Classes of usage subject to or exempt from fees	Administrative cost recovery	Verification of quantity use is universally required (e.g., metering)	Environmental concerns addressed in decision-making process
Alberta	Yes	No	N/A	Yes, through licence fees	No	Discretionary
British Columbia	Yes	No	N/A	N/A	No	No
Manitoba	Yes	Yes, costs range from $1.00 to $2.00 per 1 million litres	All uses except industrial are exempt	Yes, through licence fees	Yes, though not required by regulation, administrative practice requires metering as a condition of licences	Mandatory
New Brunswick	Yes	No	N/A	Yes, well driller fees	No	No
Newfoundland and Labrador	Yes	No	N/A	Yes, through licence fees	Yes, where licence is in place	Mandatory
Northwest Territories	Yes	Yes, costs range from $1.50 to $2.00 per 1 million litres	Fees payable where water is used pursuant to licence (eight types of undertakings require licence)	Yes, through licence fees	Generally a condition of water licensing	Mandatory
Nova Scotia	Yes	Yes, $0.35 to $0.43 per 1 million litres	Fees payable where water is used pursuant to licence (use over 23,000 litres per day)	Yes, through licence fees and annual fees	Yes, where licence is in place	Mandatory
Nunavut	Yes	Yes, costs range from $1.50 to $2.00 per 1 million litres	All water users pay fees, except domestic and emergency	Yes, through licence fees	Generally a condition of water licensing	Mandatory
Ontario*	No	Forthcoming	N/A	Yes, through well drilling and permit fees — use over 50,000 litres per day	No	Mandatory
Prince Edward Island	No	No	N/A	Yes, well driller fees	Yes	Mandatory
Québec**	Yes	Forthcoming	N/A	Yes, through licence fees	No	Discretionary
Saskatchewan	Yes	Yes, costs range from $0 to $12.53 per 1 million litres	All uses except industrial are exempt	Yes, through licence fees	Yes, where licence is in place	Discretionary
Yukon Territory	Yes	Yes, costs range from $1.50 to $2.00 per 1 million litres	Water use under 100 m^3 per day is exempt	Yes, through licence fees	Generally a condition of water licensing	Mandatory

* The charge of $3.71 per million litres of water applies to commercial and industrial water users who withdraw more than 50,000 litres per day from groundwater, starting January 1, 2009. ** Québec is considering a royalty system.

Source: (Nowlan, 2005)

Box 5.3: Water Licensing in Ontario and Québec

Criteria for issuing a water permit in Ontario and Québec apply to both groundwater and surface water and require consideration of the protection of the natural functions of the ecosystem, water availability, water use (including the impact or potential impact of the water on water balance and sustainable aquifer yield), and other issues, including the interests of anyone who has an interest in the water-taking (Government of Ontario, 2004).

In Ontario, the regulation allows an application to be refused if the proposed water-taking is in a high-use watershed as shown on the Average Annual Flow Map, and if the water taking is for certain defined uses such as water bottling and aggregate processing, unless certain conditions are met. Ontario's obligations under the Great Lakes Charter must also be considered when issuing a permit.

In Québec, hydrogeological studies and quantification of the impacts on ecosystems and other local users must accompany an application (Parliament of Québec, 2002).

Regulation of Groundwater Quality

Groundwater quality is protected through drinking-water and aquatic-health protection laws as well as environmental assessment approvals at both the provincial and federal levels, and approvals for activities such as well drilling, geothermal and energy development, and contaminated site remediation. Despite programs at all levels of government, management and regulatory actions to remedy contamination and prevent further degradation remain inadequate for sustainable groundwater management. The sustainability goal of protecting groundwater from contamination, including the remediation of already impacted groundwater, requires action on several fronts.

Groundwater quality is also protected by provincial environmental laws, which usually require companies that emit contaminants into the air or water, or dispose of waste, to obtain permits from the relevant provincial department or ministry of the environment. These laws do not distinguish between pollution of groundwater or surface water. While different legal approaches are used to limit water pollution, a common approach in Canada is known as the 'end-of-pipe' regulation, which limits the concentration or amount of a particular chemical being deposited in a water body by a particular source. Although provincial schemes typically provide for extensive investigation, inspection, contravention, and penalty provisions, in practice they are infrequently used. By contrast, the United States *Clean Water Act* (US Government, 1972) uses the 'total maximum daily load' approach, which determines the maximum quantity of a pollutant that a receiving body can tolerate in a day, and limits total deposition by all sources to less than this.

Threats to groundwater arise from concentrated point sources of pollution such as discharge of wastewater from industrial sources, as well as from diffuse non-point sources such as urban runoff and agricultural contamination. Elevated nitrate concentrations, mainly from dispersed agricultural sources, continue to persist in groundwater in a number of important aquifers across the country. Despite widespread awareness of the problem, there has been little success through a Best Management Practices approach in reducing nitrate loadings and their concentration in our groundwater resources. Voluntary control measures for agricultural runoff, even when supported by incentives, have been unsuccessful. Innovative stormwater controls show promise for groundwater recharge, but their impacts on groundwater quality are not well understood.

Groundwater Used for Drinking Water

The primary relationship between groundwater quality and human health arises from the use of groundwater as a source for drinking water. If adequately regulated, groundwater has some inherent and beneficial characteristics, including:

- accessibility in locations where reasonable quantities of high-quality surface water are not available;
- consistency of composition — i.e., groundwater quality is generally much slower to change than surface water, allowing more time to adjust water treatment responses to changing water quality characteristics (although the corollary is also true that once it is contaminated, considerable time and expense are necessary to remediate it); and
- long groundwater flow paths and natural filtration through subsoil media, which achieves some, and often substantial, pathogen removal.

For private supplies, availability of any quality of water will be the key driver of source selection because surface-water alternatives are commonly not available. When poor-quality groundwater is the only option for a private water supply, point-of-entry or point-of-use water treatment technology will be necessary.[37] For community water supplies, both the quantity and quality of available groundwater are key determinants relative to any surface-water supply alternatives. The technologies used in point-of-entry or point-of-use devices are often substantially more expensive at the scale of a community water system than conventional water treatment technology.[38]

37 Point-of-entry devices treat all the water entering a building. Point-of-use devices treat only the water at a particular outlet, such as a kitchen tap.

38 Conventional water treatment technology is usually considered to be chemical coagulation, rapid dual media filtration and chlorination for disinfection.

Box 5.4: Regulation of Drinking-Water Quality in Canada

The Federal-Provincial-Territorial Committee on Drinking Water refers to a "multi-barrier" approach to ensure the safe delivery of drinking water to the consumer's tap. This approach evaluates and implements means for ensuring high-quality drinking water within every component of the water-supply system, from the broad natural environment to the supply aquifer or reservoir, to the water treatment plant and, finally, to the water distribution system. The multi-barrier approach is not consistently applied across the country.

One key element of this approach is the Guidelines for Canadian Drinking Water Quality, published by Health Canada since 1968, which set Maximum Acceptable Concentrations (MAC) of certain contaminants after water treatment. These Guidelines are not binding and are not mandated by a national law regulating drinking water, but instead are incorporated into provincial laws in different ways.[39] Provincial laws require water suppliers to ensure that the water they supply is potable by meeting minimum water treatment and quality standards. The laws also require monitoring and water-quality testing, construction approvals, operator and laboratory certification, and public notification of water-quality problems.

A second element of the multi-barrier approach is source-water protection. To protect groundwater drinking-water sources, provincial laws may require a water management plan, such as a source-protection plan that can, among other things, set water-taking limits. Each province has different forms of water planning provisions. Ontario's new *Clean Water Act*, for example, is to date the only law in Canada that requires drinking-water source-protection plans to be prepared for most of the province.

All provinces regulate wells primarily to guard water quality, by protecting the zones around wells, but also to conserve groundwater, by controlling and sometimes limiting the rate of extraction. For example, well owners may be obligated to stop or control artesian flows.

Bottled water is considered a food and is regulated under Division 12 of the Food and Drug Regulations. Bottling facilities were subject to inspection by the Canadian Food Inspection Agency, including some analysis of water quality (Health Canada, 2007). However, the Agency indicated it will discontinue inspection of water bottling facilities in 2005 due to improved compliance.[40]

39 Environment Canada's Freshwater website provides links to water-related policy and legislation in Canada's provinces and territories. See http://www.ec.gc.ca/WATER/en/policy/prov/e_prov.htm for more information. A recent (2006) listing or comparison of provincial and territorial regulatory regimes for drinking water is available as Appendix C of the Report of the Expert Panel on Safe Drinking Water for First Nations (Government of Canada, 2006a).

40 See Table 2.5, DPR 2004-05, available at http://www.tbs-sct.gc.ca/rma/dpr1/04-05/CFIA-ACIA/CFIA-ACIAd4502_e.asp.

All provinces have requirements for regular water sampling from municipal drinking-water wells and, while most sampling is focused on the treated water, raw water sampling is usually necessary. Water-quality analyses must comply in some provinces with the Guidelines for Canadian Drinking Water Quality promulgated by Health Canada (Box 5.4). In cases where capture-zone or source-protection plans are in place for such wells, the plans usually include the installation of monitoring wells that are sampled regularly to ensure that there has not been any encroachment of contaminated groundwater into the protected area.

Because of strong municipal management and collaborative provincial oversight, and the role of the Federal-Provincial-Territorial Committee on Drinking Water, the quality of groundwater-based municipal drinking water is generally excellent across Canada. However, the frequent occurrence of microbial contamination in private and small community wells, including First Nations wells, remains unacceptable and undermines the health of a number of Canadians. A stronger regulatory environment for Canadian drinking water is necessary.

For regulatory purposes, groundwater is classified into one of two major groupings: (i) groundwater under the direct influence of surface water contamination (GUDI);[41] and (ii) 'secure' groundwater (which allows for reduced treatment requirements). Drinking-water supplies from GUDI sources are generally required to meet the same treatment requirements as surface water sources. More 'secure' groundwater sources are often exempted from expensive filtration requirements.

There are currently 67 microbiological, chemical or physical parameters (plus 78 radionuclides) listed with Maximum Acceptable Concentrations (MAC) in the Guidelines for Canadian Drinking Water Quality (Health Canada, 2008). Most parameters are listed for precautionary reasons; i.e., if present at concentrations substantially exceeding the MAC, they could pose a health risk to consumers. There is a much shorter list of contaminants that are known to have caused adverse health outcomes through exposure to drinking water and that may pose a pervasive threat to drinking-water safety. Among the major drinking-water contaminants with demonstrated health risks to humans are microbial pathogens (including viruses, bacteria and protozoa), arsenic, nitrate and fluoride (WHO, 2007).

41 Various definitions of GUDI are used, but the concept is illustrated by one regulatory guidance document: "any water beneath the surface of the ground with: i) significant occurrence of insects or other macro-organisms, algae, organic debris, or large-diameter pathogens such as *Giardia lamblia* or *Cryptosporidium*; or ii) significant and relatively rapid shifts in water characteristics such as turbidity, temperature, conductivity, or pH which closely correlate to climatological or surface water conditions" (Nova Scotia Environment and Labour, 2002).

Microbial Pathogens: These have always been the most pervasive health risks associated with drinking-water consumption.[42] Of all the microbial pathogens (viruses, bacteria and protozoa), viruses are the smallest and most likely to pass through granular media, thereby potentially posing a greater risk for groundwater contamination. Viruses are not routinely monitored in groundwater, but enteric viruses have been occasionally detected in Canadian municipal drinking-water wells by recent research funded by the Canadian Water Network (Locas *et al.*, 2007; Locas *et al.*, 2008; see also the Great Lakes Basin case study in Chapter 6).

Fortunately, fatalities caused by water contaminated by microbial pathogens are now rare in Canada. A tragic exception was the outbreak in Walkerton in May 2000, where mismanagement of the municipal water-treatment system allowed pathogen-contaminated groundwater, arising from cattle manure, to enter the drinking-water supply, making more than 2,300 individuals ill, of whom seven died (see Box 5.5). Microbial pathogens causing water-borne outbreaks usually arise from fecal wastes originating, in order of likelihood, from humans, livestock, and wildlife. Where microbial contamination is discovered, the main emergency response tool available to public health authorities is to issue a boil-water advisory (or order, in the case of commercial facilities serving the public). An investigative news story for the Canadian Medical Association Journal (CMAJ) reported a total of 1,766 boil-water advisories in effect in Canada as of March 31, 2008 (Eggertson, 2008b). These were in addition to those in place in First Nations communities, which totalled 93 in February 2006 (Eggertson, 2008a). No breakdown was available for what proportion of these situations involved groundwater sources, and the high totals reflected the reality that some provinces, like Ontario (679 boil-water advisories), included facilities like trailer parks, campgrounds, seasonal camps and gas stations, while other provinces like Alberta (13 boil-water advisories) did not report for the whole province, nor were very small systems included. British Columbia has a large number of very small community systems (more than 3,500) resulting in a disproportionate number of boil-water advisories (530) for its population, as is the case with Newfoundland (228). Many boil-water advisories have been in place for years, indicating that they are being used as an alternative to providing adequate treatment or source protection, a problem that is tied to a widespread reliance on very small systems lacking adequate means to ensure the competence necessary to consistently deliver safe drinking water (Hrudey, 2008a; Hrudey, 2008b).

42 The World Health Organization estimates that currently "1.8 million people die every year from diarrheal diseases (including cholera); 90 per cent of these are children under five, mostly in developing countries and 88 per cent of diarrheal disease is attributed to unsafe water supply, inadequate sanitation and hygiene" (WHO, 2004).

Arsenic: While arsenic may be a byproduct of many industrial processes, the most common source of arsenic contamination of drinking water is the natural minerals in geologic materials. Arsenic is abundant in the earth's crust, and groundwater at many locations in Canada has elevated levels of the element. Instances of high arsenic concentrations in drinking water around the world originate primarily from natural sources in groundwater (well water). Surface water in general contains concentrations of arsenic below the World Health Organization and Health Canada guideline levels of 10 micrograms (μg) per litre. Data from all Canadian water utilities show arsenic concentrations below the 10 μg per litre guideline level. Nevertheless, several localised areas in Canada, including Halifax and Guysborough Counties in Nova Scotia, exhibit arsenic concentrations in private well water above 10 μg per litre.

Nitrogen: Nitrogen compounds, whether from natural sources, fertiliser application or improper septic-field operation, can lead to increased nitrate and nitrite levels in groundwater because nitrogen compounds are readily oxidised to nitrite and nitrate. These ions are highly soluble in water and are easily transported through soil materials and aquifers. Elevated nitrite levels in the blood can be caused by exposure to elevated nitrate levels in drinking water, leading possibly to a disorder caused by a reduction in haemoglobin capacity of blood to transport oxygen (methaemoglobinaemia). Bottle-fed infants are particularly at risk. Groundwater can exhibit elevated nitrate concentrations in response to local land use and hydrogeological conditions.

Fluoride: The excess ingestion of fluoride can cause fluorosis, a condition that first affects the teeth. At higher exposure levels, it affects bones, leading to skeletal fluorosis, which can be a debilitating disorder. In much of Canada, fluoride is added to drinking water in carefully controlled amounts as a public health measure to strengthen dental enamel and prevent tooth decay. These levels are not harmful to health. However, fluoride can be naturally elevated in groundwater to levels that exceed those that cause the beneficial effect on dental health and cause the adverse effects of fluorosis (WHO, 2008).

Other Contaminants: There are many potential drinking-water contaminants intrinsically capable of causing adverse human health effects at sufficiently high doses, even if they have not caused documented disease outbreaks through drinking-water exposure. These contaminants require attention to ensure that they do not become a public health problem. For groundwater, some of the more common contaminants of precautionary concern include: radionuclides (from natural or human activity); uranium, for chemical toxicity to kidney function (from natural or human activity); pesticides; semi-soluble hydrocarbons (from human activity); halogenated solvents, including trichloroethylene and perchloroethylene (from

human activity); and mixed contaminant sources such as leachate from landfill and waste-disposal activities. These contaminants are difficult to treat and have the potential to cause the shutdown of municipal well fields. Proactive measures are necessary to identify contaminants of natural and human origin that may render groundwater unsafe for consumption, and to inform residents of their presence. Reconnaissance surveys and publication of information, coupled with mandatory testing of private wells in suspect areas, are necessary to protect the health of rural residents.

Finally, there can be aesthetic or nuisance factors associated with poor water quality that are related, for example, to smell, taste, excessive hardness, or appearance. Although these are not usually direct causes of adverse health effects, the noxious nature of such water sources can lead users to seek more aesthetically pleasing, but less safe, water sources. A case in point arising from the Walkerton experience is that the vulnerable shallow that caused the outbreak when it became contaminated with microbial pathogens, was commissioned and maintained by the town because its water was much softer than the deeper, more secure wells which otherwise served the town.

Looking forward, the use of large-scale water treatment technology as a means of polishing groundwater to drinking-water standards is expected to become increasingly cost-effective and will assist municipalities in maintaining the use of groundwater as a drinking-water source in urban settings. The Regional Municipality of Waterloo is already moving forward in this regard in order to re-institute one of their high production wells in Waterloo (personal communication, 2008).

Box 5.5: Walkerton — Events of May 2000

In May 2000, Walkerton, Ontario, experienced an outbreak of water-borne disease that killed seven people and caused serious illness in more than 2,000 others. This event gripped the nation's attention because of the human tragedy that unfolded and the shock that a community water supply could cause the death and illness of consumers in Canada's largest province at the start of the 21st century. Ontario called a public inquiry, headed by Justice Dennis O'Connor, which produced two detailed reports: Part 1 dealt with what happened in Walkerton (O'Connor, 2002a) and Part 2 dealt with what steps Ontario should take to prevent such failures from happening again (O'Connor, 2002b). Despite the clarity and detail of these reports, many Canadians, including professionals with an interest in water, adopted selective accounts from the mass media coverage and much misinformation about this tragedy remains.

Walkerton was served by three wells in May 2000. The well ultimately determined to be responsible for the outbreak was designated as Well 5. It was drilled in 1978

and completed in fractured limestone with the water-producing zone ranging from 5.5 metres to 7.4 metres in depth. The outbreak occurred after a heavy spring rainfall (a one-in-60-year storm) resulted in Well 5 becoming contaminated by pathogens traced to manure produced on an adjacent farm. The exact means by which the pathogens travelled from the farm manure to enter Well 5 was never established with certainty, but the karst conditions (i.e., conduits caused by dissolution of the carbonate bedrock) of the shallow aquifer allowed rapid transport of contamination once it reached the aquifer. The operator of the farm was following exemplary farm practices and was exonerated by the Inquiry. When Well 5 was commissioned in 1978, the pump test showed fecal coliform contamination after 24 hours. The hydrogeologist's report warned of the contamination risks, specified the need for chlorination, and recommended that the town purchase a buffer zone to protect Well 5, but no action was ever taken on the land-use recommendation. Microbiological and turbidity monitoring over subsequent years confirmed that Well 5 was subject to surface contamination.

The only treatment barrier required by the Ontario Ministry of Environment was chlorination to achieve a residual of 0.5 mg per litre after a 15-minute contact. If that single requirement had been continuously met, more than 99 per cent of the pathogens would have been inactivated. Although the system supervisor was supposed to measure the chlorine residual once a day, the Inquiry found that chlorine residuals were not measured on most days and that fictitious entries for residuals were usually entered on daily operating sheets.

The failure to measure chlorine residuals was critical, because the contamination most likely entered Well 5 on May 12, one week before illness became evident in the community. When asked on May 19 and 20 whether there were any problems with the drinking-water quality, the general manager of the system assured the local health authorities that the water was satisfactory, despite having received adverse microbiological monitoring results for the Walkerton distribution system on May 17. A boil-water advisory was not issued until May 21, when health authorities had concluded the water must be involved. The first victim died on May 22. At least eight days without valid chlorine residual monitoring had passed between the contamination influx and the boil-water advisory, after illness was already widespread.

The organic loading from the manure contamination would have overwhelmed the inadequate, fixed chlorine dose, leaving no chlorine residual or disinfection capacity to inactivate the pathogens entering the distribution system. Measuring the chlorine residual would have identified the problem immediately, but none was measured during this critical period.

The Inquiry revealed failures at many levels, including: ineffective regulatory oversight, reductions in funding of provincial water monitoring, inadequate watershed protection, poor system management and operations (water treatment and monitoring of the barriers for the risks facing this vulnerable groundwater system), and inadequate operator training.

Some of the prevalent misconceptions about Walkerton have ranged from the extremes of assigning all the blame on the operators to assigning all the blame on the regulatory system. The misdeeds of the operators included lying and falsifying records and were certainly inexcusable, but the Inquiry found that these operators had no idea of the risks they were bringing upon their neighbours. They continued to drink the water themselves during the outbreak. The operators were charged under the Criminal Code, but in accepting their guilty pleas the Crown accepted a statement of facts claiming that there was nothing the operators could have done once the system had become contaminated. That erroneous claim misses the critical issue that performing the chlorine residual monitoring that was required would have revealed, in real-time, that Walkerton's water was contaminated. The system could have been shut down, and a boil-water advisory called within 24 hours, rather than allowing residents to consume heavily contaminated water for eight more days as ultimately happened. This was particularly tragic because the local hospital recommended parents have their children with diarrhea drink more fluids, thereby increasing their exposure to the contaminated water during this period.

The Walkerton disaster provides a strong case for the multiple-barrier approach to assuring safe drinking water. This disaster does not demonstrate that groundwater is inherently unsafe for drinking-water supplies. Well 5 was recognised from the outset as a vulnerable shallow well (groundwater under the direct influence of surface water) and evidence demonstrated consistently that it was subject to contamination, so this vulnerable, thoroughly mismanaged scenario must not be generalised to all groundwater supplies. Because outbreaks of disease caused by drinking water remain comparatively rare in Canada, particularly in contrast with the developing world, complacency about the dangers of water-borne pathogens has become common. Yet, the source of water-borne disease in the form of microbial pathogens is an ever-present risk because these pathogens are found in human fecal waste and in fecal wastes from livestock, pets and wildlife, making any drinking-water source at risk of contamination before or even after treatment (if a bacterial source was to be introduced after treatment).

Enforcement

The foregoing has described the framework of existing regulations in respect of protecting both the quantity and quality of groundwater, but even the best rules will not be effective if not adequately enforced. The panel believes that stronger enforcement of existing regulations and controls would improve sustainable groundwater management. Among the enforcement options most in need of improvement are accurate and timely reporting of all licensed groundwater withdrawals; adherence to water-quality monitoring requirements; provision of complete documentation of geology and well construction and well abandonment details; and timely adherence to contaminated site clean-up and restoration.

5.3 ALTERNATIVE GROUNDWATER REGULATORY APPROACHES

The discussion to this point outlines what might be called the 'regulatory paradigm' that has been used to manage groundwater to date in Canada. Taken as a whole, the regulatory decisions of governments form the framework within which decisions by private agents such as farmers, households, and firms are taken. For the most part, this regulatory paradigm has set quantitative limits on water withdrawals or the deposition of wastes or, less commonly, set technological standards that have to be met. Thus, one important feature of this framework concerns the incentives or signals it provides to decision-makers regarding their water use or waste disposal. For the most part, these quantitative limits have provided relatively weak incentives for decision-makers to innovate, to conserve on water use or to consider explicitly the costs that their actions (in terms of aquifer drawdowns) may have imposed on others.

Furthermore, notwithstanding the existing regulatory framework, there are several reasons to expect private decision-making in respect of groundwater use to be inefficient and possibly unsustainable. Many of these reasons are related to groundwater in some cases having the characteristics of 'common property' as described in Box 5.6. It is nevertheless the case that economic efficiency in groundwater management is seldom a consideration in the Canadian context. Current groundwater allocation methods do not use market-based incentives such as fees, subsidies and trading systems to shift allocation to high-value uses and generally promote conservation. By introducing appropriate incentives, it may be possible to bring user decisions closer to efficient and sustainable groundwater use. The implementation of economic instruments will require determination of royalty rate structure, integration of the instruments with existing regulations, and collection of the local-scale information necessary to design and implement the instruments.

Efficiency is a term used by economists to describe an allocation of productive resources where social welfare is maximised; i.e., society is doing the best it can with its limited resources. The concept of efficient use is more commonly understood in the context of minimisation of waste. In that regard, there is great scope for broader application of available technology and further research to improve the efficiency of water use in many industrial and domestic sectors, the oil sands developments being one prime example. Economic incentives, and in some cases regulations, may also need to be considered.

The conditions needed to achieve efficiency, in the welfare-maximising sense used by economists, have received considerable attention; nowhere more so than in the use of natural resources such as groundwater (Griffin, 2006; Kondouri, 2004). Efficient withdrawal of groundwater requires that users be aware of the full costs and benefits of personal actions. The challenge lies in defining and measuring the relevant concepts and developing a regulatory environment in which the user of groundwater is made

Box 5.6: Tragedy of the Commons

Aquifers may cross property boundaries and even political boundaries. This feature, combined with the fact that it is often difficult to monitor withdrawals from an aquifer, suggests that the exploitation of aquifers may suffer from the problems often associated with other common property resources such as communal grazing areas, near-shore fisheries and wilderness areas. Withdrawals from an aquifer by a user in one time period have the potential to impose costs on others both in the same and future time periods. Costs may be imposed in the current period when one user's withdrawals lower the water level of the aquifer and thereby increase pumping costs for others, or when one user's withdrawals reduce water quality in the aquifer and thereby reduce its value to others. Furthermore, costs may be imposed on future water users because a unit of groundwater removed in the current period may be unavailable for use in future periods. Finally, in the case of shallow groundwater resources, there may be hydrological interactions between surface and groundwater resources with the effect that withdrawals from groundwater sources may reduce surface-water flows and thus impose additional costs on users of surface water and have negative implications for local ecosystems. A discussion of recent empirical studies is found in Kondouri, 2004.

In the absence of regulations compelling each user to take all current and future costs and benefits related to groundwater use into account, there are strong reasons to believe groundwater withdrawals will not be efficient or sustainable. Typically, a user is fully aware of the benefits of personal water use but only partially aware of the costs (perhaps knowing one's pumping costs but not knowing the costs being imposed on others). This results in the user overestimating the net benefits (benefits minus cost) and thus withdrawing too much water from the aquifer. Since all users tend to make the same error, a damaging depletion may result from the collective over-exploitation of the common property resource — in this case, a shared aquifer.

The actual magnitude of the inefficiency and its implications for sustainability will depend on a number of real-world parameters such as the physical character of the aquifer as well as the magnitude of the costs being imposed on others, relative to the benefits being enjoyed by the user.

aware of them. These observations have led some analysts to investigate alternative regulatory paradigms that might provide stronger incentives for innovation and conservation (Kolstad and Freeman, 2007). One alternative paradigm in particular relies more heavily on altering the economic landscape facing water users through the introduction of prices for water or the establishment of markets for water. These approaches have historically been eschewed by Canadian governments (with some recent exceptions, notably Alberta) and, thus, it may be valuable to consider briefly what is known regarding the potential efficacy of these 'economic instruments'.

There are very few empirical studies of Canadian water demands, and of these, almost none specifically consider the users' demand for groundwater (Renzetti and Dupont, 2007). As a result, what we currently know about the economic characteristics of the demand for groundwater in Canada must be inferred from existing studies of the demand for surface water in Canada or from empirical studies of groundwater demands from other jurisdictions (Box 5.7).

Box 5.7: What Determines the Demand for Water?

The socio-economic and climatic similarities between Canadian and American cities allow some inferences to be drawn from empirical studies of the United States. In a recent meta-analysis of 124 estimates of the residential price elasticity of demand, Espey *et al.* (1997) calculate an average price elasticity value of -0.5*. Furthermore, residential water demands have been found to be positively correlated, as might be expected, with income, number of family members, size of home, size of lawn and summer temperature (Griffin, 2006; Renzetti, 2002). There is some evidence that the water demands of Canadian households are positively related to the quality and reliability of municipal water supplies (Adamowicz *et al.*, 2007; Rollins *et al.*, 1997).

Industrial water use has been found to be sensitive to a variety of economic factors such as the price of water, the prices of other inputs and the level of the firm's output. Dupont and Renzetti (2001), for example, apply an econometric cost-function model to Environment Canada's Industrial Water Use Survey data for the manufacturing sector and conclude that the average price elasticity of demand for intake water is -0.8. Furthermore, water intake demand has been found to be positively related to the level of firm output and to the price of internal water recirculation (de Gispert, 2004). This last finding indicates that many manufacturing firms view intake water and water recirculation as substitutes. A portion of fluid effluent from industrial facilities and municipal sewage treatment plants may be deposited in aquifers. The economic characteristics of these activities are particularly ill-understood. However, there is limited empirical evidence that economic instruments (such as effluent charges) and environmental regulations induce both manufacturing plants and municipal governments to reduce their waste flows (Dupont and Renzetti, 2001; Renzetti, 1999).

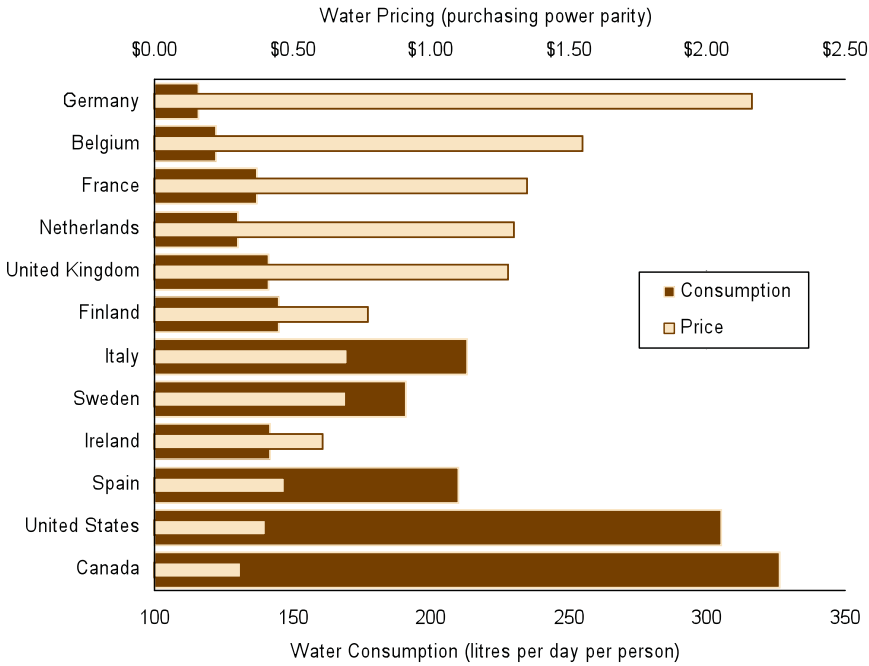
Evidence from American studies suggests that irrigation-water demands from agriculture are less sensitive to prices than industrial- or residential-water demands. Conversely, they have been found to be positively correlated with the value of the crop and evapotranspiration levels (Griffin, 2006). In the cases where farmers have access to both groundwater and surface-water supplies, there is evidence that farmers may treat groundwater as a buffer against uncertain surface-water supplies.

*A price elasticity value of -0.5 indicates that a household's water demand is predicted to fall by 0.5 per cent in response to a one per cent increase in the price of water (holding all other factors fixed).

Setting a Price for Groundwater

There are two levels of jurisdiction at which a price could be set for groundwater. The first is at the municipal level, where some water agencies rely in whole or in part on groundwater supplies to provide potable water to their customers. The second is at the provincial level, where provinces could set prices for direct abstractions by farms, industrial facilities, water utilities and other large users of groundwater.

Municipal Pricing: Municipal water prices can be designed to promote sustainable groundwater use (Figure 5.1). An important first step is that a local water agency's cost accounting must fully record all of the costs of providing drinking water. Historically, this has not been done, with water agencies typically recording operating costs and a portion of capital costs (Renzetti and Kushner, 2004), thus providing water users with an implicit subsidy and an incentive to use water unsustainably. However, recently introduced legislation in Ontario (Government of Ontario, 2002b; Government of Ontario, 2006) will require local water providers to account for all operating, capital and source-protection costs that they incur and to recover these through appropriately designed prices. While these initiatives may not have defined the 'full costs' of water supply



(Data Source: Environment Canada, 2008c; OECD, 1999)

Figure 5.1

Municipal water consumption and pricing.

as the European Union's Water Framework Directive (in which environmental costs are also included, as discussed in Box 5.1), they are an important step towards promoting the principles of demand-side management and thus of sustainable groundwater use.

Provincial Pricing: The second level for pricing groundwater is provincial.[43] The available empirical evidence on the economic features of water demand suggests that levying a groundwater abstraction royalty or tax will result in reduced withdrawals. Several European countries have levied such charges, and there is some evidence that, in addition to raising revenues to support environmental programs, the royalties have prompted industrial firms and other users of groundwater to innovate and use less groundwater (Speck, 2005).

The significant challenge in levying these charges is the difficulty of determining the appropriate rate for the royalty (see Dupont and Renzetti, 1999 for an example of such an assessment using Canadian data). In principle, the fee should reflect the marginal public cost of the groundwater use; this, in turn, would depend on a large number of hydrological, ecosystem and economic parameters (Kondouri, 2004). In order to promote efficient and sustainable use of groundwater, these charges, in theory, should be specific to the place and time of the withdrawal.

In principle, the pricing of direct abstractions of groundwater could be extended to address activities that result in changes in groundwater quality. For example, a 'pollution tax' could be levied against activities, including farming or industrial operations such as factories, that bring pollutants into aquifers. The tax would be designed to discourage such activities and to complement other environmental regulations. (This presumes that a certain amount of specified pollutants can be safely assimilated by the water system in question.[44]) The task of setting a price for point sources of groundwater pollution is similar, in principle, to that of regulating withdrawals of groundwater. However, the informational requirements for setting a price on groundwater pollution would be quite challenging because they would require an understanding of the current and future impacts of the polluting activity and the economic damages associated with them. Agricultural water pollution exhibits several particularly problematic characteristics for regulators. These include uncertainties regarding the source of emissions, the quantity of emissions from each source, the relationship between actions of polluters and emissions, and the relationship between emissions and ambient environmental quality of both surface water and groundwater. In addition, because of the crucial importance of

43 Several provinces already levy administrative fees for water abstraction permits. The basis for these fees and their impacts on users are unclear. See the Sierra Fund report (Nowlan, 2005).

44 In the United States, for example, there are a limited number of economic instruments based on allocation of 'total maximum daily load' of certain pollutants in surface water systems (Hoag and Hughes-Popp, 1997; Keplinger, 2003).

physical conditions (e.g., local soil types, groundwater-surface-water interactions and weather conditions), the analysis of non-point-source pollution, and the design of policies aimed at controlling it in a least-cost fashion, are likely to be case-specific.

Creating a Market for Groundwater

An alternative economic instrument relies on the creation of a legal and market framework, within which private agents trade their rights to water use. There is now considerable literature (summarised in Griffin, 2006) that demonstrates that well-designed water markets can improve the efficiency of the allocation of surface-water resources, although there are continuing concerns about unintended negative impacts on instream flows and third parties affected by water trades. Horbulyk and Lo (1998) and Mahan *et al.* (2002) carry out useful simulations of the workings of surface water markets under the prior appropriation regime of southern Alberta. The numerical results show a significant improvement in the efficiency of water allocation (relative to current allocations) as a result of water trades. The *Alberta Water Act* (1999) authorises transfers of an allocation of water under a licence, if approved by a Director of the provincial government. A number of transfers of surface-water licences have occurred, chiefly in southern Alberta, with more transfers expected in the future. To date there have been no transfers of licences for groundwater use, although legislation does allow the transfer of groundwater allocated under these licences.

Reallocation of groundwater licences through the introduction of markets could, in principle, be part of a framework to trade in-surface water rights or could exist on its own. Creation of a market for groundwater abstraction rights, however, presents considerable challenges (Garduno *et al.*, 2003; Griffin, 2006; Kemper *et al.*, 2003). Griffin enumerates a number of reasons why groundwater markets may have difficulty achieving the same efficiency gains that have been experienced with surface-water markets. Paramount among these is the set of external effects that one agent's groundwater use may have on current and future users (Box 5.7). For example, increased rates of pumping by one user (that might follow from purchasing or leasing groundwater rights) may increase the pumping and treatment costs of other contemporaneous users and may reduce aquifer levels for future users.

Just as the pricing of groundwater could be extended to account for users' impacts on water quality, so too could groundwater markets be employed to address water quality concerns. In fact, researchers have considered the application of tradable permits to the control of non-point-source pollution. For example, farmers within a watershed could be allotted or sold permits for the application of phosphorous or nitrogen on their crops. A trading system to limit phosphorous discharges to the South Nation River in Ontario has been implemented (Sawyer *et al.*, 2005). Farmers

who are able to reduce their use of the regulated substance will find themselves with extra permits that can be sold to farmers, municipalities and businesses facing higher costs of abatement. The challenge in implementing trading schemes for non-point pollution is two-fold. First, the damage caused by a given quantity of emissions will depend on a variety of factors. As a result, regulators will not, in general, be indifferent to the time, location and manner that the nitrogen or phosphorus is applied. These concerns may narrow the range of possible trades and, as a result, restrict the potential efficiency gains of trading. Second, it must be possible for regulators to monitor and measure nitrogen or phosphorus use to ensure that farmers are not employing more than they are allotted.

In summary, a considerable body of evidence suggests that greater use of economic instruments such as water prices, abstraction fees and tradable permits has the potential to promote sustainable groundwater use. The principal challenges facing their implementation include the lack of experience of governments in Canada with these policy instruments; a lack of understanding regarding the economic characteristics of users' groundwater demands; and the need to coordinate the introduction of market-based instruments with existing regulatory frameworks.

5.4 ALLOCATION OF RESOURCES TO GROUNDWATER MANAGEMENT

Many aspects of groundwater management are best carried out at a local level where knowledge of local conditions can be used to make day-to-day land-use decisions and satisfy long-term planning needs. However, the advanced technical expertise required to investigate complex aquifer systems and develop and calibrate the model simulation systems is costly and requires considerable skill. Allocation of staff and funding to groundwater management has not kept pace with the increasing demands placed on the resource, leaving many Canadian basins with insufficient groundwater management expertise and capacity. Several examples suggest that cooperative efforts involving the three orders of government have generated positive outcomes by combining available resources into a single, geographically focused, vertically integrated management approach (see the case studies in Chapter 6 on Basses-Laurentides and Oak Ridges Moraine).

There currently is a shortage of hydrogeologists in Canada and there will be an increasing demand for groundwater science and management skills as more rigour is applied to managing the resource. University and college programs that focus on groundwater as a resource within a framework of integrated hydrological sciences and ecosystem sustainability, watershed management, water resources economics and water law will be increasingly in demand (see Box 5.8).

Box 5.8: Training in Hydrogeological Skills in Canada

Groundwater professionals usually are registered engineers or geoscientists, but hydrogeology, in its own right, is not a registered profession in Canada. This makes it difficult to gauge the number of groundwater professionals working in Canada. Indeed, groundwater expertise can be acquired through various disciplines such as geological, civil and environmental engineering; environmental sciences; physical geography; and perhaps others. Nevertheless, hydrogeology is most commonly considered a sub-discipline of the geosciences. Furthermore, acceptance as a hydrogeologist generally requires an advanced degree (M.Sc. or PhD) with specialised training in the hydrogeological sciences.

Of the 36 Canadian universities that offer programs in the geosciences, almost half offer advanced degrees with specialised training in hydrogeology. There is a considerable range in the size and scope of the various programs, although most offer courses in the basics of physical hydrogeology, environmental geochemistry and mathematical modelling. Relevant training is also available through one or two introductory courses at the undergraduate level at several additional universities, and through environmental programs at several colleges. Though relevant, the breadth and intensity of undergraduate and college training is generally not sufficient for graduates to be considered groundwater professionals. Additional training is available through seminars and short courses offered by industry and universities or through professional associations such as the Canadian Chapter of the International Association of Hydrogeologists and the Canadian Geotechnical Society.

Given the rapid emergence of groundwater quality as a major environmental concern at the time when many of the groundwater programs were being established (about 30 years ago), university-based teaching and research has had a strong orientation towards contaminant hydrogeology. More recently, however (and possibly in response to greater awareness of global water shortages, climate change and the need for a more integrated approach to water management), greater emphasis is being put on groundwater resource development.

Estimates gleaned from membership in professional associations suggest that there could be between 700 and 1,000 groundwater professionals practising in Canada, with the largest single number employed by private consulting firms. Anecdotal information obtained from conversations with the principals of consulting firms suggests that there is currently a serious shortage of groundwater specialists (one medium-sized company indicated that it wished to hire 40 hydrogeologists over the next two years). Though incomplete, and only partially relevant to the current topic, a recent report (ECO Canada, 2008) provides a useful snapshot of the human-resource situation in one component of the environmental market, namely the investigation

and remediation of contaminated sites. The report indicates that there will be 11,500 vacancies over the next 12 months and that geologists and hydrogeologists are among the most difficult to recruit. The shortage of human resources has caused some companies to turn down contract opportunities, has slowed the pace of cleanup, and has slowed the development of this sector of the economy. Some industries facing groundwater problems (the petroleum industry, for example) are hiring staff hydrogeologists and, in response to legislation such as the *Clean Water Act* in Ontario, it is inevitable that there will be an increased demand for hydrogeologists from provincial agencies, municipalities, conservation authorities and consulting firms. Thus, while there is currently a shortage of hydrogeologists, there is reason to believe that the demand will continue to outpace the supply. Though Canada has numerous universities that train hydrogeologists, training is generally at the post-graduate level and thus the number of graduates per year is relatively small. If the current and future demand for hydrogeologists is to be met, then clearly greater resources are required to increase the capacity of our training programs.

To address the five goals of sustainability, specialised training in several disciplines is needed, including hydrogeology, hydrology, environmental chemistry, freshwater ecology, resource management, economics, planning, environmental law and perhaps others. Indeed, meeting the goals of sustainable management of groundwater is a highly interdisciplinary challenge. While specialists in the respective disciplines are clearly needed, there is also a great need for individuals with more general backgrounds who can bridge the technical and communication gaps between the respective disciplines, and particularly between the physical and social sciences. Hydrogeologists need training and experience in communicating their science to regulators, decision-making tribunals and the public in order to make sure that what the science can tell us is properly incorporated into water-management decisions.

REVIEW OF KEY POINTS

Jurisdiction for Groundwater Management

- The provinces, as resource owners, have the primary legal jurisdiction as regulators of groundwater. The federal government has legislative and proprietary powers to manage groundwater on federal lands and has many areas of policy and spending authority that can affect groundwater sustainability. There are several relevant areas, such as agriculture and environment, where responsibility is shared between the Government of Canada and the provinces.
- The *Canada Water Act*, originally passed in 1970, enables the federal government to enter into agreements with the provinces and territories to undertake comprehensive river-basin studies; to monitor, collect data and establish inventories; and to designate water quality management agencies.
- The 1987 Federal Water Policy committed to a number of actions, such as developing national guidelines for groundwater assessment and protection, and measures to achieve appropriate groundwater quality in transboundary waters. The policy remains largely unimplemented.
- The *Canadian Framework for Collaboration on Groundwater*, issued in 2003 by an *ad hoc* committee of stakeholders, has encouraged cooperation at the working level, but there is still a need for a more clear-cut, formally stated division of duties among the various levels of government.

Local Management

- Since many aspects of groundwater management are best carried out at a local level, there is an increasing trend for provinces to delegate groundwater management responsibilities to local governments and multi-stakeholder bodies. This effort is likely to be most successful when accompanied by sufficient financial and human resources, together with a requirement to take action and report back on progress.
- There currently is a shortage of hydrogeologists in Canada and there will be increasing demand for groundwater science and management skills as more rigour is applied to managing the resource.

Groundwater Management Practices

- Water-related policies and regulations have typically been concerned with influencing the *quantity* of water used, or the *quality* of water, but rarely both together.
- Criteria for issuing a groundwater licence or permit may reflect only a limited consideration of *cumulative* impacts and ecosystem preservation. Furthermore, there is to date no standard methodology for incorporating instream-flow protection into laws and regulations, although a number of provinces are examining ways to address this gap.
- No province uses information on the economic value of the proposed use as a criterion for issuing a groundwater permit. Where there is a price for permits to

take water, the charges are used only to defray administrative costs, rather than as an incentive for conservation.

Management of Groundwater Quality

- Groundwater quality is protected through drinking-water and aquatic-health protection laws as well as environmental assessment approvals at both the provincial and federal levels. Despite programs at all levels of government, management and regulatory actions to remedy contamination and prevent further degradation remain inadequate for sustainable groundwater management.
- Regulators have made progress towards limiting point-source pollution from industries such as pulp and paper. In contrast, best management practices to control non-point-source pollution from agriculture or urban run-off have had limited success, and strengthened regulations or new technical approaches should be explored.
- Because of strong municipal management and collaborative provincial oversight, and the role of the Federal-Provincial-Territorial Committee on Drinking Water, the quality of groundwater-supplied *municipal* drinking water is generally excellent across Canada. However, the frequent occurrence of microbial contamination in private and small community wells, including the First Nations wells, remains unacceptable. More effective management of drinking-water safety for individual, small, and remote systems is therefore necessary.
- Fatalities caused by water contaminated with microbial pathogens are now rare in Canada. A tragic exception was the outbreak in Walkerton in May 2000. That disaster provides a strong case for the multiple-barrier approach to assuring safe drinking water. The Walkerton tragedy does *not* demonstrate that groundwater is inherently unsafe for drinking-water supplies. It shows that this systemic breakdown of governance can occur with water supplies from any source, whether groundwater or surface water.

The Importance of Enforcement

- Stronger enforcement of existing regulations and controls would improve sustainable groundwater management. Most in need of improvement are: accurate and timely reporting of all licensed groundwater withdrawals; adherence to water-quality monitoring requirements; provision of complete documentation of geology and well construction and well abandonment details; and timely adherence to contaminated site clean-up and restoration.

Potential and Challenge of Market-based Instruments

- Current water prices at the municipal and provincial levels do not reflect the costs of water use and thus promote over-consumption and inhibit innovation and conservation. In this regard, Canada significantly lags behind international best practice.
- Current groundwater allocation methods in Canada rarely use market-based

incentives despite considerable evidence suggesting that greater use of economic instruments such as water prices, abstraction fees and tradable permits has the potential to promote sustainable groundwater use. The principal challenges facing their implementation include the lack of experience of governments in Canada with these instruments; a lack of data and understanding regarding the economic characteristics of users' groundwater demands and their impacts on others over time; and the need to coordinate the introduction of market-based instruments with existing regulatory frameworks.

Allocation of Resources to Groundwater Management

- Allocation of staff and funding to groundwater management has not kept pace with the increasing demands placed on the resource, leaving many Canadian basins with insufficient groundwater management expertise and capacity. Several examples suggest that cooperative efforts involving the three orders of government have generated positive outcomes by combining available resources into a single, geographically focused, vertically integrated management approach.

6 Assessing Groundwater Sustainability — Case Studies

Given the large area of the country and the tremendous variability in hydrogeological settings, it would be a formidable task to perform a comprehensive national assessment of groundwater sustainability in Canada. The task would be further complicated by the fragmented jurisdictional and regulatory environment; spatially and temporally inconsistent groundwater data collection and archiving; and the uneven level of understanding of groundwater-flow systems that exist nationally. To provide a snapshot of the Canadian situation, and to briefly compare it to examples from the United States, the panel has instead chosen to present a number of case studies. The locations of the case studies are shown in Figure 6.1.

(Council of Canadian Academies, 2009)

Figure 6.1
Case study locations.

Taken as a group, the case studies illustrate most of the sustainability issues that have been discussed in previous chapters; however, each case study has a different focus and these span the scientific, regulatory, and legal aspects of groundwater management. The studies demonstrate that progress has been made towards each of the five sustainability goals, with the possible exception of Goal 4 (socio-economic). There are no cases where all five sustainability goals have been addressed.

Case studies have been selected from regions of the country that have a relatively well-developed groundwater knowledge base, and thus they may not be reflective of the national situation. In many of the case studies a high level of knowledge and management has been attained only after conflicts have arisen; in others, the knowledge base is still relatively poor and sustainability goals have not been reached. Issues that are dealt with include agricultural impacts on groundwater quality, energy extraction, urban development, management at the watershed scale, and transboundary groundwaters.

6.1 PRINCE EDWARD ISLAND: IMPLICATIONS OF AGRICULTURAL NUTRIENT LOADINGS FOR GROUNDWATER AND RELATED ECOSYSTEMS

The Prince Edward Island case study (Figure 6.2) was selected to demonstrate the quantity and quality issues associated with groundwater extraction and streamflow, and nutrient loadings from agriculture. In particular:

- A moratorium on new high-capacity irrigation wells has been implemented by the provincial government until a better understanding of the potential impacts on aquatic ecosystems is established.
- Despite crop rotation requirements and agricultural best management practices, groundwater quality in many parts of the province continues to be impacted by nutrients from agricultural activities.
- Groundwater transport of nitrate to streams and estuaries has triggered environmental degradation in shallow estuaries, with consequences to shellfish harvesting, and water-based recreation and tourism.
- Because of province-wide concern, an independent commission, representing various interests, was appointed to establish a plan to deal with nitrate contamination of groundwater.

(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.2
Prince Edward Island.

Background

Prince Edward Island (PEI) is the only province that depends on groundwater for essentially all freshwater supply. Approximately 45 per cent of the population of 136,000 receives water from groundwater-sourced municipal distribution systems, while the remainder is served by individual domestic wells. The streams and rivers of the province typically receive about 70 per cent of their flow on an average annual basis as groundwater baseflow (Randall *et al.*, 1988). This dependence of the population and aquatic ecosystems on groundwater coexists within a largely agricultural economy (see Figure 6.3).

PEI is essentially one aquifer (5,680 km^2) composed of sedimentary rock formations dominated by sandstone. The volume of groundwater used on a provincial basis is a small fraction of the annual recharge. It is estimated that only one to three per cent of annual recharge is extracted from the PEI aquifer (Jiang *et al.*, 2004); on a regional scale, water-table levels on PEI have not experienced significant declines because of pumping. The PEI aquifer has inherent characteristics that make it vulnerable to contamination, including: relatively high annual recharge rates; cool groundwater temperatures (~ 10ºC) that inhibit microbial and chemical degradation processes; and relatively high bulk hydraulic conductivity in the surficial deposits and shallow, fractured rock. These factors, combined with significant agricultural land use, have led to relatively widespread impacts on groundwater quality (e.g., Savard and Somers, 2007).

(Courtesy of Kerry MacQuarrie)

Figure 6.3
A view of the landscape in an agricultural area of central Prince Edward Island.

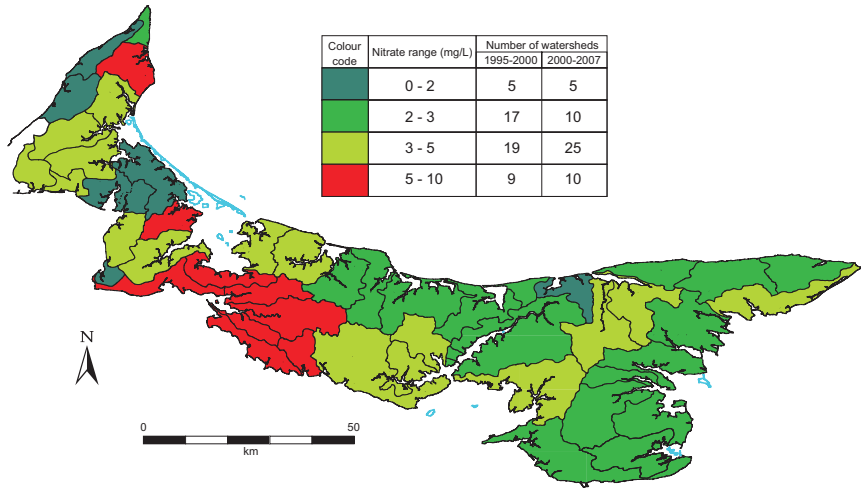
Sustainability Considerations

Groundwater Quantity: Traditionally, the extraction of groundwater has only been regulated for wells pumped at rates greater than 330 m^3 per day (Government of PEI, 2007a). An allocation permit is granted by the provincial government once it has been demonstrated that the proposed extraction does not cause undesirable impacts on other groundwater users and the environment. Allocations were assessed based on the average annual recharge to the catchment, with cumulative groundwater extractions limited to a maximum of 50 per cent of the annual recharge (Jiang *et al.*, 2004).

In response to concerns about increased groundwater extraction for irrigation, which typically has its highest demand during the dry (low streamflow) periods of the year, the provincial government imposed a moratorium on permits for high-capacity irrigation wells (CBCL Limited, 2003). The moratorium was, in effect, an application of the precautionary principle that provided the time required for more-comprehensive hydrogeological assessments of the long-term cumulative impacts on stream baseflow. Groundwater-flow models were developed for several representative catchments, calibrated with existing groundwater data and stream baseflow records (Jiang *et al.*, 2004) and used to test extraction scenarios. Even with these more-detailed hydrogeological studies, the moratorium on high-capacity irrigation wells remains in effect because there is currently insufficient information to determine the instream flow requirements for aquatic ecosystem viability and

integrity (Prince Edward Island Department of Environment, Energy and Forestry, personal communication).

Groundwater Quality: Current potato production practices on PEI have been linked to elevated nitrate concentrations (greater than 3 mg N per litre) in groundwater (Benson *et al.*, 2006). Nitrate in groundwater may pose a human health risk when concentrations exceed the maximum acceptable concentration (MAC) of 10 mg N per litre (Health Canada, 1995). In some catchments (Figure 6.4), as many as 20 per cent of the wells exceed the MAC for nitrate (Savard and Somers, 2007) and studies have attempted to determine the human health effects (Bukowski *et al.*, 2001).



(Adapted and reproduced with permission from Savard and Somers, 2007)

Figure 6.4
Mean nitrate concentration in groundwater based on domestic water well data.

Nitrate concentrations in several rivers that receive a significant component of baseflow increased at a rate of approximately 0.5 mg N per litre per decade during the 1980s and 1990s (Somers *et al.*, 1999). These streams, as well as direct groundwater discharge, deliver dissolved nitrogen to the many small estuaries around the coastline of PEI, and this has contributed to an increasing frequency of anoxia, obnoxious smells, and excessive algal growth in numerous estuaries along the northern coastline of PEI (Prince Edward Island Department of Environment, Energy and Forestry, personal communication).

The province has recently appointed an independent Commission on Nitrates in Groundwater to develop a strategy to reduce nitrate concentrations in groundwater and surface water (Government of PEI, 2008). The strategy is to ensure that:

- nitrate contamination in surface and groundwater will be brought to acceptable levels as soon as possible;
- residents will be able to rely on high-quality natural drinking water; and
- streams, rivers, ponds and estuaries will support a healthy variety of aquatic life.

The fracture network that exists in the rocks of PEI also increases the susceptibility of the aquifer to contamination from microbial pathogens; however, very limited data were available to assess the current situation. Although bacterial contamination of surface waters is a concern, Somers *et al.* (1999) noted in their work that an adequate assessment of bacterial contamination of groundwater could not be made because of the complications of sparse sampling points and site-specific factors such as unknown well integrity. Data presented by Fairchild *et al.* (2000) indicate that five of 42 wells (presumably domestic) tested positive for total coliforms; however, the data reported was collected in 1990 and 1991.

Socio-Economic Implications: The Commission on Nitrates in Groundwater (Government of PEI, 2008) identified the following socio-economic impacts resulting from nutrient loadings to aquatic systems:

- economic losses to commercial and recreational fishing and shellfish harvesting;
- reduced opportunities for water-based recreation and tourism;
- significant costs associated with the remediation of damaged habitats; and
- reduced real estate values.

No valuation is available, however, to indicate the economic magnitude of these impacts.

Approaches to Improving the Sustainable Use of Groundwater

All sectors are in agreement that nitrate leaching to groundwater must be reduced while maintaining a viable agricultural base (Government of PEI, 2007b). Possible strategies include optimised fertiliser management, such as using controlled-release fertiliser products, or a modification of the cropping systems in the rotation to more effectively manage nitrate (Agriculture and Agri-Food Canada, personal communication). These strategies are still being researched in the context of potato production in PEI.

Crop rotation legislation was enacted in the province in 2002, but it is unclear how widely it is practiced or enforced. In 2001, 40 per cent of the potato acreage was in a rotation of less than the minimum recommendation of three years and, therefore,

potentially not in compliance. The high percentage of land that was not managed in a three-year rotation was attributed to increasing pressure during the 1990s to produce high-yield crops on a limited agricultural land base (Government of PEI, 2003).

One of the stated purposes of the *Agricultural Crop Rotation Act* is "to maintain and improve groundwater quality" (Government of PEI, 2004a). Because the Act specifically identifies potatoes as a "regulated crop," it is clear that crop rotation in potato production is intended to reduce leaching of nutrients to groundwater. Indeed, the Commission on Nitrates in Groundwater (Government of PEI, 2008) recently made a strong recommendation that the provincial government should "implement a mandatory three-year crop rotation in fields under regulated crop cultivation, with no exemptions". Although other contributors of nitrate were identified by the Commission, including septic systems and cosmetic use of fertilisers, the most significant of the Commission's 30 recommendations relate to reducing nitrate leaching from agricultural crops, and specifically potatoes.

Municipal well-field protection plans are to be developed based on the concept of capture zones for pumping wells, the identification of potential sources of contamination within these capture zones, and proposed control measures that may include zoning bylaws, legally binding agreements with landowners, or the purchase or lease of sensitive lands for the purpose of preventing groundwater contamination within capture zones (Government of PEI, 2004b). The capture zones for all municipal supplies in the province have been modelled by provincial government hydrogeologists and the results have been provided to municipal governments. The municipalities are at various stages of developing plans and schedules for implementing well-field protection (Prince Edward Island Department of Environment, Energy and Forestry, personal communication).

Lessons Learned

Long-term declines in regional groundwater levels are not currently an issue on PEI, i.e., the panel's first sustainability goal is being met, and the recent flow-systems analyses that have been conducted on a catchment scale represent an important advance in groundwater management. On the other hand, the panel considers the current situation of widespread nitrate contamination and the resulting impacts on aquatic ecosystems to be unsustainable from a groundwater quality and ecosystem viability perspective (goals 2 and 3). The relatively unrestricted land-use changes that have resulted in the expansion or intensification of agriculture in many catchments point to the pitfalls of non-integrated land and groundwater resource management. Because of the long transport times of contaminants in groundwater-flow systems, it has taken decades for the effects of past land-use changes to manifest themselves in surface waters and deeper groundwater supplies. Unfortunately, similar time frames may be required for remedial actions to yield environmental benefits.

Solving these long-term groundwater quality issues will likely require multi-institutional collaboration, as exemplified by recent studies on climate change and groundwater nitrate concentrations (e.g., Savard and Somers, 2007; Somers *et al.*, 2007; Vigneault *et al.*, 2007). Current efforts to develop integrated catchment management plans, led by local stakeholder committees with support from provincial and federal agencies, appear to be a good start toward addressing the relatively widespread impacts of current land use practices. However, even with the application of the best science and a long shopping list of well-intended recommendations (e.g., Government of PEI, 2008), Canadian attempts to reduce large-scale nitrate contamination of groundwater to date have not been particularly successful (see further discussion of this in the Abbotsford-Sumas case study).

The continuing moratorium on high-capacity irrigation wells highlights the current gaps in understanding the linkages between groundwater-flow systems and the surface-water ecological systems that depend on, or are influenced by, groundwater discharge. Determining instream-flow needs and acceptable nutrient loads to estuaries are two science-based problems that place groundwater science at the interface with ecology and that will ultimately bring society to some difficult sustainability questions. Management actions with regard to instream flows may need to be iterative; that is, initially allowing a partial allocation of a proposed groundwater extraction, with follow-up ecological monitoring and evaluation before making modifications to the management decision, consistent with adaptive management principles. This would better account for the slow response time for some groundwater systems and the uncertainty in isolating ecological responses.

The relatively non-fragmented jurisdictional environment that exists within PEI, where essentially one layer of government oversees water resources, should provide a good test case within Canada for better integration of groundwater and surface water.

6.2 REGIONAL MUNICIPALITY OF WATERLOO, ONTARIO: APPLYING GROUNDWATER POLICIES AT THE MUNICIPAL LEVEL

The Waterloo case study was selected to demonstrate the challenges faced by municipalities in managing groundwater sustainably in the face of anticipated growth, more stringent regulations, and relic contaminants from historical industrial operations.

Background

The Regional Municipality of Waterloo is the largest user of groundwater for municipal supply in Ontario. It includes the municipalities of Cambridge, Kitchener and Waterloo and the Townships of North Dumfries, Wellesley, Wilmot and Woolwich.

(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.5
Region of Waterloo.

The area of the region is approximately 1,380 km^2, of which approximately one-third is urban. The population of about 507,000 is expected to grow by more than 40 per cent to 729,000 by 2031 (Region of Waterloo, 2008).

Current municipal water use is 260,000 m^3 per day and is projected to increase to 300,000 m^3 per day by 2041. About 25 per cent of the water is taken from the Grand River, and the remaining 75 per cent (approximately 200,000 m^3 per day) from local groundwater resources. A highly integrated supply system has evolved, including more than 120 wells and one surface-water intake (Region of Waterloo, 2008).

The region is located in the central portion of the Grand River watershed. Topographically, it is dominated by glacial moraine features, characterised by permeable sand and gravel deposits and a rolling-to-hummocky relief. These moraine deposits provide numerous high-yielding overburden aquifers. The hummocky topography and permeable soils also provide areas of high groundwater recharge. The moraine deposits are highly complex, with inter-layering of sands and gravel and aquitard materials making the aquifers difficult to map and characterise. Bedrock aquifers are associated with the Guelph and Amabel formations, both limestone deposits, and serve as an excellent groundwater supply for the City of Cambridge (Region of Waterloo, 2007a).

Sustainability Considerations

Groundwater Quantity: Based on the 2008 water budget calculations, it is estimated that groundwater extraction accounts for about 25 per cent of the recharge

across the region, though in local areas this could be considerably higher, possibly as much as 50 per cent (Region of Waterloo, 2007a). The region experiences water shortages during dry summer months, often necessitating watering restrictions. While supply infrastructure is a factor, seasonal declines in water levels in the supply wells are often the cause, although, with few exceptions, long-term monitoring of water levels in pumping wells and observation wells indicates that water levels have stabilised (Region of Waterloo, 2007a).

Sustainability within the broader context of ecosystem viability, and in view of rapidly increasing demand, is less certain. The Regional Municipality recognises the requirement to maintain adequate groundwater discharge to streams and wetlands; however, the effects of current withdrawals are uncertain and the scientific criteria for maintaining ecosystem viability and integrity are poorly developed.

Groundwater Quality: The region is faced with the common array of contamination issues, primarily anthropogenic. These include nitrate contamination, particularly in rural areas with permeable soils; road salt; and, on a local basis, landfill leachate, petroleum products, chlorinated solvents and other industrial chemicals.

Approaches to Improving the Sustainable Use of Groundwater

Because of the complexity of the aquifer systems, diversity of land use, high water demand and growing population, the region faces a range of groundwater issues of both a technical and management nature. Seven staff hydrogeologists ensure a constructive and informed interaction with higher levels of government, maintain a high technical standard in investigative work contracted to consultants, and ensure strong technical reviews of development proposals seeking land or water-use changes in the region.

The Regional Municipality administers a public education and conservation program, including incentives such as rebates for installation of low-volume toilets. The goal of the program is to achieve water savings of 14,000 m^3 per day (about five per cent of current municipal use) by 2015. Nevertheless, it is anticipated that an additional 40,000 m^3 per day will be required by 2041 (Region of Waterloo, 2007a), provided through:

- aquifer storage and recovery; i.e., pump from the Grand River during periods of high flow and store in aquifer, then recover during periods of low flow;
- additional groundwater wells; and
- a pipeline to Lake Huron or Lake Erie by 2035.[45]

In the wake of the identification of N-Nitrosodimethylamine in production wells in the Elmira area in 1989, the Regional Municipality implemented risk reduction

programs to better manage capture zones within the historical distribution of point-source industrial contaminants (Region of Waterloo, 2007a). A reconnaissance survey of potentially contaminated sites, based largely on provincial and municipal databases, was completed in 1996 and is periodically updated. The results of the survey have been used to characterise contaminated and potentially contaminated sites within each wellhead protection area. Levels of risk to groundwater supplies are determined through an indexing procedure that considers the number of potential contaminant sources, the size and severity of the particular source, the vulnerability of the particular aquifer, and the proximity of the contaminant sources to the well field. Delineation of the protection areas has relied heavily on three-dimensional numerical models to determine capture zones and boundaries of the two-year and 10-year time-of-travel zones around each well (Region of Waterloo, 2007a).

To address non-point sources, the Regional Municipality provides financial incentives for farmers to reduce nitrogen fertiliser application and encourages best management practices; it also has programs to reduce the application of road salt (Region of Waterloo, 2007a). In spite of these efforts, contamination of groundwater by nitrate and road salt will remain a sustainability issue for many years.

Lessons Learned

The accuracy of the risk associated with past land use is limited by the quality and completeness of the historical data. Land transfer records frequently do not include

45 At first glance, the notion of building a pipeline from somewhere like Lake Erie or Lake Huron to service a groundwater-dependent community seems to be an obvious solution. However, such pipelines have some significant implications, such as:

i) Since the water is being transported, possibly over a considerable distance, through different municipalities, there are often issues of determining appropriate and fair allocation of the costs of the infrastructure for water delivery, treatment and maintenance, and thus pricing of water; it may be argued that piping of water may foster development in areas where, due to water unavailability, development should be limited or constrained;

ii) The pipeline route from the source of water to the community it seeks to serve may become a major issue since the communities that can gain access to the pipeline will have more security for growth while communities more distant from the route may be disadvantaged, all of which leads to the thorny issue of determining which communities should have access to the water pipeline and which ones will not;

iii) As water pipelines become more commonplace, the impact on the lakes supplying water may be overlooked or underestimated, even though many consider the Great Lakes to be a finite water resource;

iv) Similarly, as communities develop in areas supplied with piped water, issues will arise concerning appropriate waste water treatment; and

v) When a municipality realises that water supplies are an issue, it often further legitimates efforts to instil conservation measures, thus raising acute awareness among the community of the value of water. Such efforts may be thwarted where water is imported from a distant source in a manner giving the impression that water supply is not an issue.

the full range of chemicals that have been used at a particular property. In the absence of an effective means for the Regional Municipality to monitor or limit the use of chemicals, there continues to be uncertainty regarding the risk of current and future practices. The possible consequences of as-yet-unidentified legacy sites continue to be a source of uncertainty and concern.

Establishing wellhead protection zones to protect water quality has a high level of uncertainty, particularly in hydrogeologically complex areas such as those encountered in the region. Risk reduction often involves either land-use restrictions or the outright purchase of property, both of which have substantial economic consequences. Application of the precautionary principal under these circumstances could result in very costly requirements that may, in fact, be impractical.

Because of the geological complexity of the aquifers, projections of sustainable yield are uncertain; thus the degree to which the potential yield of new wells can be realised is equally uncertain. Development pressures in recharge areas, and the possible effects on recharge stemming from the change in land use, add to the difficulties of predicting future groundwater availability. Finally, the effects of current withdrawals on ecosystem health are uncertain, and the scientific criteria for maintaining ecosystem viability and integrity are poorly developed.

6.3 OAK RIDGES MORAINE, ONTARIO: COLLABORATIVE REGIONAL GROUNDWATER MANAGEMENT

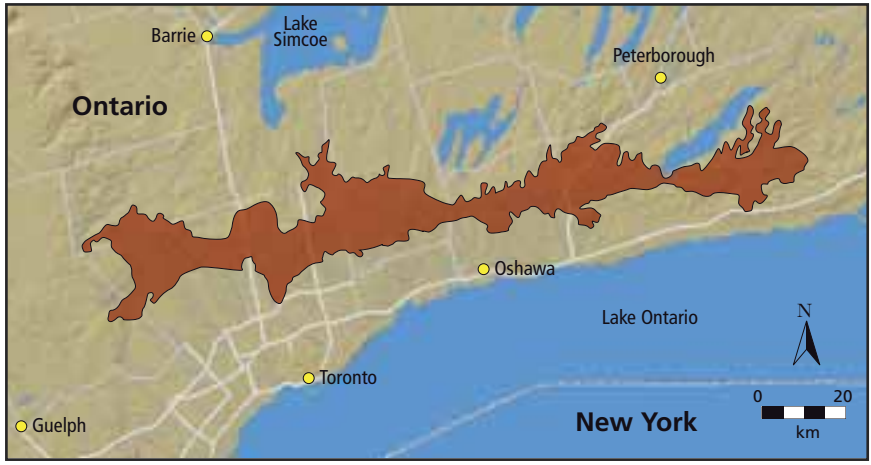
The Oak Ridges Moraine case study was selected to demonstrate the merits of a collaborative and integrated approach to groundwater management over a regional cluster of hydraulically and ecologically similar basins. In particular:

- Municipalities and conservation authority agencies in the Toronto area formed a partnership and pooled their resources for a common regional scientific approach to their collective groundwater resources.
- The characterisation program developed and maintains a data management system, a comprehensive geological understanding of the moraine, and numerical groundwater flow-modelling simulations. These tools are frequently updated and are effectively ‘living’.
- The program maintains a strong linkage to the partner planners to imbed groundwater opportunities and vulnerabilities in land-use decisions.
- The program made use of scientific contributions from all three levels of government.

Background

The Oak Ridges Moraine stretches some 160 kilometres across southern Ontario, from the vicinity of Trenton in the east to the Niagara Escarpment in the west (Figure 6.6). The moraine is the height of land separating southward-flowing drainage towards Lake Ontario from northward-flowing drainage into Lake Simcoe and other northern Kawartha Lakes. The moraine is recognised as a regional groundwater recharge area, providing the groundwater source to municipally developed aquifers and to the numerous streams with headwaters on the flanks of the moraine (Howard *et al.*, 1995).

The groundwater-flow systems are typically shallow and are strongly linked to local surface-water streams in reflection of subdued topography and the humid climate. Many surface-water streams are dependent on groundwater discharge to sustain baseflow during a significant part of the year, and the aquatic ecosystems within the streams are dependent on the quality and quantity of groundwater that discharges into the stream (Bradford, 2008).



(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.6
Oak Ridges Moraine, Ontario.

Sustainability Considerations

From a groundwater perspective, the moraine has long been the focus of significant attention by municipalities, conservation authorities and the Government of Ontario, as well as by the public owing to:

- the recognition of the moraine as a naturalised area where hydrological processes are seen as an important part of Ontario's natural heritage, including the numerous groundwater-dependent, cold-water streams emerging from the moraine flanks;

- the extensive use of groundwater in the area for municipal purposes (e.g., Newmarket, Aurora, Caledon, Uxbridge), domestic purposes (approximately 65,000 private domestic wells in York, Peel and Durham Regions alone), other industrial uses (e.g., aggregate washing), and recreational uses, e.g., some 38 golf courses are on the Oak Ridges Moraine (Garfinkel *et al.*, 2008); and
- pressing development, encroaching onto the moraine, from the rapidly growing communities surrounding Toronto, which has the effect of reducing groundwater recharge and degrading groundwater quality.

Public attention to these factors led to the passage of the 2001 provincial *Oak Ridges Moraine Conservation Act* and the accompanying Oak Ridges Moraine Conservation Plan. These documents aim to better manage land development on the Oak Ridges Moraine, require the use of modelling to develop water budgets for watersheds originating on the moraine and, for the first time in Ontario, put in place provincial land-use restrictions in wellhead protection areas.

Approaches to Improving the Sustainable Use of Groundwater

Since 2000, the municipalities of York, Peel, Durham and Toronto (YPDT) and the nine conservation authorities with jurisdiction on the Oak Ridges Moraine (collectively known as the Conservation Authorities Moraine Coalition or CAMC) formed a partnership for the purpose of establishing a groundwater management program on the moraine (see the YPDT-CAMC website). Given that most of the land-use decisions that affect groundwater resources are carried out at the local level by municipal governments and conservation authorities, it is at this level where decision-making with respect to groundwater resources must be implemented. Both the provincial and federal governments provided support of a technical or financial nature.

The central focus of this partnership (Holysh *et al.*, 2003) has been the understanding of flow systems of both groundwater and surface water. Whether related to nutrient management, water-taking permit issuance, development approvals, landfill or road salt impacts, or any other land-use decisions affecting groundwater resources, the key to making appropriate land-use development decisions is a comprehensive understanding of how water moves through watersheds and how proposed development may affect this movement or the quality of the water.

The program has produced three key products: (i) a water-related database; (ii) a geological model (Kassenaar *et al.*, 2003); and (iii) a numerical groundwater-flow model (Wexler *et al.*, 2003). These products are being used by the partner agencies to plan and assess development, and they continue to be refined to meet the growing needs of the partnership. However, for effective groundwater management, the technical understanding derived from the science must translate into meaningful

policies and decisions. The program therefore established strong links to the planners within the partner agencies. For example, a recent study investigated the best means of translating findings from the technical watershed and hydrogeological studies into Official Plan policies that guide land-use decisions across the area (Ogilvie and Usher, 2005).

The operating costs, shared among the partner agencies, are $400,000 per year, or about eight cents *per capita*, supplemented with one-time provincial grants of about $2 million.

Comprehensive Water-Related Database: One of the first YPDT-CAMC projects was to assemble a comprehensive digital database that would not only support groundwater-flow model construction, but also form the foundation for long-term groundwater management.

An important objective was to bridge both agency and disciplinary boundaries by compiling an integrated, comprehensive database covering geology, groundwater, surface water, and climate-related information across a wide regional area. This broad scope recognises that water management cannot stop at municipal boundaries and that a wide range of data sources needs to be tapped to establish the foundation for credible groundwater decision-making and effective long-term resource management. As one example of the ongoing database updating, data logger files of water levels from numerous monitoring locations are being routinely added to the database.[46]

Management of the database also seeks to overcome a common failing of data collection processes in which high-quality data are collected by skilled consultants at considerable cost, reported through various studies, and then simply lost in archived paper reports within the various agencies.

Conceptual Understanding and Detailed Geological Model: The Geological Survey of Canada (GSC) undertook a multi-year investigation of the Oak Ridges Moraine through the 1990s and, among other things, highlighted the need for an understanding of the regional sedimentology in groundwater investigations (e.g., Russell *et al.*, 2001).

The second major product from the YPDT-CAMC program has been to build on the work of the GSC and complete the construction of digital geological layering at a regional scale to represent subsurface geological and hydrogeological units.

46 The database contains information on approximately 300,000 wells, 4,500 surface-water gauging stations and 580 climate stations, as well as descriptions of outcrops and details of water-taking permits. In addition, close to 50 million temporal readings of water levels, water quality, pumping rates, climate data, and streamflows are linked to their point of measurement.

The glacial sediments laid down across south-central Ontario constitute the primary aquifers in the area, and an understanding of their morphology is critical to understanding groundwater-flow patterns on a number of scales (Barnett *et al.*, 1998).

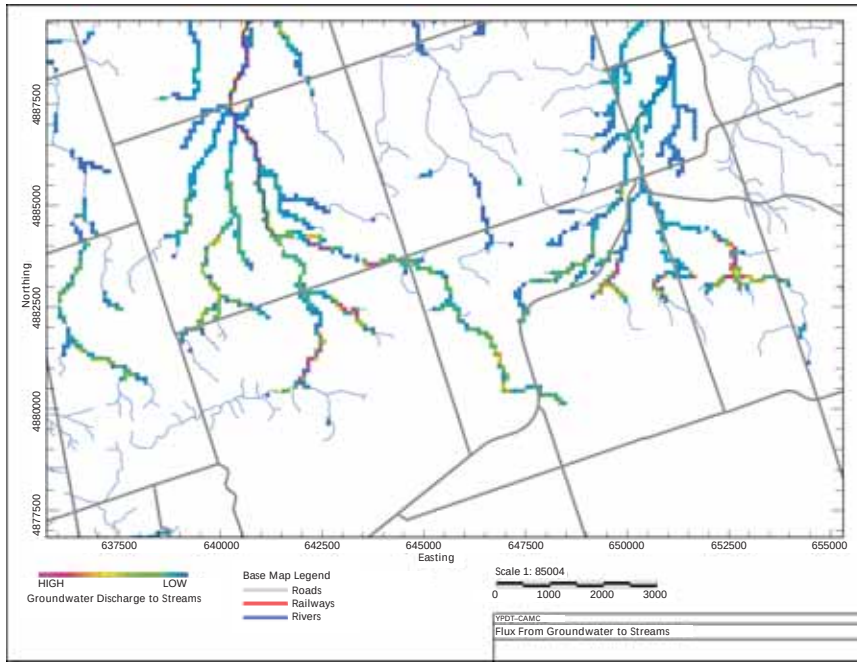
Numerical Groundwater Modelling: The third objective of the YPDT-CAMC program was to use the database and geological layering to develop numerical groundwater-flow models to assist in water management decision-making. Regional modelling of the entire Oak Ridges Moraine was undertaken based on a five-layer model consisting of about 3.3 million cells, each 240 metres by 240 metres square. The model demonstrated that regional groundwater models can be effective groundwater management tools (Kassenaar and Wexler, 2006).

Given that headwater streams on the moraine are particularly sensitive to changes in groundwater levels, gauging the full effects of development demanded simulation of the interaction between groundwater and the moraine's numerous headwater streams. Local modelling (centred on the Toronto and York Regions) was therefore undertaken, requiring eight layers with 7.1 million cells measuring 100 metres by 100 metres (Kassenaar and Wexler, 2006). The smaller cell size was necessary to better represent stream-aquifer interaction and assess drawdowns around municipal wells. However, the size of the model has posed technical difficulties, including computer memory optimization, incorporation of hundreds of kilometres of streams, addressing unconfined units, and assigning hydraulic conductivity values across such a broad area with sparse pumping-test data.

Figure 6.7 shows the predicted discharge (colour-coded) to each of the 100-metre cells along headwater tributaries within a portion of the model area under baseline conditions. Simulated discharge to streams under different land-use and pumping conditions can be compared on a cell-by-cell basis to produce maps of predicted change in the groundwater discharge to streams. Only by incorporating all streams into the model and calibrating to observed baseflows is consideration of this level of stream impact evaluation possible. This type of analysis can be used by municipalities and conservation authorities to target specific tributaries or reaches of streams for further investigation, monitoring and sensitivity analyses to assist in determining the significance of predicted groundwater level changes on streamflows.

Lessons Learned

It is believed that the local level — where data, information and tools are needed on a day-to-day basis for water management-related decision-making — is the most appropriate level for the activities carried out under the Oak Ridges Moraine program. Knowledge of the data, and being able to credibly comment, comes from the intimate knowledge gained from analyses and studies in support of day-to-day decision-making.



(Reproduced with permission from Kassenaar and Wexler, 2006)

Figure 6.7

Local model results showing the groundwater flux to the moraine's headwater streams.

Technical Lessons

- A focus on understanding subsurface depositional processes is important in developing a conceptual model and building geological layers for groundwater-flow modelling.
- Building a groundwater-flow model that incorporates the stream network in detail allowed for estimations to be made of the possible impact of groundwater level changes on surface flows.
- Even if done on a one-time basis at irregular intervals, the measurement of streamflows not influenced by precipitation or snowmelt events can provide important clues about the interconnectedness of groundwater and surface water systems. Program funds have been well spent on filling in data gaps with such measurements.
- Carefully conveying the results of groundwater-flow models and the uncertainty inherent in such results is critical to achieving support for using complex modelling approaches to address groundwater issues.

Management Lessons

- In urban groundwater-dependent areas, municipal expertise is the key to sustainable groundwater management.

- Integration and ready access to data aid considerably in typical local-level investigations and decision-making. For example, in responding to water-well complaints, the use of the YPDT-CAMC program database to quickly depict groundwater levels from nearby wells and precipitation records from nearby climate stations on the same graph allows managers to evaluate whether or not drought is a factor to be considered.
- However, while the overall objectives and outcomes of a regional database are invaluable, coordinating the incoming data streams from the partner agencies is burdensome. In addition, disseminating the data is often hampered by confidentiality requirements for some segments of the data, particularly data that may affect property value.
- Over the life of the program, researchers have advanced differing geological models that demand changes in the conceptual geological understanding, with cascading implications on all aspects of the program.
- An important aspect of the program is that the groundwater-flow model is managed as a 'living model' and updated on a regular basis. Nevertheless, the model has, at times, been inappropriately applied by consultants working for the partner agencies, with results misinterpreted in the absence of a complete understanding of the model or the uncertainties in the results.
- Linking the science and understanding gained through the program to the planning process provides credibility and support to the program since it helps to ensure the relevance of any initiatives undertaken.
- To facilitate the process, technical staff must have a passion for understanding water movement through the surface and subsurface environments; the capacity to ask effective questions of the data, interpretation and numerical model; and the ability to synthesise the information to answer the questions, and present and discuss the significance with effective communication skills. These and other staff with skills in quaternary geology, regional groundwater flow systems and numerical modelling are difficult to find.

6.4 ATHABASCA OIL SANDS: CHALLENGES FOR SUSTAINABLE GROUNDWATER MANAGEMENT OF MEGA-DEVELOPMENTS

The Athabasca case study was selected to demonstrate the challenges encountered when ensuring that enforceable regulations and management objectives, based on a scientific understanding of the groundwater resource on a regional scale, are in place in advance of a rapidly expanding mega-development. As the case study demonstrates, and in light of the sustainability criteria advanced in this report, the cost and success of a protracted regulatory response are uncertain at best, and sustainable groundwater management is unachievable to date. This case study reflects the body of material available in August 2007.

Background

Alberta contains the second-largest proven concentration of oil in the world, the vast majority of which is found in oil sands deposits. Oil sands are contained in three major areas of northern Alberta covering approximately 140,000 km^2. Oil sands production from all three deposits is expected to triple from the 2005 level of one million barrels per day to three million by 2020, and possibly to five million by 2030 (Alberta Energy, 2008). The Athabasca oil sands region, located near Fort McMurray, is the largest reservoir of crude bitumen in the world, covering an area of over 40,000 km^2 (Figure 6.8) (OSDC, 2008b). It is estimated to contain between 1.7 and 2.5 trillion barrels of bitumen, with approximately 10 per cent recoverable at the current price-technology mix (OSDC, 2008a). For bitumen processing, typically 2.0 to 4.5 m^3 of water, mostly from the Athabasca River, are required to produce 1 m^3 of synthetic crude oil (Griffiths *et al.*, 2006), despite efforts to recycle water.

(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.8
Athabasca oil sands region.

The Athabasca deposit is the only large oil sands reservoir in the world that is suitable for large-scale surface mining, although most of it can be produced using only the more recently developed *in situ* technology. With approximately 500 km^2 of land already disturbed by oil sands surface-mining activity, there have been

serious disruptions to the more local groundwater systems as a result of the removal of up to 75 metres of overburden and the creation of large pits. These pits end up as tailings ponds filled with wastewater, sandy-to-clayey material, and bitumen generated from the mining and bitumen processing. Tailings ponds already cover an area of over 50 km^2 and are some of the largest human-made structures on the planet (Peachey, 2005).

In situ recovery methods are used to extract the bitumen at depths typically greater than 75 metres. The most common extraction technique involves steam injection (steam-assisted gravity drainage (SAGD)). A mix of non-saline and saline groundwater is most commonly used for generating the steam. Although 90 to 95 per cent of the water used for steam is reused, 1 m^3 of bitumen produced still requires about 0.2 m^3 of additional groundwater (NEB, 2008). Eventually, most of the groundwater used for steam injection or processing ends up either being deep-well injected or stored in tailings ponds. This groundwater is considered lost as a resource for consumptive use.

Hydrogeological Setting

The land cover in the Athabasca oil sands area is primarily wetlands and boreal forest. These are underlain by varying thicknesses of overburden, comprising a range of coarse materials in buried valleys or glacial deposits and modern organic deposits sitting atop thick clay tills and sandy tills. The overburden is vertically punctuated by downcutting glacial and post-glacial meltwater channels and modern stream courses (Parks, 2004).

The Athabasca oil sands sit predominantly in the Cretaceous McMurray Formation of the Mannville Group. A typical hydrostratigraphic section through the Mannville Group can be subdivided into four aquifers separated by three intervening aquitards. The intervening aquitards are the bitumen-saturated middle and upper McMurray sandstone and the Wabiskaw and Clearwater shales (Barson *et al.*, 2001).

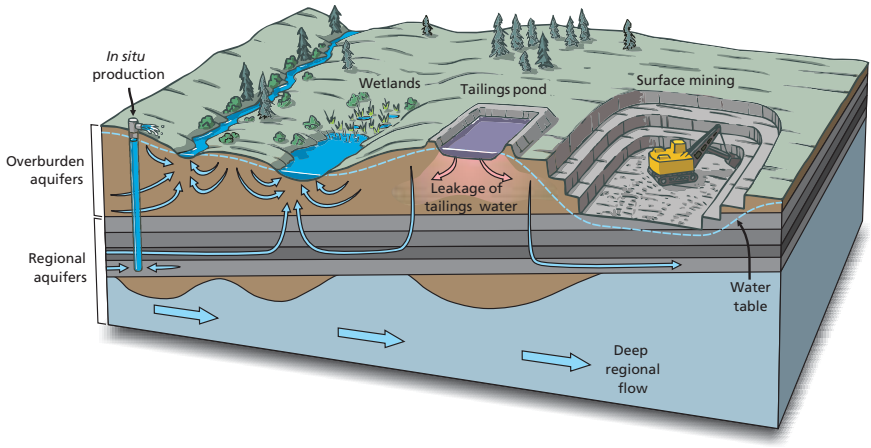
North of Fort McMurray, the oil sands are exposed near the banks of the Athabasca River, whereas they occur at greater depths in the south, down to approximately 400 metres below ground. The oil sands deposits, which are poorly cemented sandstones, can be as much as 80 to 85 metres thick in some areas. The oil sands behave as aquitards because they are highly saturated with viscous bitumen.

Several hydrogeological units are used or have the potential to be used as a groundwater resource. A key unit is the brackish basal sand aquifer within the McMurray Formation, in areas where the bitumen content is low. It is used for *in situ* production, although at shallower occurrences it will be dewatered during mining operations. Buried preglacial valley aquifers, such as the Wiau Valley aquifer, with cumulative

flows of almost 8,000 m^3 per day at springs measured along the Athabasca River (Stewart, 2002), and glacial channel aquifers also have the potential to be significant sources of groundwater.

Sustainability Considerations

The scale and rate of growth of oil sands operations has created significant changes to the groundwater resources in the area. Key groundwater issues are shown schematically in Figure 6.9. These issues are discussed in terms of the sustainability criteria developed earlier in this report.



(Adapted and reproduced with permission from Alberta Research Council, 2007)

Figure 6.9
Schematic diagram of key groundwater issues in the Athabasca oil sands region.

Groundwater Quantity: Large and extensive disturbances of the natural landscape have resulted from surface mining, where up to 75 metres of overburden is removed, followed by the pumping of groundwater to prevent flooding of the open pit, and resulting in the creation of new shallow groundwater-flow systems. Critical field data for understanding these changes in flow systems are difficult to obtain close to the mining operations because monitoring and pumping wells commonly have a limited life expectancy as a result of the advance of the mine face. In addition, pumping tests to determine aquifer characteristics are not completed away from the mine because the discharge water is saline, and it can only be discharged where proper facilities exist (Baxter, 2002).

Approximately 80 per cent of the area with oil sands is at depths that require *in situ* methods designed to increase the mobility of the viscous bitumen so that it can be captured by production wells, commonly achieved using the SAGD process.

When water is recycled, the net requirement for this process is about 0.2 m^3 per m^3 of bitumen produced (NEB, 2008). Since more than four-fifths of the total bitumen reserves in Alberta are accessible only by *in situ* methods, the demand for groundwater for *in situ* production could be as great as, or greater than the demand for surface water for oil sands mining, unless new extraction processes are adopted (Griffiths *et al.*, 2006).

A regional understanding and conceptual hydrogeological model for the area remains incomplete in the absence of coordinated and focused studies. The preglacial buried aquifers and the glacial channel aquifers, although potential sources of freshwater, only have rough estimates of regional-scale groundwater-surface-water interactions, despite over three decades of hydrogeological attention (Parks, 2004). The emphasis in existing assessments of regional hydrogeology in both the published descriptions, as well as in industry reports, has focused mostly on bedrock aquifers at the expense of the shallow but variable Quaternary aquifers that, although difficult to describe, are subject to many of the impacts. Knowledge is lacking as to whether the aquifers in the Athabasca oil sands region can sustain these groundwater demands and losses.

Compounding the challenge is the fact that, while public, the information collected for regulatory requirements is not available in a consistent, integrated format. Thus, it is difficult for stakeholders to integrate studies, build on previous work, share data and generally ensure that sufficient research is integrated within the regulatory process that leads to management decisions. Similarly, in the absence of a common and integrated groundwater database, modelling the effects of supply wells on surface water features is limited by the availability of data to characterise the various regional aquifer units.

Groundwater Quality: Roughly two tonnes of oil sands are excavated to produce one barrel of oil, and the sand and associated process water is discharged to large tailings ponds. The tailings-pond dams may be constructed out of some of this processed sand. There is a concern that this has resulted in more-permeable zones in the dams that may leak and act as migration pathways for the contaminants in the tailings water. Of particular concern is the proximity of the tailings ponds to the Athabasca River, with a potential to detrimentally affect both human and aquatic ecosystem health downstream.

A thorough understanding of the hydraulic controls on SAGD operations, critical for constraining the injection and production fluids and preventing cross-formational migration and contamination of productive aquifers, is absent. The key parameters that control the extent of leakage, the confining pressures in the overlying layers, the integrity of the aquitards and the presence of downward

gradients are generally difficult to measure comprehensively and therefore are not well characterised. Away from the bitumen, the degree of hydraulic connectivity to down-cut and often buried glacial scours and to modern river courses needs to be better understood before more underground injection sites are approved (Barson *et al.*, 2001; Baxter, 2002). The SAGD operations that are more vulnerable to leakage across formations are those located in discharge areas close to river valleys. Poorly cemented and improperly completed or abandoned *in situ* wells, which could potentially lead to the upward migration of injection or production fluids, are another risk. Hydraulic connection could also be established between the deeper zones after the amount of bitumen is reduced, which can result in downward migration from shallower zones (Barson *et al.*, 2001).

Ecosystem Impacts: The Alberta government does not require operators to restore the land to 'original condition' but only to 'equivalent land capability'; i.e., it must support a range of activities similar to its previous use before oil sands development. However, when reclaimed, the surface-mined sites are expected to have less wetland, more lakes, and almost no peatlands (NEB, 2006). Also, as noted above, the aquatic ecosystems are vulnerable to leakage from tailings ponds located near the Athabasca River.

Governance: Alberta Environment and the Energy Resources Conservation Board (formerly the Alberta Energy Utilities Board) are the two main provincial government regulators for groundwater-related issues in the Athabasca oil sands. Two main regulatory tools are the Environmental Impact Assessments (EIAs) and various approvals to develop, divert, operate and reclaim or remediate. The Federal Department of Fisheries and Oceans also has a regulatory role, primarily through the *Canadian Environmental Assessment Act* (CEAA). Joint panel reviews (provincial and federal) have been undertaken for oil sands applications under a combined EIA and CEAA process.

Alberta's environmental risk management approach to energy development proposals could be interpreted to tolerate adverse impacts on aquifers if no end user exists, e.g., if no water wells are installed. This interpretation occurred in the joint panel review comments on the Algar project (80 kilometres south of Fort McMurray), where effects on the aquifer from pumping were considered to be not 'relevant' as there were no identified users within the study area, other than another oil sands development (Millennium EMS, 2007).

Groundwater is currently allocated with reference to the estimated sustainable well yield, rather than on a basis of acceptable diversion rates from an aquifer. Barson *et al.* (2001) report that "finding and sustaining the large volumes of fresh (non-saline) (ground)water necessary for steam production, without jeopardizing groundwater

resources in the area, is a challenge that could limit the large-scale commercial development of the oil sands resource". The current permitting process based on EIAS focuses on Regional Study Areas that do not extend much beyond lease boundaries, rather than on regional flow systems.

The Surface Water Working Group of the Cumulative Environmental Management Association (CEMA), a multi-stakeholder organization established to provide effective regional environmental guidelines, objectives, and thresholds noted that "there are currently no collaborative water-related research projects being undertaken by the industry." There are concerns that CEMA struggles to match the pace of development in the oil sands (e.g., Kennett, 2007), and was unable to include groundwater in its initial scope of work. Environmental groups have withdrawn from this organization because some 'consensus' recommendations have not been accepted by the industry.

Industry operators hire consultants to undertake studies, the subjects of which include the demands and impacts on groundwater, the results of which are submitted to the appropriate regulator and are publicly available. There are uncertainties as to whether these organizations have the staff with the requisite hydrogeological expertise and the freedom to evaluate whether the environmental reports and ongoing monitoring are adequate to ensure sustainable groundwater management.

Approaches to Improving the Sustainable Management of Groundwater Resources

The following key questions, which address the key issues critical to sustainable management of groundwater resources, remain largely unanswered (modified from Alberta Research Council, 2007):

- How do low-flow levels in the Athabasca River affect shallow groundwater, and how does aquifer dewatering in the mining activities affect surface water systems?
- What are the effects of increased mining activities, changing land cover, or diversion of groundwater out of mined areas on groundwater recharge?
- Will increased oil sands operations dewater or reduce non-saline aquifer supplies as well as depressurise or dewater saline aquifers?
- How will changes in water quality, resulting from aquifer disturbance and tailings-pond leakage, affect the quality of groundwater and surface water resources?
- What data are required to assess the claim that deep injection of steam and waste does not negatively impact the regional and local aquifer systems, and are these data available?
- What are the regional threshold objectives to ensure sustainable groundwater management?
- Do planned developments have adverse impacts on water in adjoining jurisdictions (e.g., Northwest Territories or Saskatchewan) and downstream ecosystems?

To overcome the governance and research gaps and address the hydrogeological data and knowledge challenges outlined above, detailed scientific studies structured under a regional management framework could be used (Kennett, 2007). This framework would have specific groundwater sustainability objectives, defined on a regional basis, with consideration of cumulative effects, and would be established prior to issuing oil sands project approvals. Establishment of regional planning tools based on cumulative impacts was acknowledged in the Alberta government's Oil Sands Ministerial Strategy Committee (2006). Adopting this approach would change the government's EIA project-by-project approval process.

Several new initiatives from both government and industry indicate a growing recognition of the critical consequences of the rate and scale of growth of the oil sands for the sustainability of groundwater resources in the Athabasca oil sands region. These include:

- Alberta Environment's Athabasca Oil Sands (AOS) Groundwater Quality Study and Regional Groundwater Quality Monitoring Network — Phase 1 Design of Monitoring Program;
- proposed new policy legislation: Cumulative Effects Management from Alberta Environment and an Integrated Land Management Framework from Alberta Sustainable Resources Development (Alberta Environment, 2007; Alberta Environment, 2005);
- SAGD Regional Groundwater Modelling Initiative;
- pooling of data by individual operators for larger-scale interpretations; and
- groundwater studies (beyond regulatory requirements) being undertaken by individual operators.

A critical next step would be the development of a strategic framework to identify and evaluate the areas of research and the knowledge and technology needed to respond to future issues of groundwater sustainability in the Athabasca oil sands. One key requirement is a delineation of what is needed for long-term sustainability — including an examination of cumulative regional effects — and what is needed for the more short-term, current, and local issues.

Finally, the question remains as to who should be involved to ensure that implementation is based on sound science. A high demand exists in Alberta for experienced hydrogeological experts, which challenges the ability of regulators to recruit experienced hydrogeologists. The Alberta Water Research Institute has been mandated to increase its number of researchers, and it is hoped that this number will include hydrogeologists.

Lessons Learned

There continue to be uncertainties about the capacity of the groundwater resources in the Athabasca oil sands region to supply the needs of the oil sands operators and about the impacts of the operations on groundwater, interconnected surface waters and aquatic environments. These uncertainties highlight the need for improved knowledge and governance of the groundwater resources on both local and regional scales and for inclusion of cumulative effects.

The definition of clear groundwater objectives (allocation, required quality) prior to the approval of the oil sands projects is critical. These objectives need to be based on (i) adequate knowledge of current hydrogeological systems and their linkages to land use and surface-water environments and (ii) accurate and updated predictions of future, cumulative effects on these systems. This approach would improve the ability of stakeholders to determine the acceptability of the proposed developments.

For the developments that are already approved, the efforts to mitigate groundwater impacts require the collaboration of numerous stakeholders and adequate numbers of skilled hydrogeologists in various levels of government, research institutes, and industry or consultants.

6.5 ABBOTSFORD-SUMAS AQUIFER, BRITISH COLUMBIA AND WASHINGTON: EXPLORING MEANS OF REDUCING AGRICULTURAL LOADINGS

The Abbotsford-Sumas aquifer case study was selected to demonstrate that there can be international dimensions to the management of local groundwater resources and to emphasise the importance of vertical integration in our management regimes and governance structures. In particular, the Abbotsford-Sumas aquifer highlights the complexities of addressing contamination that crosses international borders, and the role of fairness in protecting groundwater from further deterioration.

Background

The Abbotsford-Sumas aquifer covers an area of approximately 200 km^2 under British Columbia and Washington State. It is an important source of water for domestic, municipal, agricultural, and industrial uses on both sides of the border, supplying approximately 110,000 people in Canada and the United States, and is the sole source of supply for communities such as Clearbrook, British Columbia.

The aquifer is shallow, comprised of a thin layer of largely unconfined permeable glacial outwash sands and gravels. The water table is close to the surface and susceptible to contamination from land-use practices, primarily agriculture, which

(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.10
Abbotsford-Sumas aquifer.

is the dominant land use on both sides of the border. Groundwater generally flows from north to south, with the result that land-use practices in British Columbia impinge on drinking-water quality in the adjacent area in Washington State.

Contamination of the aquifer has been a concern since the 1950s (with regular groundwater sampling carried out since the mid-1970s and intensified since the mid-1990s), despite the introduction of a number of regulatory and voluntary initiatives on both sides of the border during the past fifteen years. Raspberry production and waste-management practices associated with poultry production (16 million birds producing approximately 600,000 m^3 of manure per year) are the two land uses primarily associated with the nitrate contamination of the aquifer (ASASF, 2007). Nitrate leaches easily into the soil and groundwater as it is soluble in water and mobile in the soil.

Washington State counties and the state government are concerned that nitrate from the Canadian side of the border has reached the capture zones of their drinking-water wells. The aquifer is identified as one of the "most severely contaminated aquifers" in the state (ASASF, 2007). Transboundary water agreements include the 1909 Boundary Waters Treaty and a 1996 Memorandum of Understanding between the Province of British Columbia and the State of Washington on referral

of water-rights applications, in order to provide for timely prior consultation on water quantity allocation permits related to the aquifer.

Sustainability Considerations

Groundwater Quality: Well sampling identified an increase in surplus nitrogen compounds from 1971 to 1991, attributed to a shift away from dairy production and towards poultry production and crops requiring more nitrogen. Approximately 70 per cent of water samples between 1991 and 2007 exceeded the 10 mg nitrate as nitrogen per litre drinking-water guideline, with individual values as high as 91.9 mg per litre (Environment Canada, 2004a). Elevated nitrate concentrations occurred more frequently in areas where agriculture was the primary land-use activity and where the water table was close to the surface (Hii *et al.*, 2006).

In 1995, a nitrogen isotope study indicated that the nitrate was coming mainly from poultry manure being used to fertilise crops. While the implementation of best management practices (BMPs) has resulted in 80 to 90 per cent of the poultry manure being shipped off the aquifer, the subsequent shift to inorganic fertilisers has simply changed the source of the nitrate contamination, as young groundwater increasingly bears the isotopic signature of inorganic nitrogen fertiliser (ASASF, 2007). Recent research suggests that the application of inorganic fertilisers in the spring may lead to an ideal situation for rapid nitrate leaching (ASASF, 2007), a situation that is currently unaddressed by BMPs. After a decade of concentrated public awareness and the implementation of BMPs, the significant increase in nitrate concentration over the past five years is a surprising and disappointing result.

Governance Systems: Recent regulatory changes have focused on controlling the impacts of agriculture on the environment. The British Columbia government released an agricultural waste-control regulation and associated code of practice in 1996, containing minimum requirements for avoiding the flushing of manure, for the storage of manure in contained facilities, and for covering manure piles in the rainy season. The State of Washington passed a *Dairy Nutrient Management Act* in 1998 that required all dairy farmers to implement an approved Dairy Nutrient Management Plan by the end of 2003.

Many voluntary efforts have also been directed at reducing nitrate levels, including the formation of coordinating groups and industry self-monitoring. Coordinating efforts include:

- A Canadian federal-provincial groundwater coordinating committee, active since 1992.
- The Abbotsford-Sumas Aquifer Stakeholder Group (ASASG), active since 1995, composed of representatives from federal, provincial and local government agencies,

agricultural and industry groups, NGOs and Washington State participants. The ASASG has sponsored a public education campaign involving signage, environmental pledge booklets, and school presentations.
- The British Columbia Provincial-Industry Partnership Committee on Agriculture designed to reduce agricultural impacts on the environment.
- A bi-national multi-sectoral advisory body, the Abbotsford-Sumas Aquifer International Task Force, established in 1992, which strives to collect and coordinate scientific data, manage activities threatening the aquifer, and assist with legislation and policy advice; each jurisdiction maintains decision-making authority and responsibility to implement recommendations of the Task Force.
- A Canadian Water Network study on the use of BMPs.
- Industry self-monitoring programs consisting of BMPs promoted through the Industry Stewardship group and its subgroups, such as the Sustainable Poultry Farming Group, and environmental farm plans, which enable producers to identify potential environmental improvements on their farms.

Approaches to Improving the Sustainable Use of Groundwater

A wealth of scientific data has been collected over several decades and there has been extensive hydrogeological mapping in both the United States and Canada, with an effort to integrate this knowledge into a regional numerical groundwater model. This model was developed in Canada and has been used jointly by American and Canadian researchers, including simulation of climate-change impacts and nitrate transport.

The numerous governance and policy responses employed to date have not yet abated the contamination. Many involved with management of the aquifer acknowledge that voluntary programs alone will not minimise the problem. BMPs have been developed successfully for certain sectors, such as auto recyclers, but lower levels of success are witnessed with agricultural producers. Regulators note that there are few cases where the implementation of BMPs has improved groundwater quality at the scale of an aquifer; that enforcement of the provincial Code of Agricultural Practice is minimal; and that the voluntary environmental farm plans do not yet appear to be having an impact. Stricter controls on agricultural producers, industrial operations and individual households may be necessary, but there is currently little momentum for stricter regulation at the provincial level, and there are few resources for enforcement of existing controls.

A governance gap persists, particularly in the coordination of the numerous agencies charged with aquifer management. Environment Canada is responsible for the overall management of the transboundary effects of Canadian practices on the United States. The provincial and regional health and environment ministries,

agencies, and boards also share responsibility. The British Columbia Ministry of Environment is responsible for pollution prevention and control. The Fraser Valley Health Authority is responsible for drinking water and community health. The City of Abbotsford is responsible for land-use allocation and planning and also for managing drinking-water provision in its role as water purveyor. The provincial Ministry of Environment, Fisheries and Oceans Canada, and Environment Canada together manage the environmental impacts of groundwater withdrawals and contamination (Hoover *et al.*, 2006).

Furthermore, there is no institutional framework for managing cumulative effects on the aquifer. Canadian groundwater managers are interested in piloting new governance mechanisms. Models that have been suggested include the geographically similar, agriculturally dependent Southern Willamette Valley Groundwater Management Area (Oregon), though the legal backdrop in that case is markedly different.

Lessons Learned

Improved management of the Abbotsford-Sumas aquifer depends on finding ways to translate the accumulated knowledge into changes on the ground. Research has identified several factors of success associated with a delegated water-governance model (Nowlan and Bakker, 2007). Three of these factors in particular are not present in the existing aquifer governance structures:

- Financial sustainability is a key factor of success. The existing coordinating bodies have minimal resources.
- A second success factor is policy feedback, i.e., a formal mechanism whereby decisions may result in changes to specific policies in clearly specified areas, under specific conditions. In the case of the aquifer, recommendations are often ignored. For example, recommendations emerging from a 2005 meeting of the British Columbia Washington Environmental Cooperation Council — which had noted that the intensity of agriculture was the key problem on the aquifer, that stronger regulation and increased compliance was needed, and that a change to the Agricultural Waste Control Regulation in British Columbia was needed — have not been implemented (ECC, 2005).
- Finally, committed participants will increase the chances of success of a water governance partnership. Also, equity among the different groups of participants will increase the level of commitment. However, agricultural producers in the Abbotsford-Sumas aquifer region note an inequity in how producers are treated. For example, growers in Delta, British Columbia, receive payment from the federal government for providing bird habitat, while Abbotsford raspberry farmers who protect soil quality and prevent contamination receive no compensation. The issue of equitable payment for protection of ecosystem services is a gap in the current management context.

6.6 THE GREAT LAKES BASIN: LESSONS IN LARGE SCALE TRANSBOUNDARY MANAGEMENT

The Great Lakes case study (Figure 6.11) was selected to demonstrate that, while local-scale groundwater management is important, large basin-scale issues require independent management and research, especially if there are transboundary issues between provinces or nations. Vertical integration of the management bodies, from the local level to the international level, is necessary.

(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.11
The Great Lakes basin.

Background

It has been estimated that 'indirect' groundwater discharge to the Great Lakes basin accounts for approximately 22 per cent of the United States supply to Lake Erie, 42 per cent of its supply to Lakes Huron and Ontario, 35 per cent of its supply to Lake Michigan, and 33 per cent of its supply to Lake Superior. This supply is provided mainly by sustaining baseflow of rivers and streams discharging to the lakes (Grannemann *et al.*, 2000). On the Ontario side, it is estimated that about 20 per cent of the supply is from groundwater. Estimates of direct exchanges of water between groundwater and the lakes are completely inadequate (Grannemann *et al.*, 2000).

These indirect and direct discharges to the lakes affect water levels, chemical composition, and biotic systems, some of which are wholly dependent on groundwater (Grannemann *et al.*, 2000). Groundwater, like surface waters, may be contaminated by pollutants such as nutrients or pesticides from agricultural lands or urbanised areas, but in general is of good quality. In an era of warming waters due to climate change, groundwater inflow areas often provide essential habitat for cold water species of fish and other biota.

Sustainability Considerations

Groundwater Quantity: In general, it is thought that direct discharges from groundwater contribute to the total water supply, but there are a few locations in which drawdown of groundwater results in flows from the lakes into aquifers. In the western shore region of Lake Michigan, high-volume water withdrawals are made from the Cambrian-Ordovician aquifer system in the region from Chicago to Milwaukee. The high-volume pumping produced cones of depression in aquifers under both cities, with declines in groundwater levels as great as 274 and 114 metres respectively (Grannemann *et al.*, 2000). After 1980, pumping rates were reduced in the Chicago area and levels recovered as much as 76 metres in some locations, but continued to decline in areas of southwestern metropolitan Chicago. In these areas of high pumpage rates and declining groundwater levels, it is likely that flows reverse, resulting in a lowering of the lake levels, but so far by small amounts. Pumping of groundwater in this area also affected water quality through increased concentrations of radium and radon (Grannemann *et al.*, 2000). There is little knowledge of pumping rates and lowering of groundwater levels elsewhere in the basin. However, with the recent (2007) record low levels of Lake Superior and the very low levels in Michigan-Huron, any additional draw-downs, however small, are a cause for major concern.

Thus, in general, available evidence (Grannemann *et al.*, 2000) suggests that groundwater influences in the Great Lakes basin are important for the lakes and inflowing rivers and streams, yet quantification of quantity and quality effects is elusive because of major gaps in measurements and knowledge.

The International Joint Commission, in its 2000 report, summarised the major gaps in knowledge as follows (IJC, 2000):

- There is no unified, consistent mapping of boundary and transboundary hydrogeological units.
- There is no comprehensive description of the role of groundwater in supporting ecological systems.
- Although some quantitative information is available on consumptive use, in many cases the figures are based on broad estimates and do not reliably reflect the true level and extent of consumptive use.

- There are no simplified methods for identifying large groundwater withdrawals near boundaries of hydrological basins.
- Estimates are needed of the effects of land-use changes and population growth on groundwater availability and quality.
- There is inadequate information on groundwater discharge to surface water streams and inadequate information on direct discharge to the Great Lakes.
- There is no systematic estimation of natural recharge areas.

While these serious knowledge gaps apply to both the American and Canadian sides of the basin, the paucity of useful and reliable information is much more pronounced in Canada than in the United States. The United States Geological Survey has undertaken significant work on its side of the basin (Holtschag and Nicholas, 1998), but work by federal and provincial agencies and academia in Canada has been much more sporadic and less intensive.

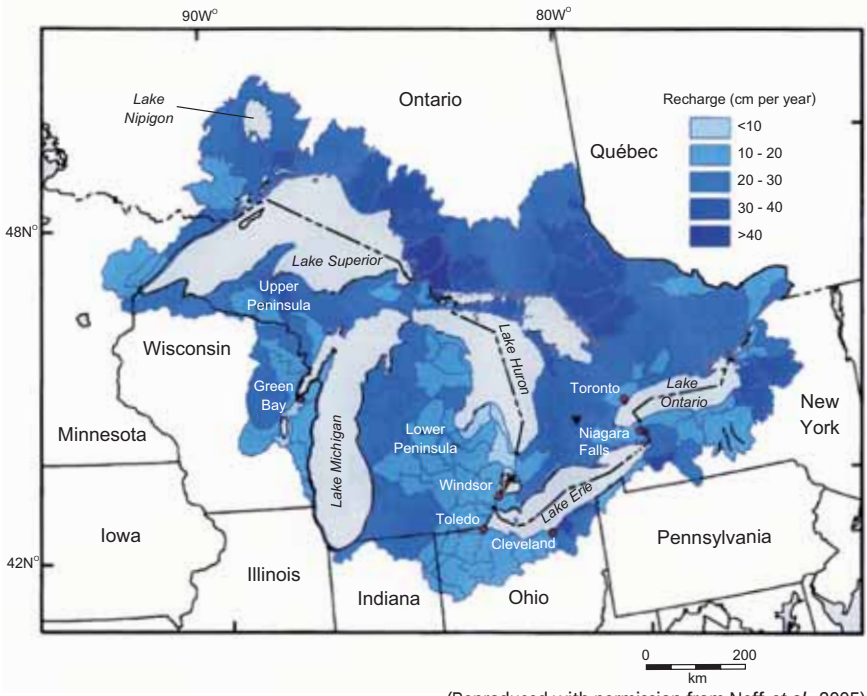
In 2004, the IJC reviewed progress on the recommendations made in its 2000 Report. It noted that the new Great Lakes Charter Annex, signed by the eight States and two Provinces (Ontario and Québec) concerned with the Great Lakes-St. Lawrence system, requires both countries to better understand and conserve groundwater as well as surface-water resources. However, the IJC also noted that while some additional hydrogeological work was evidently underway, it was not aware of any that had been completed (IJC, 2004).

The 2004 Review went on to say that "The Commission wishes to stress the critical importance of the recommendation that governments should commence a project to map and characterise all of the groundwater aquifers in the Great Lakes basin. Such a project would dramatically enhance the ability to manage these vital waters and advance scientific understanding of these unseen resources" (IJC, 2004).

In 2005, the United States Geological Survey began a five-year program to improve fundamental knowledge of the water balance of the Great Lakes basin, including the flow, storage, and withdrawal of water by humans. Interim findings suggest consistent and accurate estimates of recharge are needed to understand how recharge might affect groundwater availability and use. The USGS and Environment Canada (Neff *et al.*, 2005) collaborated to provide the first integrated study of long-term average groundwater recharge to the shallow aquifers in the United States and Canada within the Great Lakes region. Additional work has focused on the United States side of the basin. Sheets and Simonson delineated the basin groundwater divides to illustrate the area contributing groundwater to the lakes, and how groundwater divides can differ from surface-water divides (Sheets, 2006).

This difference makes the assessment of individual water-budget components challenging. Coon and Sheets provided an estimate of the groundwater in storage in the Great Lakes basin based on hydrogeological data from the Regional Aquifer System Analyses conducted by the United States Geological Survey from 1978 to 1995 (Coon and Sheets, 2006). Hodgkins *et al.* analysed historical changes in precipitation and streamflow in the United States Great Lakes basin from 1915 to 2004 and attributed increases in the annual seven-day runoff from 1955 to 2004 to human influences, including urbanisation (Hodgkins *et al.*, 2007). Currently, the USGS is developing a groundwater-flow model of the groundwater system within the Lake Michigan basin.

In 2004, the Groundwater Program of the Earth Sciences Sector of Natural Resources Canada started a project to develop a conceptual hydrogeological framework for southern Ontario, which includes the Great Lakes basin (Figure 6.12). This has led to the mapping and full assessment of one of the regional-scale aquifers within the basin — the Oak Ridges Moraine. However, limited resources have obliged the Earth Sciences Sector to conduct assessments only where considerable data already exist and where collaboration with the provinces is possible.



(Reproduced with permission from Neff *et al.*, 2005)

Figure 6.12
Shallow groundwater recharge rates in the Great Lakes basin.

Groundwater Quality: The revised Great Lakes Water Quality Agreement of 1987 recognised the potential of groundwater flows into the Great Lakes. Annex 16, Pollution from Contaminated Groundwater, focuses on the coordination of "programs to control contaminated groundwater affecting the boundary waters of the Great Lakes system" (IJC, 1978). Under the Great Lakes Water Quality Agreement, Annex 16 calls on the Parties to the Agreement to "identify existing and potential sources of contaminated groundwater affecting the Great Lakes" (IJC, 1978). Although focused in its scope, the Annex is unique in that it is one of the few international and bilateral agreements that expressly establish obligations with respect to groundwater. The Agreement requires the parties to map hydrogeological conditions in the vicinity of existing and potential sources of contaminated groundwater, and to develop standard approaches for sampling and analysis of contaminants in groundwater in order to assess the degree and extent of contamination and estimate the loadings of contaminants. Annex 16 also requires the parties to control the sources of contamination of groundwater and the contaminated groundwater itself, once the problem has been identified.

In 2006, a number of working groups reviewed the Great Lakes Water Quality Agreement and reported on the status and recommendations of the agreement and its annexes (US and Canada, 2006). With respect to Annex 16, a working group made a number of findings, including one indicating that the Annex does not reflect the environmental challenges facing the Great Lakes in relation to groundwater quality and groundwater quality-quantity interactions, and another indicating that there is insufficient mapping of groundwater resources in the Great Lakes basin. Among other things, the working group recommended that a revised Annex should reflect the reality of groundwater-surface-water interaction and the contamination of groundwater by non-point sources. It also recommended that the Annex include "programs for developing maps of groundwater resources that reflect their multiple layers and the different flow patterns across the basin." It further stated that management of Great Lakes water quality "is closely tied to the management of Great Lakes water quantity, including the management of groundwater quantity and flow" (US and Canada, 2006).

A further report by the Science Advisory Board to the IJC on water quality issues was available at the time of writing this panel report, but not the new full report on groundwater. Relevant issues in the basin that are addressed by the Science Advisory Board (IJC, 2008) include:

- Viruses from human fecal waste are common in groundwater due to malfunctioning septic and seepage systems and leaking sanitary sewers. Bacterial measurements do not correlate well with viral contamination.

- Ontario surveys in the 1990s showed that 14 per cent of wells consistently exceeded the guidelines for nitrogen compounds and 34 per cent exceeded bacterial guidelines.
- On-site human-waste treatment systems (OSSs) are proliferating even though it is estimated that 20 per cent of such systems fail to treat wastes adequately. In Ontario, 25,000 new or replacement OSSs are being installed annually.
- There may be a million or more underground storage tanks in the basin (10,000 in Ontario), of which an estimated five per cent to 35 per cent are leaking toxic substances such as oil, gasoline, diesel fuel, solvents and other waste fluids.
- Groundwater contaminant discharges from the industrial chemical complex into the Niagara River, and hence into Lake Ontario, do not appear to be decreasing.
- Ontario has an estimated 500,000 abandoned oil and gas wells, although a full inventory is not available and mandatory reporting has been 'problematic.'
- Ontario jurisdictions provide subsidies for decommissioning or improving water wells and for upgrading septic systems.

Nevertheless, additional work is being done. Phase Two of the Groundwater Program (2006–2009) includes plans to develop an understanding of the dynamics of groundwater in the basin, of general water budgets across southern Ontario, and of the scope of hydrogeological research gaps and priorities in order to assist in future planning and priority setting in the basin (Rivera, 2006). Some collaborative efforts between the United States Geological Survey and the Earth Sciences Sector are also underway (Rivera, 2007).

Lessons Learned

Despite calls for action from the Commissioner for Environment and Sustainable Development (CESD, 2001; CESD, 2008), from the International Joint Commission (IJC, 2004), and the recent initiatives from the Earth Sciences Sector of Natural Resources Canada, it is fair to say that only limited survey and analyses of groundwater in the Canadian portion of the Great Lakes basin had been carried out by the end of 2007, and that whatever current knowledge we do have is largely fragmented and incomplete. Thus, although much valuable work has been completed by the United States Geological Survey on the United States portion of the basin, a comprehensive assessment of the role of groundwater in the Great Lakes basin and its effects on lake-water quantity and quality remains elusive.

6.7 BASSES-LAURENTIDES, QUÉBEC: GROUNDWATER SCIENCE TO HELP MANAGE CONFLICTS AND PLAN GROUNDWATER USE

The Basses-Laurentides case study was selected to illustrate how a groundwater mapping project could be used to help managers and land planners resolve conflicts and plan groundwater use. Highlights include the merits of cooperative groundwater characterisation projects shared among municipalities and multiple layers of

government, and the capacity requirements at the municipal level necessary to build on the characterisation and develop the systems for supporting land-use decisions.

Background

The Basses-Laurentides region covers an area of approximately 1,500 km^2 immediately north and west of Montréal. It is under the jurisdiction of four regional municipalities (Figure 6.13). The region has a population of approximately 250,000, one quarter of which use groundwater from regional aquifers as their sole source of supply.

(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.13
Basses-Laurentides region, Québec.

The regional municipalities felt that they lacked sufficient information to properly manage land use, to make the best use of the region's groundwater, and to help resolve conflicts among water users. A three-year regional hydrogeology project was therefore undertaken in 1999, led by the Geological Survey of Canada (GSC) in close partnership with the four regional municipalities (Savard *et al.*, 2002). The regional municipalities were involved in elaborating the objectives of the project to ensure that results would help them better manage their water issues. Additional financial and technical support was provided by universities, other federal government departments, provincial agencies, and by

the United States Geological Survey. The general objective of the project was to improve scientific knowledge of groundwater quantity and quality in order to assist in planning of groundwater use and to establish limits for sustainable groundwater extraction. The project budget of approximately $3.6 million was shared among the three orders of government.

The regional aquifers are sedimentary rocks that are overlain by unconsolidated quaternary deposits, primarily low-permeability clay that covers 75 per cent of the study area, limiting infiltration and recharge and inducing confined conditions in the bedrock aquifers. Glacial till of variable thickness and permeability covers the remaining area and hosts the main recharge areas. Recharge to the bedrock aquifers varies locally from zero to approximately 300 mm per year, with an average of 45 mm per year over the study area — or less than five per cent of the average annual precipitation of 1,040 mm (Hamel, 2002).

Compilation of groundwater usage data showed that the total annual groundwater extraction is 18 x 10^6 m^3, which represents approximately 18 per cent of the estimated aquifer recharge (Nastev *et al.*, 2006). Domestic usage from municipal and private wells represents approximately 31 per cent of the total extraction, and agricultural activities represent about 14 per cent. Groundwater extraction from quarries accounts for more than half of the total withdrawal rate, and extraction by water bottlers accounts for less than three per cent.

Sustainability Considerations

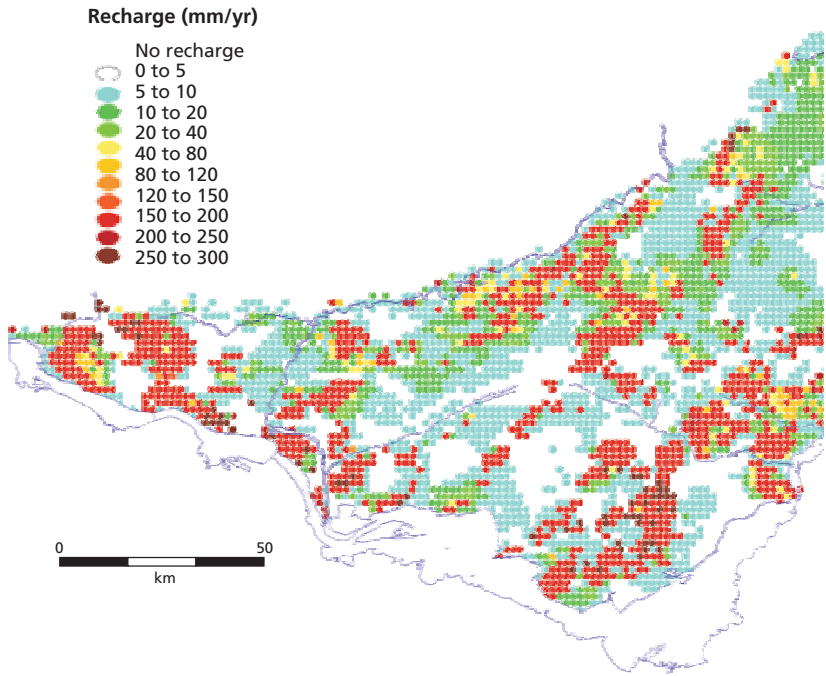
Groundwater Quantity: Near-surface groundwater levels and frequent flowing wells led to a perception in the area that groundwater was abundant. However, starting in the 1990s, a gradual decline of water levels was noted in some private wells, the number of flowing wells diminished, and some springs disappeared. Farmers claimed inherited rights to groundwater and were concerned about long-term groundwater availability. Tensions between groundwater users developed and water bottlers were targeted as bearing some responsibility for the groundwater problems. While these events coincided with periods of lower-than-average precipitation, they also coincided with the arrival of water-bottling firms and a general increase in groundwater extraction rates.

Groundwater Quality: Isolated cases of groundwater contamination, and the presence of several landfill sites, contributed to the population's concern about the sustainability of groundwater quality. Based on the analysis of samples, groundwater quality meets provincial drinking-water standards for almost all samples and there is very little evidence of human contamination (Cloutier *et al.*, 2006). Elevated salt concentrations were noted in some samples and are attributed to a mixture of ancient Champlain Sea water diluted with recharge water.

Approaches to Improving the Sustainable Use of Groundwater

The GSC developed a work plan to investigate and understand recharge to the bedrock aquifers and the spatial distribution of the quality and quantity aspects of groundwater. This work plan included water-level measurements, pumping tests, constant injection tests, specific capacity tests and analysis of the chemical composition of groundwater samples. Data were compiled into a database and distributed to the municipalities.

As a land-use planning tool, and to highlight the role of the recharge areas, groundwater vulnerability was assessed using the DRASTIC[47] method, which accounts for the nature of the geological units close to ground surface when computing a vulnerability index (Savard *et al.*, 2002). Good correlation was found between the highly vulnerable zones and the recharge zones shown in Figure 6.14. Maps produced during the project identified approximately 35 per cent of the study area where land-use planning should account for higher groundwater recharge and vulnerability (Savard *et al.*, 2002).



(Courtesy of Andréanne Hamel (Hamel, 2002))

Figure 6.14
Spatial distribution of recharge for the fractured rock aquifers of the Basses-Laurentides.

47 One of the most widely used groundwater vulnerability mapping methods is DRASTIC, named for the seven factors considered in the method: Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone media, and hydraulic Conductivity of the aquifer (Aller *et al.*, 1985).

A numerical groundwater-flow model for the region was developed to assess the sustainability of future groundwater extraction in the region by computing average drawdown in the aquifer for different average withdrawal rates (Nastev *et al.*, 2006).

The current withdrawal rate of 18 x 10^6 m^3 per year produces a simulated annual drawdown of 0.6 metres in the aquifer, compared with a simulation without groundwater withdrawal. This drawdown is less than the seasonal water level fluctuation in the aquifer and thus is estimated to be sustainable. At an extraction rate of 24 x 10^6 m^3 per year, a drawdown of 2.2 metres is predicted in the aquifer, which is estimated to be sustainable, based again on annual water level fluctuations in the aquifer. Withdrawal rates between 24 x 10^6 m^3 per year and 51 x 10^6 m^3 per year could be used but would require tight control. Rates greater than 51 x 10^6 m^3 per year are assumed unsustainable, as the average regional drawdown becomes greater than eight metres. In light of the surficial geology, it was assumed that baseflow to streams and rivers is not affected by extraction of the groundwater, and the flow model did not consider surface water flow.

In support of land-use decisions, a spatially variable suitability index for groundwater extraction in the region was developed by combining simulated drawdown maps, groundwater quality zones, and aquifer vulnerability maps to indicate the areas most suitable for future groundwater extraction.

Upon completion of the project, the following recommendations were provided by the GSC to the local municipalities to support the implementation of the study findings (Savard and Somers, 2007):

- Groundwater vulnerability maps should be integrated into land-use planning.
- Maintaining groundwater quality should be a priority. Regular monitoring of groundwater quality in municipal wells is recommended.
- Establish wellhead protection areas for all municipal wells.
- The groundwater database should be maintained, updated, and used for local hydrogeological work.
- The local technical and scientific capabilities need to be increased.
- A groundwater management committee should be created for the region to integrate groundwater-management and land-use planning.

To date, one of the regional municipalities has integrated results from the regional hydrogeology project into land-use planning (MRC d'Argenteuil, 2005), and indicates that groundwater protection is a priority and that land-use planning will account for it. The project database is available to municipal staff and updates are planned. It is nevertheless reported that the municipalities do not have the expertise or resources to adopt and apply the knowledge base provided by the regional study.

Lessons Learned

The regional hydrogeology project required techniques and tools specifically designed for fractured rock aquifers, but these are not routinely available to hydrogeological consultants or professionals. The capacity and equipment of the GSC and partner agencies was thus an important factor in the success of the project.

The project helped paint a much clearer picture of the regional hydrogeology, including groundwater quality, vulnerability, aquifer recharge, and usage patterns. There is, however, still a lack of sufficiently detailed data at the local scale, for example, at the scale of a municipal pumping well.

The partnership among government agencies, universities and local authorities was effective as the partners received a greater return on their investment than would occur with a series of independent projects. Key findings included:

- Regional mapping is expensive, especially when field work is required. Most municipalities do not have the required budget, nor do they have the technical expertise.
- Characterisation of fractured rock aquifers requires different tools and methods, compared with non-fractured aquifers. The tools and methods exist but are still not widespread in practice.
- Contrary to popular belief, water bottlers extract only a very small fraction of all groundwater in the region, with impacts limited to local effects.

6.8 PRAIRIE GROUNDWATER

The Prairie groundwater case study demonstrates the importance and vulnerability of groundwater in Canada's largest agricultural region (Figure 6.15), and the possible severity of anticipated climate change impacts.

Background

Groundwater provides domestic water for over 1.4 million prairie residents, i.e., about 30 per cent of the population (Statistics Canada, 2003). In rural areas, its importance is even greater, with 90 per cent of domestic water supply being groundwater-sourced (Plaster and Grove, 2000). Reliance varies from 43 per cent in Saskatchewan, to 30 per cent in Manitoba and 23 per cent in Alberta, reflecting the influence of large urban centres that derive their water from surface water. On a local scale, the patchy occurrence of high-yield aquifers with acceptable water quality constrains development and stimulates piped surface-water systems through programs such as those offered by the Saskatchewan Water Corporation. Drought impacts, such as the failure of wells during the recent drought (1999–2003) in the rapidly growing belt of rural residences south of Saskatoon,

(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.15
Prairie groundwater.

have prompted the building of pipelines to deliver treated river-water to rural residences where population density and groundwater uncertainty warrants. The most prominent of these is the City of Regina, which has moved from substantial groundwater use to water supplied by pipeline from Lake Diefenbaker in the South Saskatchewan River basin. Prairie hydrology is characterised by low precipitation, intermittent runoff generation and relatively large storage due to deep soils, many substantial aquifers and poorly drained post-glacial topography. Evaporation and runoff are limited by the cold semi-arid to sub-humid climate. Snowfall and subsequent snowmelt provide runoff and spring evaporation, but most summer rainfall infiltrates soils to later evaporate when taken up by roots and transpired by plants. This means that local-scale water resources can be limited and very sensitive to changes in climate, land-use and artificial drainage. The perception of plenty caused by seeing stored water in prairie lakes, ponds, and wetlands in wet years does not match the reality of low throughflow rates in the hydrological cycle.

The semi-arid to sub-humid conditions of the Prairies and the frequent occurrence of heavy soils restrict recharge of groundwater to local areas of coarse-textured soils or to seasonal ponds in topographic depressions (Fang and Pomeroy, 2008; Hayashi *et al.*, 2003; Lissey, 1971). Furthermore, many prairie-derived streams are underlain by heavy glacial till and have minimal groundwater connections and consequently little baseflow. Apart from a few natural springs, surface runoff occurs when the input of rainfall or snowmelt exceeds the infiltration capacity of the soil (Pomeroy *et al.*, 2007). It is typical of many first-order prairie streams to become

completely dry shortly after the snowmelt period because of the lack of groundwater contributions.

However, where groundwater is discharged on hillslopes (Hood *et al.*, 2006) and in deep valley bottoms, it sustains important vegetation communities and provides wooded shelter in otherwise treeless, semi-arid plains. Groundwater can play an important role in maintaining summer and drought baseflow in streams emanating from Prairie uplands such as the Cypress Hills, Moose Mountain, Wood Mountain, Riding Mountain and the Manitoba escarpment. A reduction in groundwater discharge from these uplands due to extensive drought or climate change would negatively impact aquatic life, not only in the streams that rely on baseflow, but also in the riparian ecosystems.

Sustainability Considerations

Groundwater Quantity: Most Prairie water use is in the south, while most of the water supply is in the north or in rivers that cross the Prairies from wetter regions in the mountains, parklands and prairie uplands. Past drought in the south has shown that many local surface-water supplies are unreliable, and alternatives include pipelines from larger river systems and local groundwater. Heavy pumping from aquifers that rely mostly on recharge originating from wetlands may result in drying-up of these wetlands and could also lead to drying out of springs and associated wetlands (Van der Kamp and Hayashi, 1998).

Artificial drainage of wetlands in the central and eastern Prairies has been associated with higher streamflow and has resulted in a dramatic reduction in wetland and pond coverage. As many of these wetlands are the primary groundwater recharge zones for the Prairies, long-term effects on aquifers are expected, but current observational systems are inadequate to evaluate the extent of these effects.

Deep-buried valley aquifers have been considered an important source of water supply in times of agricultural droughts. However, as shown by Maathuis and Van der Kamp (1998), heavy pumping from such aquifers leads to significant drawdowns extending tens of kilometres from the pumping centre, and the recovery of the water levels to original static levels may take decades or even centuries. Such aquifers remain invaluable during droughts, but proper management is needed to assure recovery after droughts.

Groundwater Quality: The last few decades have seen dramatic increases in intensive livestock operations (feedlots) and in drilling for oil and gas. Contamination of unconfined and partly confined aquifers has been attributed to oil and gas well

drilling and intensive livestock operations in parts of the Prairies (Bruce Henning,[48] personal communication).

Approaches to Improving the Sustainable Use of Groundwater

Technical Implications: All three Prairie Provinces have completed detailed groundwater maps for much of the settled agricultural zone, although this activity is not yet complete for all aquifers. With the exception of the Assiniboine Delta region, these maps have not been linked into a continuous geographic database or generally mapped to the major river basins for purposes of comprehensive water resource assessments. This creates difficulty both in assessing surface-water resources and in estimating sustainable use for certain aquifers. Since solutions to inadequate groundwater supply can require diversion of river-system waters, assessment of groundwater sustainability needs to be done at the large scales at which surface-water systems operate. The cross-border and cross-basin nature of some of the major aquifers makes improved understanding of surface and groundwater interactions important for sustainable management of water in the region, as water use increases with population and economic growth.

There are networks of monitoring wells run by all provinces, which are used to update the status of the major aquifers, but these are not compared across the region. Such comparisons would permit the detection of large-scale climate change or land-use impacts on recharge, or of a regional over-use that could affect inter-provincial surface supplies from source areas. Integration of provincial databases for transboundary aquifers where water demand is likely to increase (e.g., Alberta-Saskatchewan border) is desirable.

Unconfined, shallow, surficial aquifers are affected most strongly by changing surface hydrology due to wet and dry cycles and so require more intense monitoring and frequent reporting to be managed sustainably. Greater information on the recharge rates of confined aquifers is required if these aquifers undergo further development as permitted by treatment systems.

Certain aquifers such as the Assiniboine Delta Aquifer in southern Manitoba are unconfined and have both high recharge and withdrawal rates. As such, they can be affected by drought and wet cycles. Climate fluctuations impact both precipitation and streamflow water inputs to the delta and withdrawals by evaporation and irrigation for intensive agricultural water use in the region. Climate change and upstream wetland drainage resulting in poor streamflow quality add further

48 Bruce Henning of Henning Drilling Ltd. is a southern-Alberta water, oil and gas well driller with over 40 years experience and over 2,000 wells to his credit. He has maintained extensive records of changes to groundwater conditions over this time.

uncertainty to the sustainability of these aquifers. Assessing the dynamics of surficial aquifers requires a comprehensive simulation of the atmospheric inputs, surface hydrology and groundwater hydrology. New models that couple atmosphere, hydrology, land surface, and groundwater are being developed in the Drought Research Initiative (DRI) by researchers at the University of Manitoba (Loukili *et al.*, 2006). These land-surface-hydrology-groundwater coupled models can be driven by the output of climate models. There is a strong need for coupled models to be deployed in order to better predict the sustainable use of water in aquifers such as the Assiniboine Delta aquifer.

Management Implications: Under current practices in the Prairie Provinces, most groundwater is allocated on the basis of single-point withdrawals. However, with the exception of a few aquifers, the provinces do not have sufficiently detailed aquifer-management information to be able to fully account for the availability of natural recharge and, therefore, the sustainable yield of the aquifer. While proponents have to demonstrate that their use is sustainable and must include existing users in their analysis, insufficient information and understanding may hamper consideration of the impacts of cumulative withdrawals on the aquifer and thus the sustainable allocation of water.

With anticipated increased consumption for urban, oilfield, livestock and irrigation use in southern Alberta and Saskatchewan, alternative sources of water will be explored, and these will inevitably include groundwater. With improved treatment technologies and lack of surface-water alternatives, groundwater supplies with high dissolved-solid concentrations (currently considered to be undesirable) may be seen as new viable water sources. This could result in substantial increases in groundwater withdrawals in southern Alberta and parts of Saskatchewan. Many of these aquifers have seen sustainable use only because withdrawals were very low, and may be unable to withstand the enhanced use that could develop. Recharge to these aquifers will have to be carefully monitored, and use will have to be managed to ensure sustainability, as high dissolved-solid concentrations are indicators of low recharge rates and long residence times underground.

Integrated surface and groundwater quality measurement programs are needed to better assess the current and developing threats to groundwater quality. In some cases legislation may need to be reassessed, or simply be enforced, so that the regulatory system can adequately control contamination of groundwater reserves. For instance, there have been cases where the development of solutions to groundwater contamination issues is left to local watershed associations or municipalities, with no rigorous provincial enforcement backed by scientific evidence (Smith Creek Watershed Association, personal communication).

Further development and implementation of best management practices and regulations for agriculture and the oil industry to minimise groundwater contamination can help to alleviate the development of these problems before remediation is required. For example, the development of continuous cropping patterns and minimum tillage systems for cultivated land in the Prairies has led to more efficient use of precipitation inputs for crop growth but less excess water available for groundwater recharge from wetlands or internally drained lakes. The reduction in summer-fallowed acreage in the last two decades, and conversion of cropland to grazing land, has reduced snowdrift formation and meltwater runoff to wetlands (Fang and Pomeroy, 2008; Van der Kamp *et al.*, 2003).

There is a long history of prominent groundwater research and monitoring conducted by the Prairie provincial research councils and universities. However, the agencies responsible for groundwater regulation and management (typically environment and agriculture ministries) are institutionally separate from this research and monitoring. This has been addressed in some cases by the development of comprehensive provincial water departments or authorities. For instance, the recent development of the Manitoba Water Stewardship department (integrating all water activities of the Manitoba government) and the development of the Saskatchewan Watershed Authority (with groundwater monitoring transferred from the Saskatchewan Research Council to the Authority) are examples of consolidation of monitoring and management. Alberta's Water for Life strategy attempts to bring a stronger science basis to water management. Further work is necessary to ensure clear lines of communication among groundwater researchers, policy-makers and regulators.

Local-scale water management is conducted on the basis of local watershed associations or authorities in most prairie jurisdictions. These local authorities have some decision-making powers with respect to irrigation, drainage and contamination issues, and have tremendous insight into local water-management issues. Some of their decisions have an impact on groundwater supply and management. In many instances, there is insufficient hydrogeological expertise available to these authorities to allow them to sustainably manage groundwater resources. Sustainable management of aquifers is further compromised where aquifers extend outside small drainage basins and cannot be managed effectively by local watershed authorities. This mismatch between watershed management and aquifer extent deters the comprehensive assessment of the groundwater-surface-water system and proper management of either surface or groundwater resources. One solution is to group or cross-link watershed authorities into sets of aquifer authorities, and provide these groups with suitable hydrogeological expertise to ensure sustainable management of groundwater.

Box 6.1: Role of the Prairie Provinces Water Board Agreement

In 1948, Alberta, Saskatchewan, Manitoba, and the Government of Canada signed the Prairie Provinces Water Board Agreement (PPWBA). The PPWBA established the Prairie Provinces Water Board (PPWB) with a mandate to recommend the best use of interprovincial waters and to recommend allocations among provinces (PPWB, 2005). Groundwater is currently not apportioned among the provinces because adequate supplies of surface water have, for the most part, historically been available in transboundary regions; with low groundwater withdrawals, apportionment of groundwater has not been a priority. In any case, there has often been insufficient knowledge of transboundary aquifers upon which to base apportionment decisions. The PPWB may consider groundwater projects and activities that have interprovincial implications and make recommendations to governments on these matters. However, the PPWB currently has not developed objectives or guidelines on groundwater apportionment.

The PPWB has a Committee on Groundwater that deals with questions related to the use and the quality of groundwater shared by the provinces. One of the goals of the PPWB is to ensure that interprovincial groundwater aquifers are protected and used in a sustainable manner. In order to meet this goal the PPWB is working to define and quantify aquifers along the boundaries on an as-needed case-by-case basis and to develop a method to apportion the water within transboundary aquifers. However, no agreement on an apportionment formula for shared aquifers has been made.

Nevertheless, as the importance of groundwater is growing, the PPWB wants to prevent possible transboundary issues by developing concepts for managing and apportioning interprovincial aquifers. Plaster and Grove (2000) note that any future Prairie Province groundwater apportionment agreement should have, as its overriding principles, the obligation not to cause appreciable harm, the equitable and reasonable use of shared waters, the obligation to give prior notice of water resource developments, and the duty to negotiate in good faith. Of these principles, the equitable and reasonable use of shared waters is considered the most essential. In addition to this basic principle, several factors need to be considered in any apportionment scheme. These include:

- priority of use;
- sustainable yield of the aquifer;
- joint apportionment of surface water and groundwater;
- specification of pumping locations and amounts;
- existing PPWB apportionment agreement; and
- provincial allocation methods.

The current challenges to the PPWB include:

- authorities over water are shared amongst jurisdictions;
- actions in one jurisdiction may affect other jurisdictions;
- the volume and timing of flows in streams that originate in the Prairies are highly variable throughout the year and from year to year;
- water use and consumption in southern Alberta and southwestern Saskatchewan is a large percentage of available supply;
- population and economic activity are increasing;
- climate change will affect timing and volume of available water;
- monitoring must be rationalised within existing budgets;
- threats to surface water and groundwater quality are increasing; and
- need for knowledge related to transboundary aquifers.

In order to address some of these challenges, the PPWB Committee on Groundwater has proposed that a conceptual aquifer plan project be undertaken (PPWB, 2006). The project would provide a better understanding of the kind of information that is needed to allocate, or apportion, surface and groundwater within a complete hydrological balance at transboundary locations. The committee is also currently discussing methods to quantify sustainable yield and quantify groundwater and surface water interactions.

Some interprovincial aquifers near Cold Lake, Alberta, may be affected by advancing oil sands development in Alberta (see Section 6.4). Development of oil sands has been proposed in Saskatchewan along the border region adjacent to current Alberta developments. Trans- and near-border oil sands developments are likely to pose new challenges that will require more information than is currently available if the PPWB is to ensure the equitable and reasonable use of shared groundwater systems.

Lessons Learned

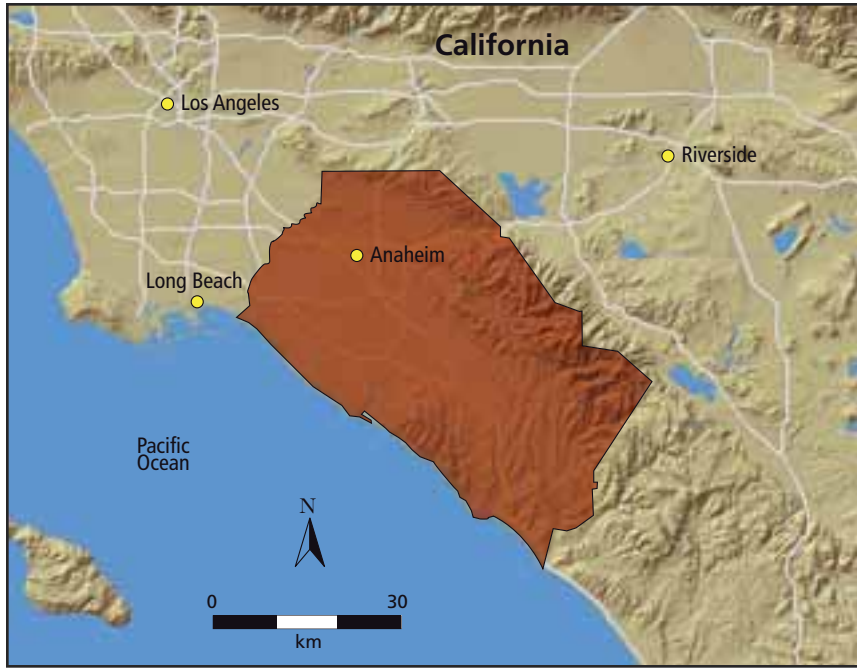
The Prairies are very dependent on groundwater for rural water supply; however, recharge of groundwater is restricted and, in some cases, very sensitive to changes in surface water and climate. The provinces do not have sufficiently detailed aquifer management information to be able to fully account for the availability of natural recharge and, therefore, the sustainable yield of some aquifers. There are particular vulnerabilities to drought, land-use change, and climate change that will require improved surface-groundwater predictive models. Sustainable, comprehensive management of Prairie water resources would be improved by better information on aquifer recharge, assessed in the context of major river basins and with consistent mapping and databases of aquifer characteristics across provincial boundaries.

Contamination from oil and gas exploration and exploitation and from intensive livestock operations may pose threats to groundwater quality in certain regions; it requires careful monitoring and more stringent regulation.

Further work is necessary to ensure clear lines of communication among surface and groundwater researchers, policy-makers, and regulators. Combinations of watershed authorities or cross-linking of authorities to form aquifer management authorities with enhanced hydrogeological expertise could substantially improve groundwater management.

6.9 ORANGE COUNTY WATER SUPPLY, CALIFORNIA: ENGINEERING SOLUTIONS FOR PROTECTING AND ENHANCING AQUIFERS

This case study considers a situation in which the goals of protecting supplies from depletion and contamination were violated, but in which scientific understanding, innovation, and engineering led to a sustainable system.



(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.16
Orange County, California.

Background

Orange County, California, is located in the southeastern part of the greater Los Angeles metropolitan area (Figure 6.16). The northern part of the county is underlain by the Orange County Groundwater Basin, which is managed by the Orange County Water District (OCWD). About 2.3 million people live in the basin, which receives an average of only 33 to 38 cm (13 to 15 inches) of rainfall annually. Despite the semi-arid climate and long history of groundwater extraction, the groundwater basin sustainably provides more than half of all the water used within the District.

Sustainability Considerations

Groundwater Quantity: Beginning in the late 1800s, settlers turned Orange County into a thriving agricultural centre, and groundwater was used to supplement flows from the Santa Ana River. There were hundreds of wells in the basin by the early 1890s, and by 1933 the increased groundwater demand had lowered the water table enough to prompt the California Legislature to create the Orange County Water District to protect and manage the basin. By the 1950s, years of heavy pumping had lowered the water table below sea level, and salt water from the Pacific Ocean had encroached as far as eight kilometres (five miles) inland. Subsurface mapping showed that the intrusion was primarily taking place across a seven-kilometre (four-mile) section of coastline called the Talbert Gap, through sediment laid down as an alluvial fan millions of years ago.

Groundwater Quality: As the region east of Orange County began to grow in population in the 1980s and 1990s, it became clear that the wastewater and stormwater discharges of these upriver communities would markedly increase the discharge of the Santa Ana River. In fact, the water in the river is usually composed primarily of tertiary-treated wastewater from these upstream dischargers. While recognizing that this water represented a significant new source for Orange County if it could be captured and stored, OCWD also understood that it would have elevated levels of nitrate, dissolved organic matter, heavy metals, petroleum hydrocarbons, and other pollutants.

Approaches to Improving the Sustainable Use of Groundwater

Groundwater Quantity: Extensive characterisation was done of the basin's properties through the digitization and interpretation of hundreds of borehole logs, water-level and discharge data from a large network of monitoring wells, and other inputs. This information was used to create and update a 'living' numerical model, which is used extensively for sustainable water management.

The threat to the water supply by salt-water intrusion led the OCWD and the Orange County Sanitation District (OCSD) to conceive a hydraulic barrier system to prevent further salt-water intrusion and protect the basin. Various sources for

the water necessary to create this barrier were evaluated. These included deep-well water, water imported from other basins, reclaimed wastewater, and desalted seawater. The source of injection water finally adopted was a mixture of deep-well water and recycled secondary effluent. The first blended, reclaimed water from the plant now known as Water Factory 21 was injected into the coastal barrier in 1976, and the plant now produces about 85,600 m^3 per day (22.6 million gallons (Mgals) per day) of high-quality water for recharge.

The reclaimed water was chosen for many reasons. These included cost considerations; reduced dependency on water imported into the basin from the Colorado River and elsewhere in California; essentially constant availability during drought or emergencies; and reduced discharge of wastewater to the ocean.

Presently, 23 injection wells located about seven kilometres (four miles) inland recharge freshwater to the aquifers. This water flows both landward and seaward, simultaneously blocking further movement of seawater into the basin and replenishing the aquifer used for drinking water.

Groundwater Quality: Many years of research and negotiations with water management, public health, and wildlife management agencies led to the development of a network of constructed wetland ponds behind Prado Dam in Riverside County, east of Orange County. These wetlands reduce nitrate levels to below current drinking-water requirements and otherwise improve the water quality. This water, together with supplies imported from the Colorado River and from the State Water Project, is then captured along a 10-kilometre (six-mile) section of the Santa Ana River that belongs to OCWD. The system uses interlaced levees built of sand to slow the river's flow so that more of the water can percolate through the bottom of the river channel. It also uses diversion structures to channel water into nine recharge basins with depths ranging from 15 to 47 metres (50 to 150 feet), which were formed in years past by sand- and gravel-mining operations.

Lessons Learned

The extensive use of recycled wastewater for water supply in Orange County has raised a number of serious concerns as to its safety with respect to both pathogens and organic contaminants. To respond to this question, the Orange County Water District has, at times, assembled teams of experts in fields such hydrogeology, toxicology, epidemiology, and geochemistry, and given them wide latitude for directing the District's research in these areas. This has led to important work on identifying residence times of pathogens (a key to virus survival) and geochemical transformations of organic compounds in the subsurface. The large investment in science has also had the indirect benefit of building institutional confidence among water users.

The cost of the extra treatment, underground storage and recovery of wastewater for Orange County is in the range of US$0.30 to 0.50 per m^3 (US$400 to 600 per acre-foot), which is relatively high in absolute terms. Yet the cost of the cheapest alternative, imported water purchased from the Metropolitan Water District of Southern California, is about US$0.53 per m^3 (US$650 per acre-foot), and the cost of other alternatives, such as seawater desalting, is higher. In Orange County, the water is used for domestic, industrial, and commercial purposes, all of which are of relatively high value compared with most irrigation applications, especially fodder crops such as hay. Appraisals of water projects must address not only the costs of alternative sources of supply, but the value of the product water in its final uses (NRC, 2008).

6.10 DENVER BASIN, COLORADO

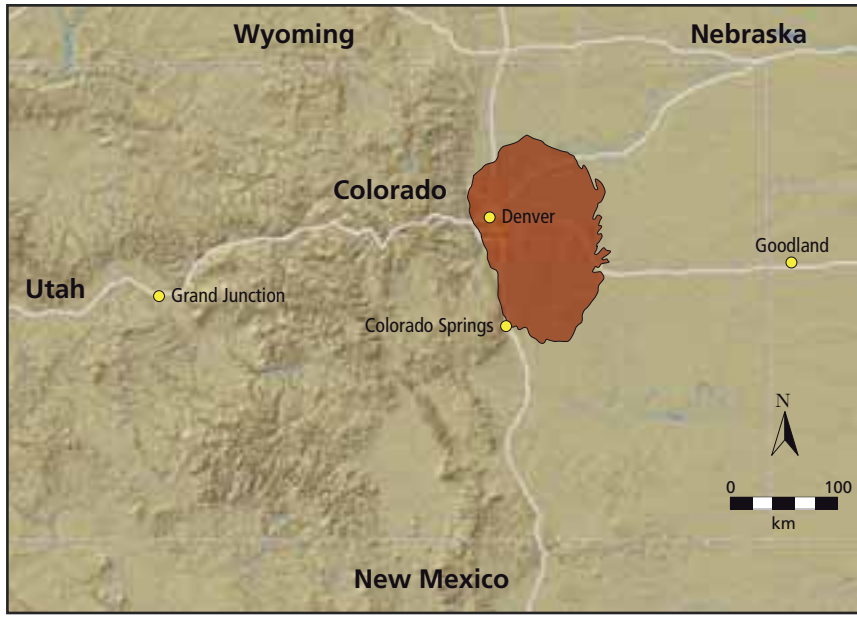
This case study demonstrates that governance may favour socio-economic objectives over maintenance of water level goals, especially in non-recharging aquifers with few ecosystem functions.

Background

The Denver Basin (Figure 6.17) is an important and essentially non-renewable source of groundwater for municipal, industrial, agricultural, and domestic uses in the eight-county Denver metropolitan area (home to 56 per cent of Colorado's population, or slightly more than 2.4 million people according to the 2000 census). The lack of available surface-water rights and accelerated urban growth has resulted in extensive development of the Denver Basin aquifers as both primary and supplemental sources of water supply (Topper *et al.*, 2003).

The Denver Basin aquifer system is a thick, layered sequence of sedimentary aquifers that underlies an area of about 18,000 km^2 (7,000 mi^2) on the eastern front of the Rocky Mountains in northeastern Colorado. The aquifer system, which is under confined conditions in most of the basin, is composed of four aquifers: Dawson, Denver, Arapahoe, and Laramie-Fox Hills. Typically the Dawson aquifer is unconfined. The remaining aquifers are under confined conditions in most locations and not in direct contact with surface water. Water can be produced from all of the sedimentary units, though the Arapahoe aquifer is the most productive and most frequently tapped by municipal supplies.

The Denver area has a semi-arid climate in which potential annual evaporation is about five times larger than annual precipitation. Most recharge to the Denver Basin aquifer system occurs in the high outcrop areas. The principal means of groundwater discharge are withdrawal from wells and inter-aquifer movement of water from the bedrock to overlying alluvial aquifers (Robson and Banta, 1995).



(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.17
Denver Basin, Colorado.

Surface water in the western United States is generally governed by the legal doctrine of 'prior appropriation,' where rights to the surface water are granted for any 'beneficial use.' These rights are granted in order of application, and thus are 'first in time, first in right.' Colorado groundwater law is complicated, but in general it defines any groundwater as 'tributary' to surface water (i.e., assumes it is well-connected to a stream), and thus it is regulated by prior appropriation unless it can be proven to be 'non-tributary,' or isolated from a stream. If groundwater is determined to be isolated from the surface water system, additional rules apply. Because Colorado surface water resources are fully appropriated, the fate of non-tributary groundwater has been hotly debated over the years.

Sustainability Considerations

Groundwater Quantity: Drilling in the Denver area produced flowing artesian wells as early as 1884. By 1890, artesian pressures were used for fountains at Union Station and for operating the organ bellows at Trinity Methodist Church. Pressures began to drop in the mid-1890s, but it was not until the 1950s that new technology, population growth, and drought would combine to force groundwater regulations (Topper and Raynolds, 2007).

Current estimates are that the basin contains 250 x 10^9 m^3 (200 million acre-feet) of recoverable water in storage. Although less than one per cent of this volume has been produced from the aquifer since predevelopment, water levels are declining at a rate of about nine metres per year (30 feet per year) in the most heavily pumped areas. Water levels in the Arapahoe aquifer south of Denver have declined nearly 90 metres (300 feet). Computer simulations of the aquifer system predict that the Arapahoe aquifer could become unconfined by the year 2020. Future prospects for this aquifer are of great concern to water managers (Topper and Raynolds, 2007).

Approaches to Improving the Sustainable Use of Groundwater

With surface water fully appropriated within the basin, there is a continued need for water to meet the demands of an increasing population. In 1985, state legislation created special rules that allocated deep Denver Basin groundwater. With this legislation, the state agreed that it was acceptable to mine the 'non-tributary' Denver Basin aquifers by taking out more water than was being recharged, even if negative consequences resulted.

The 1985 legislation defined non-tributary groundwater as "water which in 100 years will not deplete the flow of a natural stream at an annual rate greater than 1/10th of one per cent of the annual depletion of the well." The legislation also recognised that some of the deep Denver Basin aquifers were not completely isolated from overlying streams, and so were not non-tributary. These Denver Basin aquifers were termed 'not-nontributary,' generally within the outcrop areas. 'Not-nontributary' groundwater, by definition, is not directly connected to surface water, but may show connection over long time frames. Thus, two per cent of the not-nontributary groundwater used must be replaced by return flows (Topper and Raynolds, 2007).

State statutes presume that the productive life of the Denver Basin aquifer system will be at least 100 years, and well permits are issued based on pumping one per cent of the underlying aquifer volume per year. Of course, hydrogeological estimates were made to determine this volume. These estimates are based on measured water levels and the storage properties of the individual aquifers in the basin. Groundwater research in the basin continues in order to track the resource, improve the understanding of the system, and evaluate new information as it develops using a 'living model' approach.

Lessons Learned

Water level declines have been accepted as an inevitable consequence of the use of Denver Basin groundwater, and groundwater is being used in an unsustainable way. Ultimately, future groundwater availability in the Denver Basin may be based on economics rather than on legislation or the remaining volume in storage. As

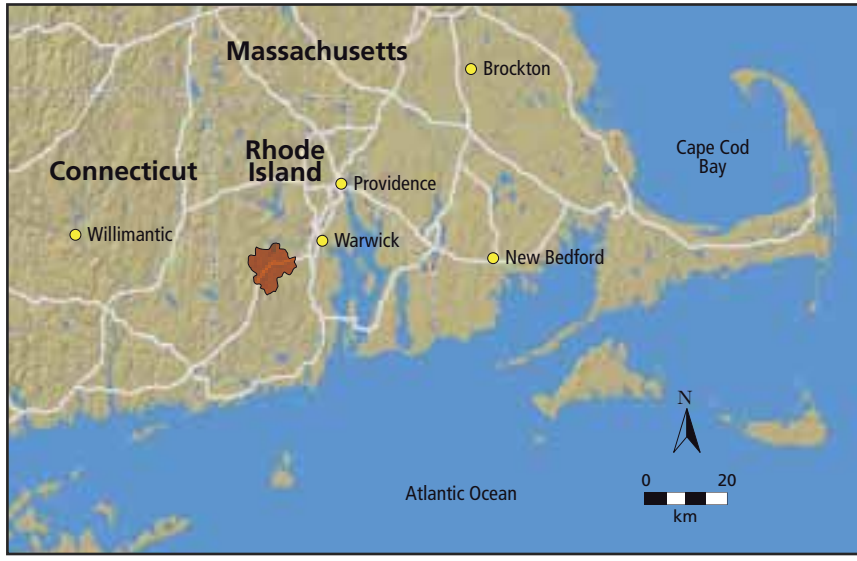
water levels decline due to over-pumping and well interference, flow rates decline, wells must be deepened, and lift costs rise. The cost of the water may rise to a point where it is no longer economically feasible to produce it. Colorado has compromised future groundwater availability with current use to enable development in areas that have no alternative water supply at this time. The hope is that additional options for water supply will develop in the future.

6.11 BIG RIVER BASIN, RHODE ISLAND

The Big River case study was selected to demonstrate that, with advances in groundwater modelling methods, the spatial and temporal patterns of groundwater abstraction can be optimised for the protection of riparian ecosystems.

Background

There would appear to be adequate water resources in the northeastern United States. Streams and lakes are plentiful. Precipitation is relatively abundant in the range of 100 to 125 cm per year (40 to 50 inches per year), and is typically distributed somewhat uniformly throughout the seasons. An example from Rhode Island (Figure 6.18) illustrates a common groundwater development issue that arises in the northeastern United States, despite relatively abundant water resources and productive aquifers.



(Reference map provided by Earth-To-Map GIS Inc.)

Figure 6.18
Big River basin, Rhode Island.

Water demand is increasing throughout Rhode Island, and the Rhode Island Water Resources Board (RIWRB), which is responsible for developing and protecting the State's major water resources, is concerned that increasing demand may exceed the capacity of current sources. RIWRB determined that development of approximately 60,000 m^3 per day (16 Mgal per day) of additional water supply in the area of the Big River basin southwest of Providence was necessary for future population growth and economic development in central Rhode Island. A proposed reservoir, on the books since the 1960s, has not been approved. Water managers were forced to turn to groundwater to meet the projected needs.

Sustainability Considerations

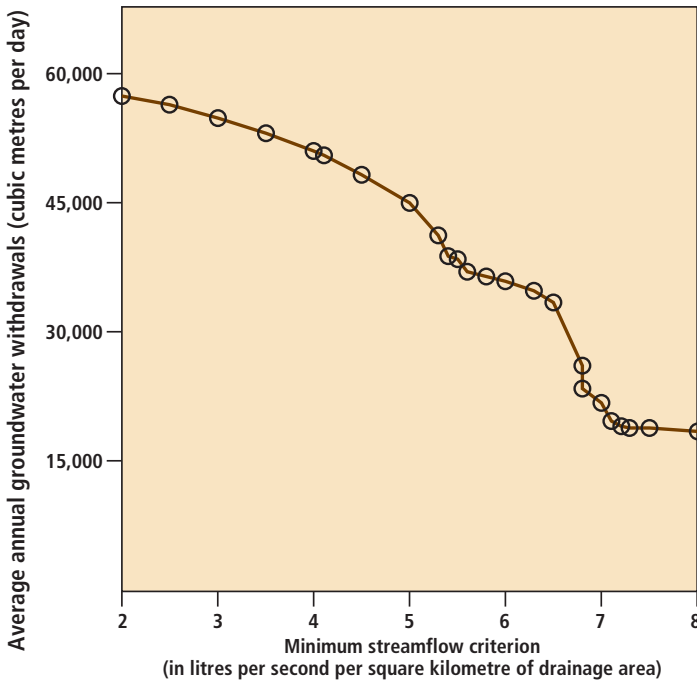
Ecosystem Protection: Shallow, high-yielding sand and gravel aquifers are an important source of water for many communities. Typically, wells that pump from these aquifers are located close to streams that are in direct hydraulic connection with the underlying groundwater system. Pumping from these wells reduces streamflow by capturing groundwater that would otherwise discharge to the streams and, in some cases, by drawing water out of the streams and into the adjoining aquifer.

Approaches to Improving the Sustainable Use of Groundwater

Previous investigations showed that groundwater could not be developed without reducing streamflow. What was not known, however, was what pumping rates could be sustained without unacceptable consequences on the streamflow. Where should the pumping wells be located to minimise the rate of streamflow depletion and the timing of that depletion?

The USGS, in collaboration with RIWRB, recently developed a simulation-optimisation model for the basin to determine the maximum amount of groundwater that could be pumped from 13 wells distributed across the basin while simultaneously maintaining minimum streamflow rates at four locations in the basin. The values of the minimum streamflow rates were varied in a series of model runs to test several management criteria that were being considered by the State (Granato and Barlow, 2005).

Groundwater pumping rates were calculated for several simulations. Each streamflow criterion is plotted in Figure 6.19 as the minimum amount of streamflow required at each of the four streamflow-constraint sites per square kilometre of drainage area to each site. For the criteria shown in the figure, model-calculated average annual pumping rates from the basin ranged from a minimum of about 19,000 m^3 per day (five Mgal per day) for the most restrictive criterion to a maximum of about 57,000 m^3 per day (15 Mgal per day) for the least restrictive. The graph indicates that relatively small changes in the streamflow criteria can result in large changes in model-calculated pumping rates. The nonlinear shape of the graph is



(Adapted and reproduced with permission from Barlow, 2005)

Figure 6.19
Relation between minimum streamflow criterion and total groundwater withdrawals calculated by the optimization model of the Big River basin, Rhode Island. (Each open circle on the figure represents a model run.)

a function of the unique hydrological and hydrogeological characteristics of the Big River Basin and the specific set of well sites and streamflow locations used in the simulation-optimisation model (Barlow, 2005).

Lessons Learned

Experience in the Big River basin illustrates that the relation between groundwater and surface water is complex. Adding specific streamflow criteria further complicates development strategies.

Incorporating and understanding the hydrological system via a computer model allows the groundwater scientist to evaluate groundwater availability in many ways, and to adjust those evaluations as societal decisions about water management change. An evaluation of multiple management strategies would not have been possible without groundwater modelling. Comparing these management strategies would have been difficult to determine by use of multiple simulations managed manually.

Simulation-optimisation models take groundwater modelling a step further by automating and quantifying an approach that allows repeated simulations designed to test different hydrological stresses, such as the effects of different well locations or pumping rates on streamflow. Simulation-optimisation modelling proved to be the most effective approach to evaluate the potential management options.

Detailed knowledge of the aquifer system, combined with recent improvements in simulation techniques, improved understanding of aquatic ecosystem needs, and new regulatory requirements allowed the establishment of minimum streamflow standards and permitted regulators to effectively define the maximum sustainable use of this system.

7 The Panel's Findings: A Framework for Sustainable Groundwater Management in Canada

7.1 THE GROWING IMPORTANCE OF SUSTAINABLE MANAGEMENT OF GROUNDWATER

Groundwater is the main source of water for almost ten million Canadians. It is critical to human health, to important aspects of the economy, and to the viability of many aquatic ecosystems. Groundwater is often the preferred source for communities, farms and individual households since it can be close to users, is relatively inexpensive and is often of better quality than heavily used surface waters. As surface waters become less reliable in a changing climate, there may well be more reliance on groundwater. The need for sustainable groundwater development, and the emergence of many issues that will place roadblocks on the path to sustainability, make it imperative that steps be taken to improve groundwater management in Canada.

Threats to groundwater include:

- rampant urbanisation;
- climate change;
- burgeoning energy production;
- intensification of agriculture; and
- contamination from diverse sources.

While not yet a national 'crisis,' the growing and emerging threats to groundwater require that Canada move with despatch towards a more sustainable management of this vital resource. Experience with over-exploitation and contamination of groundwater in other countries provides lessons to be heeded.

Aquatic ecosystems, which depend on groundwater contributions of flows to rivers and lakes, need more deliberate attention and protection in groundwater withdrawal allocations.

The developing energy-water nexus requires special attention. Oil sands developments, coalbed-methane extraction, irrigation for biofuel crops, and increasing use of geothermal energy all necessitate careful management of related groundwater resources and require measures to increase water-use efficiency.

The persistence of contamination of drinking water, as indicated by boil-water advisories and water-borne illnesses, is an ever-present threat to health. Heavy-rain events preceded two-thirds of water-borne disease outbreaks in North

America (including the Walkerton tragedy), and the frequency of severe storms is expected to increase with a warmer climate. Nitrates in groundwater in many agricultural areas are a persistent problem, potentially posing a threat to the health of infants and, because of transport through the hydrological cycle, creating the threat of adverse effects in receiving waters that contain fish and other aquatic species.

Recharge of groundwater aquifers is threatened in some areas by sprawling urban development and, more broadly, by climate change.

Existing problems in transboundary aquifers and the impact of groundwater on surface waters shared by Canada and the United States will grow as population and usage increase. Although the International Joint Commission (Canada-US) has, at times, interpreted the Boundary Waters Treaty to include groundwater, this is a somewhat imperfect treaty for the purpose. The United Nations General Assembly is considering a draft convention on Transboundary Aquifers that should be considered for adoption by Canada and the United States. Examples of transboundary issues involving groundwater include the Abbotsford-Sumas aquifer and the Great Lakes basin, as described in Chapter 6.

Public attitudes have also been evolving, with an increasing emphasis on environmental values. Never before has the quality and availability of water been of greater importance for Canadians.

7.2 SUMMARY OF THE PANEL'S RESPONSE TO THE CHARGE

The charge to the panel asked, "What is needed to achieve sustainable management of Canada's groundwater resources, from a science perspective?" The answers to that overarching question, and to the four sub-questions in the charge, form much of the content of this report. What follows is a summary, drawn from the main text, of the panel's response to the original charge.

> ***Primary Question:***
> What is needed to achieve sustainable management of Canada's groundwater resources, from a science perspective?

Sustainability Goals

What is meant by sustainable management of groundwater? In earlier times, the avoidance of over-pumping and consequent decline of the water table was the sole objective of users and management agencies. A broader view of the role of groundwater is reflected in the following sustainable-management goals developed by the panel to guide its assessment:

- Protection of groundwater supplies from depletion: Sustainability requires that withdrawals can be maintained indefinitely without creating significant long-term declines in regional water levels.
- Protection of groundwater quality from contamination: Sustainability requires that groundwater quality is not compromised by significant degradation of its chemical or biological character.
- Protection of ecosystem health: Sustainability requires that withdrawals do not significantly impinge on the amount and timing of groundwater contributions to surface waters that support ecosystems.
- Achievement of economic and social well-being: Sustainability requires that allocation of groundwater maximises its potential contribution to social well-being (interpreted to reflect both economic and non-economic values).
- Application of good governance: Sustainability requires that decisions about groundwater are made transparently, through fully informed public participation and with full account taken of ecosystem needs, intergenerational equity, and the precautionary principle.

Each of these five goals is necessary and none, in itself, is sufficient. The goals are also interrelated. The question of what constitutes 'significant' within the context of the first three goals involves judgment and is ultimately a societal decision that should be informed by scientific knowledge and sustainability principles, including the precautionary principle. The goals are also directions to guide data-gathering, groundwater modelling, groundwater management, and economic decision-making.

Evidence indicates — as outlined, for example, in the Canadian case studies in Chapter 6 — that a comprehensive sustainability framework has not yet been adopted in Canadian jurisdictions. Adoption by federal, provincial and local jurisdictions of such a framework, based on goals along the lines of those set out above, would be valuable in guiding efforts in groundwater management.

The measurement of sustainability with these, or similar goals, as benchmarks is a task requiring further development. More specifically, the assessment of sustainability will usually require the definition of several independent measures that are representative and easily retrievable from program databases. The measures should be designed to permit comparison with sustainability targets, reference values, ranges or thresholds, and therefore be able to serve as triggers for action when indicated.

The Requirement for Integration

Sustainability requires that groundwater and surface water be characterised and managed as an integrated system within the context of the hydrological cycle in a watershed or groundwatershed. In many jurisdictions, groundwater and surface

water are studied and managed separately, as are water quality and quantity. Special efforts are needed to overcome this problem.

For the sustainable use of groundwater, the land-use planning and water-resource development process must consider the long-term availability and vulnerability of local groundwater resources and the potential for cumulative impacts. Hydrogeological studies can be effective in integrating groundwater concerns into land-use planning provided, of course, that the groundwater investigations precede the land-use development. The groundwater studies to provide this knowledge are best undertaken on a basin-scale and with a flow systems basis that requires detailed knowledge of recharge, sustainable yield and discharge conditions.

In many cases, groundwater management is a shared undertaking among several levels of government and includes a role for the public. The case studies of Oak Ridges, Basses-Laurentides, Waterloo, and Abbotsford-Sumas are good examples of coordinated and integrated cooperation among different levels of government and are worthy of wider emulation.

Sub-question 1:
What current knowledge gaps limit our ability to evaluate the quantity of the resource, its locations and the uncertainties associated with these evaluations?

A Framework for Analysis and Understanding

There are four investigative components that, when managed in an integrated manner, should lead to credible forecasts of groundwater behaviour in a sustainable-management context. These are: (i) a comprehensive water database (including geology and groundwater data as well as current stresses such as extraction, climate, and streamflow); (ii) an understanding of the geological framework through which the groundwater flows; (iii) a quantitative description of the hydrogeological regime, including the extent of major hydrogeological units and parameters such as hydraulic conductivity; and (iv) an appropriate groundwater-flow model.

Lack of Basic Data

See the response to sub-question 3.

Requirements to Understand Groundwater Flow

In Canada there are key gaps in our knowledge of the large-scale groundwater-flow dynamics (recharge, sustainable yield, discharge) that are essential for sustainable management. There is a need to develop a common framework for categorising aquifers at different scales (provincial, regional, or local). The development of such a framework would allow local studies to link to broader provincial and national

assessments to facilitate a comprehensive understanding of groundwater-flow systems on a national scale.

The last comprehensive assessment of Canada's groundwater resources was published in 1967. The Groundwater Mapping Program managed by the Geological Survey of Canada (GSC) has undertaken to assess 30 key regional aquifers. At current rates, it is expected the mapping will not be complete for almost another two decades. In view of the importance of better hydrogeological knowledge as input both for models and for better groundwater management in general, a more rapid pace of aquifer mapping is necessary.

Understanding the Groundwater Needs of Ecosystems

Due to the infancy of the research into the baseline requirements of ecosystems — related, for example, to instream flow needs and temperature — it is difficult to identify cases in Canada where groundwater is being managed to sustain ecosystem health and thus to determine the quantity of water that can be extracted sustainably from an aquifer. In particular, there is no standard methodology for incorporating instream flow protection into laws and regulations, though a number of provinces are examining ways to address this gap.

Groundwater Implications of Energy Developments

Clear groundwater objectives (allocation, required quality) should be defined prior to the approval of any new energy-extraction projects. These objectives should be based on (i) adequate knowledge of current hydrogeological systems and their linkages to land and surface-water environments, and (ii) accurate and regularly updated predictions of future cumulative effects. Currently, adequate knowledge is lacking as to whether the aquifers in the Athabasca oil sands region can sustain the groundwater demands and losses in view of projected future development.

Impacts of Climate Change on Groundwater

Owing to climate change, the combination of reduced recharge in much of southern Canada and increased demand in a warming climate will affect groundwater levels in the coming decades. Much more research on this issue is urgently needed to ensure sustainability of supplies and to assess impacts on ecosystems. For example, models that couple atmosphere, land surface, hydrology and groundwater should be developed to permit better assessment of the impacts of changes in both climate and land use.

Sub-question 2:
What do we need to understand in order to protect the quality of groundwater supply — for health protection and safeguarding other uses?

Protecting the Quality of Drinking Water

The quality of groundwater-based municipal drinking water is generally excellent across Canada. However, the frequent occurrence of microbial contamination in small community wells, including wells in First Nations communities, is unacceptable and undermines the health of a significant number of Canadians. A stronger enforcement and regulatory environment for Canadian drinking water for communities may be necessary, supported by adequate resources and training of water providers.

Jurisdictions in Canada recognise the need for source-water protection as the first barrier to protect drinking-water quality. Nevertheless, available data are generally insufficient to properly delineate source-protection zones, especially in complex aquifer settings. Better geological understanding is needed to improve the accuracy of models used to delineate the source-protection zones.

Monitoring Groundwater Quality

There is considerable disparity in the requirement for, and the thoroughness of, groundwater quality monitoring across the country. Requirements vary from province to province with respect to water quality data for newly drilled domestic wells, but typically only bacteria or coliform testing is required.

There is no national assessment of trends in groundwater quality; however, the National Water Research Institute and the Geological Survey of Canada are now collaborating on collecting needed information. There may be a requirement for a (selective) groundwater-quality monitoring network, coordinated nationally, to detect any large-scale and long-term trends in groundwater quality due to changes in global or regional precipitation, chemistry, or other continental-scale factors.

Identifying Groundwater Contaminants

Proactive measures are necessary, at the local level, to identify substances that may render groundwater unsafe for consumption and inform residents of their presence. Common naturally-occurring examples are arsenic, radon gas and fluoride. Reconnaissance surveys and publication of information, coupled with mandatory testing of private wells in suspect areas, are needed to protect the health of rural residents. Human-caused contamination may result from agriculture, contaminated sites, or leaking storage tanks and sewer systems. These sources need to be identified, remediated where possible, and inventoried in provincial databases, and advisories need to be provided to groundwater users. Little is known about the transport and fate in the subsurface environment of new forms of contamination that may be present in treated sewage effluent, e.g., pharmaceuticals and personal-care products. This knowledge gap should be filled. Resources allocated to such threats to groundwater quality have not kept pace with needs.

Persistent Nitrate Contamination

Elevated nitrate concentrations, mainly from agricultural sources, continue to persist in many important Canadian aquifers. Despite widespread awareness of the problem, there has been little success in significantly reducing the incidence of nitrate contamination. Adoption of best management practices in agriculture has not been sufficient to adequately address this problem with potential impacts on the health of infants. Further efforts are therefore needed to address the technical, regulatory, and economic factors that are responsible.

Rural Groundwater Quality

Considering the currently poor quality of water in many rural wells, the inadequate monitoring programs and inconsistent educational programs that promote and assure rural well-water quality, the fact that most source-water protection initiatives are focused on municipal wells, and the prospect for further intensification of agriculture, it is apparent that rural groundwater quality requires increased attention, including community-based outreach programs addressing water wells and aquifers.

Sub-question 3:
For groundwater supply and quality monitoring purposes, what techniques and information are needed? What is the current state of the art and state of practice, and what needs to be developed in Canada?

The Need for Better Data

While all provinces and local agencies have ongoing water level monitoring programs, the number of observation points is generally insufficient and water quality data are not a priority of these programs. Systematic analyses of these data are not done in many cases, and no mechanism exists to identify emerging threats or evaluate the need for action, except in a reactive mode. With some exceptions, the resources dedicated to systematic water-related data collection have failed to keep pace with the demands of development over the past 20 years; for example, the number of stream gauges in Canada has declined from 3,600 to about 2,900.

Data on Groundwater Withdrawals

There is a critical lack of data on groundwater allocations, including allocations to municipal, industrial and agricultural users; on actual withdrawals of groundwater; and on volumes discharged or reused. Since groundwater cannot be managed effectively at any scale without these data, responsible agencies should assign a high priority to their collection. Environment Canada's Municipal Water and Wastewater Survey is currently the best source of national data on groundwater extraction for domestic and municipal purposes, but due to a poor response

rate from many small municipalities to this voluntary survey, it is incomplete over large sections of the country. Measures to improve the response rate by assisting municipalities with the survey, and linking the collected data with provincial records of municipal water works, are necessary to better document groundwater use in Canada.

Climate Data

Existing networks of climate stations are inadequate for providing a year-round accounting of precipitation or temperature for many aquifers, thus increasing uncertainty which could lead to inappropriate groundwater management decisions. This is particularly critical in areas of high topographic relief and in remote regions, such as British Columbia and northern Canada.

Integration of Data

Agencies that undertake monitoring activities should implement hydrological monitoring systems that capture and integrate climate, surface water, groundwater and extraction or consumption data. Provincial water well records usually fail to capture better-quality geological data that could be obtained if other boreholes, such as those drilled primarily by consultants for hydrogeological or geotechnical investigations, were included.

Structure to Facilitate Management and Sharing of Data

Although many hydrogeological data are collected, there are few systematic efforts to assemble them into a collective database to improve understanding of groundwater. For example, there is considerable ongoing loss of valuable groundwater-related data principally collected in various reports and research studies carried out by consulting firms, universities and non-governmental agencies.

Given the poor record of groundwater data management across the country, it is critical that the collection, maintenance and management of groundwater-related data, and ready access to this data, be a priority for action across Canada. While Canada does not need a comprehensive national groundwater database, it is important to agree on a structure and set of best practices (perhaps based on a design and practices similar to those of the National Water Information System of the United States Geological Survey) to facilitate the sharing of data among the provinces and between the provinces and the federal government. The Groundwater Information Network (GIN, see Chapter 4) is developing standards for data management to facilitate sharing of information. Groundwater monitoring at all levels must be more strongly supported, and a platform for sharing data, such as the GIN, needs to be further developed through federal-provincial cooperation.

Sub-question 4:
What other scientific and socio-economic knowledge is needed to sustainably manage aquifers in Canada and aquifers shared with the United States?

Improved Understanding of the Value of Groundwater

An enhanced understanding of the value of groundwater's contribution to Canada's economy, environment, and society could promote more efficient decision-making regarding water allocations, water-related infrastructure, expenditures for source-water protection, and remediation of contaminated waters. Despite the availability of empirical estimation techniques and the efforts in other countries to value their water resources, relatively little research has been carried out in Canada regarding the value of water. There is effectively no current information on the valuation of groundwater by its users.

Market-Based Instruments to Support Sustainable Management

Current groundwater allocation methods in Canada rarely use market-based incentives, despite considerable evidence that greater use of economic instruments such as water prices, abstraction fees, and tradable permits has the potential to promote more sustainable groundwater use. The principal challenges facing their implementation include the lack of experience of governments in Canada with these instruments; a lack of data and understanding regarding the economic characteristics of users' groundwater demands and their impacts on others over time; and the need to coordinate the introduction of market-based instruments with existing regulatory frameworks.

In principle, use of economic instruments could address activities that result in changes in groundwater quality; however, the information requirements for setting a price on groundwater pollution are very challenging. The analysis of non-point source pollution (e.g., from agricultural activity), and the design of policies aimed at controlling it in a least-cost fashion, are likely to be case-specific.

The integration of economic models with hydrological models would provide managers with a powerful tool to promote sustainable groundwater use. To date, models reflecting links between economic activity and groundwater have tended to be devoted primarily to the use of groundwater in agriculture.

Encouraging the Efficient Use of Water

Municipal water prices can be designed to promote sustainable groundwater use. An important first step is that a local water agency's cost-accounting must fully record all of the costs of providing drinking water. Water agencies have typically recorded only operating costs and a portion of capital costs, thus providing water users with an implicit subsidy and an incentive to use water unsustainably.

Application of available technology and further research to improve the efficiency of water use in many industrial and domestic sectors — the oil sands developments being a prominent example — should be encouraged. Economic incentives, and in some cases regulations, may also need to be considered to encourage efficiency.

Valuing Ecosystem Benefits

Methods for assigning value to the ecosystem benefits derived from groundwater are poorly understood and incomplete. For the governance process to equitably balance ecosystem needs with socio-economic needs, comparable accounting procedures are necessary in both domains to quantify the value of water. The failure to fully account for the value of ecosystem functions means that the governance process will likely favour socio-economic interests over ecosystem interests.

7.3 LEGAL AND INSTITUTIONAL CONSIDERATIONS

An adequate base of scientific knowledge is necessary, but not sufficient, for the sustainable management of groundwater. As documented throughout this report, many of the most challenging hurdles lie in the domain of institutional and political factors, including fragmented and overlapping jurisdictions and responsibilities, competing priorities, and traditional approaches and ways of thinking.

Coordinated Governance and Management

The provinces, as resource owners and regulators, have the primary legal jurisdiction over groundwater. The federal government has legislative and proprietary powers to manage groundwater on federal lands and has many areas of policy and spending authority that can affect groundwater sustainability. There are several relevant areas, such as agriculture and environment, where responsibility is shared by the Government of Canada and the provinces. Local governments also have a significant influence on groundwater protection through their land-use powers.

The Canada Water Act, originally passed in 1970, enables the federal government to enter into agreements with the provinces and territories to undertake comprehensive river basin studies; to monitor, collect data, and establish inventories; and to designate water quality management agencies. It has seen little use recently, but could play a beneficial role in groundwater management in the future. *The Canadian Framework for Collaboration on Groundwater*, issued in 2003 by a committee of provincial and federal government representatives, has encouraged cooperation at the working level, but there is still a need for a more clear-cut, formally stated division of duties among the various levels of government.

Considering the interjurisdictional nature of groundwater management, and in light of the positive experiences in interjurisdictional cooperation outlined in several case studies in Chapter 6, the panel would advocate:

- that provincial agencies assist in the establishment and support of local agencies, based on provincial priorities that use flow-system-based, groundwatershed-scale hydrogeological analyses;
- that local agencies — at the scale of the basin, watershed or aquifer — design field programs, gather data, and develop models in order to use them in an adaptive-management style and make decisions, or support provincial decisions in respect of such matters as allocations, source protection, and land use planning; and
- that federal agencies support the basic and applied science needed to underpin sustainable groundwater management; work, as mutually agreed, with provincial and local authorities (including First Nations) to develop the specific hydrogeological and environmental knowledge that is required to implement sustainable-management strategies; and apply sustainability principles to the management of groundwater on federal lands and in boundary and transboundary waters.

Improved Laws and Regulations

There are several areas where the legal protection of groundwater quantity and quality could be improved, as noted throughout the report, specifically: protecting instream flow, addressing nitrate contamination and other agricultural impacts, preventing groundwater contamination, and assessing the cumulative impacts of activities that affect groundwater.

The Importance of Enforcement

Stronger enforcement of existing regulations would improve sustainable groundwater management. Most in need of improvement are: accurate and timely reporting of all licensed groundwater withdrawals, adherence to strengthened water-quality monitoring requirements, provision of complete documentation of geology and of well construction and well abandonment, and timely adherence to requirements for contaminated site clean-up and restoration.

Upgrading Capabilities to Support Sustainable Management

Local Capacity Building: Allocation of staff and funding to groundwater management has not kept pace with the increasing demands placed on the resource, leaving many Canadian basins with insufficient groundwater management expertise and capacity. Groundwater management at a local level, through a regional municipality or a watershed authority, will only be successful when accompanied by sufficient financial and human resources, together with a requirement to take action and report on progress. Several examples suggest that cooperative efforts involving the three orders of government have generated positive outcomes by combining available resources into a single, geographically focused, vertically integrated management approach.

State-of-the-Art Modelling: In most provinces, the use of models by regulatory agencies lags behind state-of-the-art application. Thus, as provincial authorities increasingly seek sustainable groundwater allocation strategies, there is a need to improve their capacity to employ basin-scale groundwater management models.

Need for Skilled People: There is currently a shortage of hydrogeologists in Canada and there will be an increasing demand for groundwater science and management skills as more rigour is applied to managing the resource. There is a need for hydrogeology training programs that integrate coverage of hydrological sciences and ecosystem-sustainability with other relevant fields such as watershed management, water resource economics, and water law.

7.4 A RESEARCH AGENDA

This report has identified a number of topics requiring further research. Action to initiate, accelerate, and fund these research activities requires priority attention in the relevant federal government agencies, including granting councils; in provinces and their research institutes; and in the academic community. Government-university collaboration can be productive in this field. The following do not constitute an exhaustive list but represent areas identified by the panel in the course of its work. In no specific order of priority, they are:

- Improved and more cost-effective methods for hydrogeological characterisation;
- Improved techniques for data analysis and reporting on groundwater quantity, quality, and usage;
- Development or improvement of guidelines and techniques to assess the quantity, quality (including temperature), and timing of groundwater flows to sustainably support aquatic ecosystems;
- Assessment of ongoing climate impacts on groundwater quantity and quality, including impacts of permafrost degradation on groundwater, and the design of appropriate adaptation strategies;
- Development of models that couple atmosphere, land surface, hydrology and groundwater, to help assess impacts both of land-use change and of climate change and variability;
- Improved techniques for delineating recharge and source-water protection zones for land-use planning;
- Research to understand the technical, regulatory, and economic factors that are responsible for persistent elevated nitrate concentrations in important aquifers;
- Assessment and reporting on the concentrations in groundwater of naturally occurring but potentially harmful contaminants (e.g., arsenic, radon), ubiquitous products such as pharmaceuticals, and bacterial and viral contamination;

- Continued research on the transport, fate, and remediation of contaminants;
- Research to improve the efficiency of water use in many industrial and domestic sectors, particularly in energy production; and
- Research on design and implementation of pricing and economic instruments to promote sustainable groundwater use.

7.5 REPORTING

The federal government, in cooperation with the provinces and territories, should report on the current state of groundwater in Canada, and on progress toward sustainable management. Such a report should be completed within the next two years and then updated at regular intervals, possibly every five years.

In this regard, there is a need for further development of appropriate and agreed-upon measurements or indicators of the key dimensions of groundwater sustainability, in order to guide management and to chart progress.

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Appendix 1: The Basics of Groundwater Science

Hydrogeological Environments: Although groundwater is present almost everywhere below the land surface, one should not envision groundwater as a subterranean river or lake. Only in the rare situations associated with cave formation in limestone might one encounter such conditions. A more realistic image would be a firm sponge, with its solid framework representing the geological host material, and its connected network of pores filled with very slowly moving groundwater.

Soils, unconsolidated deposits, and porous and fractured rocks provide the hydrogeological environments for the occurrence of groundwater. In this capacity, they play two distinct roles: (i) they provide storage for the huge volumes of water that are held in the subsurface; and (ii) they provide the controls on the rates of groundwater flow that occur through the subsurface portion of the hydrological cycle. It is important that this duality of the groundwater resource be recognised at the outset. It is the huge stores of groundwater that attract the attention of large water users, but it is the renewable flow through the system that plays the greatest role in defining the sustainable yields that must be considered by water resource managers.

Porosity: Porosity reflects the storage capacity of a geologic deposit, defined as the percentage of a sample of the material that is occupied by pores. Porosities of sand and gravel deposits, like those found in fluvial valleys, or in glacial-outwash fans[49] on the Prairies, are usually about 30 to 40 per cent. Porosities of fractured crystalline rock, like that found on the Canadian Shield, are much lower, usually less than one per cent. Even at the lower end of this range, it is apparent that the huge volumes of subsurface geologic materials in a country as large as Canada give rise to a potentially very large volume of groundwater in storage.

Hydraulic Head: The hydraulic head is a measure of energy with both a gravity and a pressure component; it is readily measured in the field by the elevation of the water level. Groundwater flows through most types of geologic media from points of high hydraulic head to points of lower hydraulic head. In an area of equal fluid pressure, groundwater will flow under gravity from higher elevations to lower. Under conditions of horizontal flow, where the gravity component remains constant, groundwater will flow from positions of higher fluid pressure to lower. The change in hydraulic head over distance is called the hydraulic gradient (analogous to the atmospheric pressure gradients that drive winds). Gradients in

49 Sand and gravel transported away from a glacier by streams of melt water and either deposited as a floodplain along a pre-existing valley bottom or broadcast over a pre-existing plain in a form similar to an alluvial fan.

groundwater-flow systems may be directed downwards, upwards, or horizontally in different parts of the system.

Groundwater Flow: Groundwater flow is directly proportional to the hydraulic gradient that is driving the flow. Hydraulic gradients usually do not vary much from one place to another. The controlling factor on the rate of flow therefore resides in a proportionality factor, which is a property of the material through which the water is flowing. This material property is known as 'hydraulic conductivity' (or its closely allied cousin, 'permeability').

Hydraulic conductivity values can vary over many orders of magnitude, with values as high as 10 cm per second in the most permeable deposits, and as low as 10^{-10} cm per second in the least permeable ones. This range gives rise to huge differences in the rates of groundwater flow in different geological environments. Flow rates in high-permeability materials like unconsolidated sands and gravels, or highly fractured and porous basalts and limestones, could be of the order of hundreds of metres per year. Flow rates in low-permeability materials like unweathered marine clays, or sparsely fractured crystalline rocks, could be as low as a few centimetres per century.

Groundwater flow rates are typically much slower than those of surface water, and this gives rise to much longer residence times for groundwater relative to surface water. Residence times of a water particle in the surface-water portion of a watershed are of the order of a few weeks to a few months, while those for the groundwater-flow system can run to many thousands of years.

Aquifers and Aquitards: Geologic formations that exhibit values of porosity and hydraulic conductivity at the higher end of the range are known as aquifers. Two of the most common definitions describe an aquifer as: (i) a geologic unit that can yield significant quantities of water to wells, or (ii) a geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients. Less-permeable geologic units that tend to retard the flow of groundwater are known as aquitards. Most hydrogeological environments consist of some combination of aquifers and aquitards. For example, in a system of flat-lying interbedded sedimentary rocks, the more-permeable sandstone and limestone units would be the aquifers and the less-permeable shales, the aquitards.

The definitions of aquifer and aquitard are purposely imprecise with respect to bounding values of hydraulic conductivity. The use of the undefined term 'significant quantities of water' in the definition of an aquifer makes it clear that 'aquifer' is a relative term. A quantity of water that is significant in one hydrogeological environment (or to one particular user) may be insignificant in another

circumstance. For example, in a bedded silt-sand sequence, the silt would be an aquitard, but in a silt-clay sequence, it might be an aquifer. Similarly, for a domestic well, a particular formation might yield suitable quantities of water and be considered a good aquifer, however the same unit might be entirely inadequate for supplying larger quantities needed for a municipal well and therefore would be considered a poor aquifer in that context.

Hydrogeologists differentiate unconfined aquifers from confined aquifers (Figure A1). In Canada, unconfined aquifers usually occur in surficial deposits where the water table is the upper boundary of the saturated thickness of the aquifer. In order for a well to tap the groundwater resource, it must be completed below the water table. The moisture that exists in the unsaturated zone above the water table is held by capillary and adsorptive forces, and will not flow into an open borehole. In most of Canada the water table lies just a few metres below ground surface. Confined aquifers occur at depth in geological formations that are bounded above and below by less-permeable aquitards. The differentiation is necessary because the mechanisms by which water is delivered to a pumping well, and the impacts such pumping has on the groundwater-flow system, are different in the two cases.

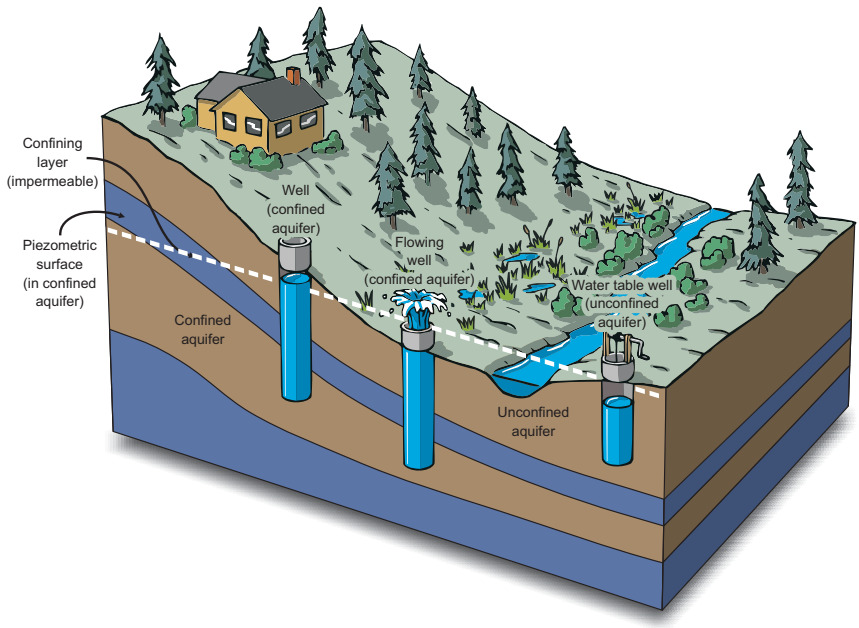

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Figure A1
Confined vs. unconfined aquifers.

Groundwater-flow Systems: Groundwater flow through the subsurface hydrogeological environment is an integral part of the hydrological cycle. Flow takes place through the sequence of aquifers and aquitards that make up a groundwater basin, delivering water from recharge areas to discharge areas. Recharge usually occurs in topographically higher areas of a groundwater basin. Water-table elevations tend to be a subdued reflection of surface topography, and the differences in water-table elevation provide the driving force that moves groundwater by gravitational flow from recharge areas toward discharge areas at lower elevations.

In recharge areas, the hydraulic gradient at the water table is directed downward, and recharging waters enter the groundwater-flow system to begin their slow journey through the groundwater basin. The exact routes of flow are controlled by the detailed topographic configuration, and by the lithology, stratigraphy and structure of the geologic formations, which define the three-dimensional distribution of aquifers and aquitards in the basin (Figure A2).

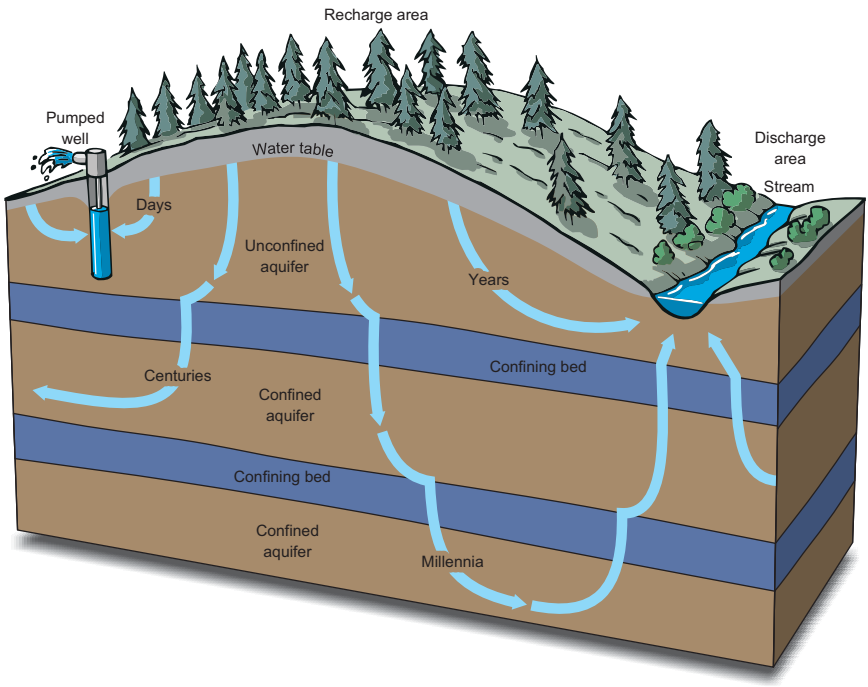

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Figure A2

Simplified local, intermediate and regional flow system schematic.

Discharge areas are usually located in valleys and lowlands. There the hydraulic gradients are directed upward toward the land surface. Discharging groundwater re-enters the surface-water regime as inflow to lakes or baseflow to streams, or to become evapotranspiration from wetlands. The upward discharge of groundwater laden with salts dissolved from long flow paths through soluble rock formations often leads to the occurrence of saline soils in groundwater discharge areas, especially in the less humid prairies of Canada. Many Canadians are familiar with one very prominent discharge area, Banff Hot Springs. Hot springs are the discharge points for groundwater-flow paths that traverse rocks at depth that are still hot from long-ago volcanic or igneous activity.

Recharge and discharge areas and the connecting flow system between them can be found at a variety of scales from local to intermediate to regional. Although there is no hard and fast rule as to what constitutes a local groundwater-flow system, as opposed to a regional one, it can generally be considered that at a local scale the recharge and discharge area would be adjacent to each other, whereas at a regional scale the recharge area would be at the upper end of the groundwater basin and the associated regional discharge area would be far removed, near the lower end of the basin. Intermediate flow systems and their corresponding recharge and discharge areas would fall between them.

Groundwater basins often mirror surface-water basins in their size and extent, but it is not always so. In some hydrogeological environments, typically those that feature extensive horizontally bedded sedimentary units or those with large buried valley systems, major aquifers can deliver significant flows of groundwater beneath major surface-water divides.

Groundwater-Surface-Water Interactions: Groundwater and surface water are intricately connected. For example, groundwater that discharges into streams creates the baseflow that sustains stream flow in the periods between stormwater runoff events. While it is true that basin-wide water tables tend to fluctuate somewhat through the seasons, the effect on regional hydraulic gradients is small. The flow of groundwater into a given reach of a stream therefore remains relatively constant over time. The sharp changes in flow rate that are observed in many Canadian streamflow records are caused by surface runoff from storm events or seasonal snowmelt. The sustained low flows that are of such importance for water supply, fish habitat, and navigation are provided by groundwater inflows and, in the case of managed rivers, releases from storage structures such as dams. Nevertheless, it is acknowledged that in some regions, such as the Prairies, confined bedrock aquifers do not directly relate to surface watersheds and therefore the groundwater and the surface water systems may be considered decoupled over the time frames of interest.

Groundwater discharge is also responsible in large part for the maintenance of many wetlands. Without sustained groundwater inflows, these ecologically rich habitats would dry up. Canadian wetlands take many forms, from the pothole sloughs on the prairies to the myriad of small wetlands in the St. Lawrence lowlands of Ontario and Québec, and groundwater plays a sustaining role in most of them. Groundwater inflows also play a role in the hydrological balance of Canada's many lakes, both large and small, including the Great Lakes.

Pumpage of groundwater from aquifers for the purposes of water supply diverts some of the discharge that would have gone to surface water bodies and delivers it instead to pumping wells. Over-drafting, such as has occurred in groundwater basins in the southwestern United States can actually reduce baseflow to zero, leading to seasonally dry riverbeds and loss of wetland habitat.[50] Groundwater discharge to streams, wetlands and lakes often serves a critical function in maintaining sensitive aquatic species. The management of groundwater resource development must therefore consider impacts on both the groundwater and the surface-water regimes.

Well Yield, Aquifer Yield and Basin Yield: Water resource managers want to know how much water they can safely pump from the aquifers that lie within their jurisdiction. The concept of *yield* can be applied on three distinct scales. In the early years of groundwater science, the unit of study tended to be a single well; in later years, the aquifer; and now, the groundwater basin as a whole. Well yield can be defined as the maximum pumping rate that can be supplied by a single well without causing a lowering of the water level in the well to below the pump intake; aquifer yield can be defined as the maximum rate of withdrawal that can be supplied by all the wells in an aquifer without causing an unacceptable decline in hydraulic heads in the aquifer; and basin yield can be defined as the maximum rate of withdrawal that can be supplied by all the wells in all the aquifers in a groundwater basin without causing unacceptable declines in hydraulic head anywhere in the groundwater system, or causing unacceptable changes to any other component of the hydrological cycle. It should be clear that a basin-wide definition is the one that has the most relevance to the concept of sustainable groundwater yield.

Hydrogeologists track the changes in available groundwater storage by carrying out regularly scheduled measurements of water levels in monitoring wells. Falling water levels in monitoring wells, if they occur over long periods of time, may indicate unsustainably high pumpage of the groundwater resource.

50 The Ogallala Aquifer covers an area of 647,000 km^2 and underlies much of New Mexico, Texas, Oklahoma, Kansas, Colorado, Nebraska, Wyoming and South Dakota and supports one-fifth of the irrigated agricultural land in the United States. In some places, extraction is 14 times recharge (Brentwood and Robar, 2004).

Groundwater Quality: Precipitation and snowmelt consist of relatively pure water, exhibiting only very low levels of dissolved chemical constituents. However, as infiltrating water passes through the unsaturated zone to become groundwater recharge, and then follows its flow path through the hydrogeologic environment to its discharge point, its chemistry is altered by a variety of geochemical processes, including mineral dissolution, ion exchange, and osmotic filtering, among others. The primary chemical process is dissolution of the soils or rocks through which the water flows. Overall, the total dissolved solids (TDS) content of the water increases with the length of flow path and residence time in the subsurface. Groundwater near recharge areas tends to be lower in TDS than that near discharge areas. Water in deeper aquifers tends to have higher TDS than that in shallow aquifers. In the extreme, groundwater may become too saline, or too high in some particular chemical constituent, to be suitable as a source of drinking water without treatment. Most of Canada's major aquifers deliver water of suitable quality, but there are also some places where use is limited by poor natural quality. Frequently, treatment processes can be implemented to reduce some nuisance parameters such as iron, manganese, and hardness.

Groundwater may also be rendered unusable due to a range of human activities. There are many documented cases in Canada of groundwater contamination from chemical plants, petroleum refineries, wood-processing plants, mines, waste-management facilities, gas stations, and other commercial and industrial facilities (Government of Canada, 2005). Among the most common contaminants are metals, petroleum products, chlorinated solvents such as dry-cleaning fluids and degreasing agents, and other organic chemicals.

The usual impact of these point pollution sources is the development of long, narrow plumes of contaminated water that advance through the subsurface at about the same rate as the groundwater flow itself (Figure A3). The contaminants may spread out and be diluted somewhat by the processes of molecular diffusion and hydrodynamic dispersion, and their rate of advance may be retarded somewhat by sorption of some of the chemical constituents onto the aquifer material. In addition, some organic contaminants such as petroleum products may be partially consumed, or biodegraded, by subsurface bacteria. Despite these mitigating factors, rates of plume advance can reach several hundred metres per year in permeable sand-and-gravel aquifers.

The presence of pumping wells in the vicinity of a contaminant plume will tend to draw the plume toward (and eventually, into) the wells. For any pumping well, it is possible to define a capture zone that encompasses all the 'flow tubes' that will eventually deliver water into the well. Modern preventive practice seeks to protect the recharge areas to these capture zones from pollution.

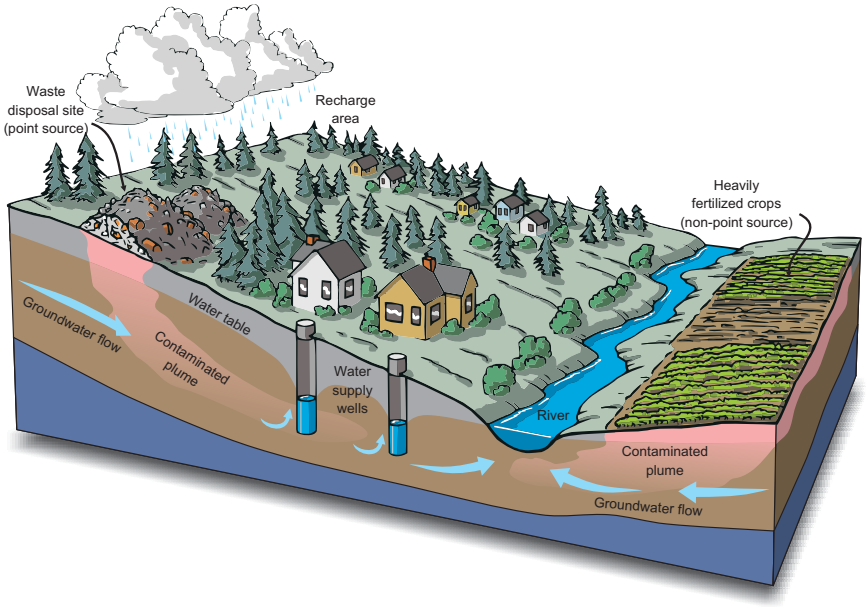

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Figure A3
Plumes of pollution from point and non-point sources of pollution.

Another class of groundwater contaminants arises from non-point pollution sources. These occur primarily in the agricultural sector from the use of fertilisers and pesticides. The most widely documented agriculturally based contamination in Canada is nitrate pollution from fertiliser application.

Microbial contamination may constitute the most common water-quality concern with respect to groundwater supplies in Canada. Such contamination is most common in rural areas where septic fields are widely used, and in agricultural areas where manures are commonly applied. Due to the short life spans of most bacterial species, coupled with small pore spaces that tend to inhibit significant movement of bacteria in the subsurface environment, bacterial contamination is generally restricted to shallow wells or aquifers. Nonetheless, poor well construction or other short-circuiting mechanisms such as fractures can allow bacteria to travel to deeper wells.

Groundwater-Related Hazards: Groundwater plays a role in several water-related hazards that come to public attention. Most obviously, over-pumpage of shallow groundwater tends to exacerbate the impacts of drought by reducing the most reliable component of stream flow during dry periods. The question of how such impacts might play out in the context of climate change will be an increasing preoccupation in future years.

Over-pumpage of groundwater is also directly responsible for cases of seawater intrusion and land subsidence. The intrusion of seawater into coastal aquifers is caused by a reversal of hydraulic gradients due to the installation of pumping wells near the coast. Land subsidence occurs when groundwater is pumped from stratified hydrogeological environments that feature interbedded sand and clay layers. The reduced fluid pressures created by the pumping from the sand layers cause the clay layers to compact, and this compaction leads to subsidence at the ground surface. Neither of these impacts has been widely reported in Canada, but there are many documented occurrences in the United States and other areas of the world where the soils are less consolidated and groundwater consumption is high.[51]

51 See for example data from the United Nations Economic and Social Commission for Asia and the Pacific available at: http://www.unescap.org/enrd/water_mineral/Land_cons.htm.

Appendix 2: Highlights from the Call for Evidence

The Expert Panel on Groundwater arranged for a Public Call for Evidence on what is needed to achieve sustainable management of Canada's groundwater. The 'Call' was posted on the Council's website from July 30 to November 2, 2007, and responses were invited from the general public. The following questions were asked:

- What are the opportunities, challenges or emerging crises for sustainable groundwater management in Canada?
- Do important gaps exist in knowledge or access to knowledge on groundwater issues? If so, what are they?
- Are there important gaps in the application of existing knowledge on groundwater? If so, what are they?
- Are there gaps in capacity (e.g., infrastructure, appropriate skills, information systems, regulatory frameworks) for sustainably managing groundwater in Canada?
- What should be the priorities for filling the gaps?
- Are there jurisdictions or particular situations in Canada which are exemplary (i.e., cases where groundwater is managed in particularly successful or innovative ways)?
- Do you have any additional concerns or insights on the management of groundwater in Canada which you believe would be helpful to the expert panel?

Specific notice of the Call for Evidence was sent by email to more than 70 contacts with an interest in groundwater across Canada, representing the provincial governments, NGOs, associations, think tanks, and individuals across Canada. In the end, 36 submissions were received. Not all authors agreed to make their submissions public. The 27 respondents listed below agreed to make their submissions public. To view the submissions, visit the Council's website at: www.scienceadvice.ca.

The following are the 27 submitters who agreed to have their submissions made public:

PROVINCIAL GOVERNMENTS

- Government of British Columbia: Ministry of Environment, Water Stewardship Division, Science and Information Branch
- Alberta Environment
- Government of Saskatchewan: Saskatchewan Watershed Authority
- Government of Nova Scotia: Nova Scotia Environment and Labour

NGOS

- Canadian Institute for Environmental Law and Policy (CIELAP)
- Conservation Ontario
- Pembina Institute
- Pollution Probe
- Scott Findlay, on behalf of H_2O Chelsea Community Water Research Program
- Sierra Club of Canada
- WWF-Canada
- Township of Langley (British Columbia)
- Technical Subcommittee of the Abbotsford-Sumas Aquifer Stakeholders Group (ASASG)

PROVINCIAL GROUNDWATER ASSOCIATIONS

- British Columbia Ground Water Association
- Saskatchewan Ground Water Association

OTHER ASSOCIATIONS

- Canadian Association of Petroleum Producers
- Canadian Bottled Water Association

INDIVIDUALS

- Bob Betcher, Hydrogeologist
- Brian Beatty, Hydrogeologist
- Bruce Peachey, President, New Paradigm Engineering
- Charles Lamontagne, Hydrogeologist
- Fred and Lynn Baechler, Hydrogeologists
- Grant Ferguson, Hydrogeologist
- Grant Nielsen, Hydrogeologist
- Mary Jane Conboy, Hydrogeologist
- Terry Hennigar, Hydrogeologist
- Yannick Champollion, Hydrogeologist

The following highlights represent what were concluded to be the most important themes that emerged throughout the 27 submissions. They are organised according to the following categories:

- General Context
- Key Knowledge Gaps

- Management or Policy
- Data and Information
- Skills or Training
- Energy
- Exemplary Cases

GENERAL CONTEXT

- The so-called 'myth of abundance' is a major impediment to proper stewardship.
- There is a perception that water is a gift from nature and that it should come free of cost.
- Canada (as a nation) can help to define what 'groundwater sustainability' means.
- The biggest opportunity or challenge in the dry to semi-dry western part of the country is the increasing need for groundwater to fill a larger role for water supply as surface water sources become increasingly utilised to capacity.
- The federal government should fund research and locally focused projects in each province using local people who have expert knowledge.
- While the panel is charged with carrying out an evaluation of sustainable groundwater management in Canada, in developing their report they should be in a position to compare how sustainable groundwater management is carried out in this country with approaches taken in other parts of the world, including the multi-jurisdictional sharing of responsibility.
- Increased data collection and improved compilation for public access is necessary and, in the absence of sufficient data, the precautionary principle should be used.
- Holistic adaptive management on a basin scale is seen as the correct approach to sustainability.
- An integrated approach to water resource management supports sustainable groundwater management by connecting groundwater and surface water, connecting quantity and quality, connecting allocation and water conservation, and connecting groundwater availability with planning for urban growth.
- The federal role should be to work one stage higher than the provinces; that is, not applying known and time-proven practices over and again, but carrying out research and studies which the provinces don't generally do.
- Looking forward, new challenges to sustainability may include tensions over whether development over a finite period is likely better than no development at all, the need to distinguish and allocate between consumptive and non-consumptive use and the need to promote groundwater knowledge in stakeholder's communities.

KEY KNOWLEDGE GAPS

- Impacts of new chemicals, currently pharmaceuticals and endocrine disruptors.
- Interaction with the biosphere, i.e., aquatic life in streams.

- Impact of land use, especially that of high-density subdivisions on individual wells, forestry and agriculture.
- The connections between groundwater, surface water and the increasing impacts of climate change.

MANAGEMENT AND POLICY

- The real management of the groundwater resource is done at the provincial level, with some jurisdictions even looking at management at the municipal or watershed level. As such we need to focus our attention, for now, on the provinces when discussing sustainable groundwater management. If there are available resources in this country that could be applied to all the mapping, studies and regulatory frameworks that are needed for sustainable groundwater management, then we should focus those resources in the provinces, not in federal agencies.
- Fragmentation of regulatory responsibility and oversight is a commonly noted obstacle to sustainable use; greater integrated action at all levels of government is warranted, perhaps including regulated frameworks for sustainable use. The technical expertise is largely available to develop a basin-scale understanding of our groundwater resources; what is missing is government commitment, as agencies are preferentially focused on regulatory enforcement rather than on developing a better understanding of the resource.
- Establish a national vision and strategy for groundwater and groundwater management, with the input of provinces and territories; develop national indicators for groundwater to measure progress.
- The Canadian research or applied research focus has been so much on contaminant hydrogeology that it seems we have been largely ignoring fundamental issues surrounding basic understanding of groundwater system interactions.
- Undertake Integrated Inventories: It is time to update our inventory techniques by looking at the entire hydrological cycle (groundwater — streams — lakes — near shore coastal environments and climate) so hydrogeologists can aid decision-makers in managing 'ecosystems'.
- In British Columbia, a current major challenge is the lack of a legal framework for regulating the extraction of groundwater. Legal requirements (and corresponding capacity) for regulating, monitoring and reporting groundwater extraction need to be developed or updated.
- There is a need for a review of water allocation policies affecting different, competing sectors using water.
- There is a need for complete, comprehensive watershed-scale basin plans that provide an integrated understanding of the surface water and groundwater systems.
- Regulatory agencies often do not require a proponent to carry out sufficient 'macro' studies when large-scale developments are proposed (i.e., the volume beyond what may be influenced by a relatively short-term pumping test).

- It is critical that the jurisdictions in Canada give greater consideration to the use of water pricing as a tool of demand management. The costs can be accounted for in permitting programs.
- There is concern that in parts of the country the rate of increase in groundwater use will outpace the science and data available for proper management and that the precautionary principle requires further application.
- Physical science and data are not in themselves sufficient for sustainable use; there must be specific mechanisms to shift the values of users towards stewardship. Multi-disciplinary teams (hydrogeology, hydrology, ecologists, resource managers, etc.) need to be assembled. Sustainable development will require further understanding of water valuation and application of full-cost accounting.
- Industry groups express concern over different rules for different sectors, and the time and effort required to seek water-taking permits is not commensurate with the duration of the permit. Some groups seek greater availability and transparency of water data, others seek less.
- Sustainability of groundwater should be measured using metrics that can change to reflect current and forthcoming pressures.
- Reducing agricultural non-point sources continues to be a management challenge as nitrogen levels in groundwater are increasing in many parts of the country despite considerable abatement efforts.

DATA AND INFORMATION

- At present, there is a general shortage of data on actual use of groundwater in most jurisdictions in Canada. Where available, the data are not segregated into different use categories. Information on the real cost of water should also be made available to the public. There is a need for maintaining and regularly updating a user-friendly database on groundwater use, quality and quantity for the whole nation.
- Promote consistent groundwater management methods by developing national best practices for: groundwater management programs, groundwater monitoring networks, groundwater database structures, etc.
- Old, hard-copy groundwater data should be converted to electronic databases to facilitate data sharing and data analysis.
- Greater use should be made of the Internet to provide access to groundwater information.
- There is a need for a common public groundwater data set across Canada and development of a web-based knowledge-decision support-advice tool that relies on the common data set for local government, water suppliers, and the public to gain basic knowledge about groundwater generally and specifically in their local area.
- There is a need for sustained funding to collect and manage groundwater data (i.e., well construction reports) as well as for the legal authority to collect other groundwater data (e.g., pumping test data, water quality data).

- A consistent framework for monitoring and data collection and the application of appropriate standards for data, meta-data, mapping and web-based services are required.
- Many local communities do not have the tax base to acquire capacity to apply groundwater knowledge in local decisions; the groundwater resource in many local communities is still viewed as a mysterious and uncertain resource. Consideration should be given to developing a web-based knowledge-decision support-advice tool that relies on data, information in provincial (and federal) groundwater databases and expert knowledge to allow local governments to develop a basic understanding of the local groundwater resource.
- We need more emphasis on monitoring the impacts of large-scale withdrawals; a single monitoring well is generally not enough. The monitoring wells must be appropriately sited, the data reported and a regular review carried out by the regulator.
- There are still major gaps in data collection, data entry, and database management. The information system should be able to provide continuous access to a sophisticated Water Atlas where users could zoom in on any area in the province and have access to:
  - 3D aquifer maps with the capacity of generating cross-sections;
  - real-time groundwater levels;
  - location and use of any well and water intake;
  - river flows and water levels;
  - water chemistry; and
  - completed studies (local numerical models, capture zone analyses, pumping tests, etc.).
- It may be more important to address the needs of people consuming groundwater known to be contaminated before investing in the considerable resources to undertake complete mapping of all aquifers.
- National and provincial standards are needed for data collection, compatible archiving and retrieval frameworks, reasonable extraction limits, and legislated protection with enforcement for vulnerable and threatened aquifers.
- Develop aquifer inventories (quality and quantity) and groundwater use data.
- Enhance groundwater monitoring programs, including regular reporting of results.
- In many senses the gaps in knowledge are local gaps; an aquifer is being developed but we don't know the full dimensions of the aquifer and the complex geology or hydrogeology within the aquifer and the surrounding aquitards or how the aquifer is connected to the unsaturated zone where recharge is occurring or how it discharges to surface water sources. These are typically local gaps that can be answered (partially) through site investigation.

- A national-scale, common-standard, geo-referenced database of groundwater quality and quantity information may encourage stakeholder interest and involvement by overcoming the fragmented and inconsistent data sets available through the provinces. Available data is fragmented within and across all levels of government and often veiled by issues of privacy or commercial competitive advantage.
- Efforts are needed to develop aquifer classification frameworks that support sustainable groundwater management, and methods are needed to use numerical groundwater modelling more effectively in groundwater management at a regional scale.
- Groundwater management is increasingly linked to surface water and ecosystem management. The scientific research and modelling-management tools necessary to effectively address multidisciplinary issues and ecosystem needs require further development.

SKILLS AND TRAINING

- There is a general lack of sufficiently qualified staff within most government agencies. Regulatory agencies in the provinces must recognise the need for qualified staff and ensure that people taking responsibility for groundwater monitoring are properly trained.
- More effort needs to be put into incorporating groundwater science in the training of professionals, technologists and trades people (e.g., water operators, plumbers, drillers, excavators).
- There is a lack of capacity in local government and with small and medium water suppliers. This is an important issue in British Columbia because of the lack of groundwater extraction regulations; the local extent of many aquifers in the province, and local decision-making, can impact the quantity and quality of the local resource.
- We need to ensure that groundwater is taught as a core program in engineering and geology programs and that groundwater is also taught in college programs where many of the environment officers and health inspectors come from.
- Additional support for, or pressure on, universities to expand their capabilities in hydrogeology would be valuable, particularly if there is a renewed emphasis on applied research and physical hydrogeology, something that seems to have been unfashionable over the past 10 or 20 years. An additional emphasis on applied or physical hydrogeology would generate graduates who could help the provinces in the sustainable management of groundwater withdrawals.
- Major universities across Canada (e.g., University of Waterloo, University of British Columbia, University of Calgary and Simon Fraser University) have developed academic groundwater programs in the last 20 years. These universities produce under-graduate and graduate students with excellent training in hydrogeology.

- A larger number of hydrogeologists graduating from university is required to meet the projected workforce demands.
- Expertise is necessary to better understand the links between ecosystem health and diversity and the discharge of groundwater to surface water.
- While Canada holds an impressive reputation for producing high-quality groundwater professionals, the global standard is shifting from 'finding water' to 'managing water,' and we must ensure our professionals are equipped to retain our reputation in this new area.
- Within parts of Canada, there may be room for improvement with respect to the skills and education required to be a professional hydrogeologist.
- Managing groundwater on a basin scale will entail multi-disciplinary teams. The necessary hydrogeological expertise will be broad, including quaternary geology, field methods, geophysics, hydrostratigraphy, isotope geochemistry, integrated groundwater-surface-water numerical modelling, cumulative impact assessments, contaminant remediation, data management, etc. Universities should seek to expose students to the full range of necessary skills and exemplify how these areas of expertise are integrated.
- A more integrated provincial and national research strategy may be valuable as the pace of groundwater research expands.

ENERGY

- In northern Alberta, improved monitoring and much research are needed to address the impacts of oil sands mining and *in situ* bitumen production on groundwater.
- A challenge in groundwater management is the current exclusion of oil, gas and coalbed-methane (CBM) exploration from groundwater legislation.
- What are the potential impacts of *in situ* leaching of uranium in southern Alberta?
- How might the wastewater from bitumen production be treated so as to avoid the creation of tailings ponds?
- The hydrogeological community should be prepared to address the groundwater implications of a growing commercial and domestic interest in geothermal energy.

EXEMPLARY CASES

- The private-well network operated by the Township of Langley, British Columbia, is an innovative example of how to collect and provide public access to groundwater quality data.
- The initiatives coming out of Alberta's data within its Water for Life strategy and policy are resulting in the development of comprehensive basin plans for key watersheds, such as the South Saskatchewan, where the stewardship approach of managing surface water and groundwater as one resource is being applied, and where regulation in groundwater development and use has been instituted.

- Groundwater evaluation in Manitoba incorporates physical hydrogeology, geochemistry and age dating, and 3-D modelling. All this work is being done by provincial staff with provincial financing and with some research support from the Geological Survey of Canada.
- Ontario's well-tagging program improves our knowledge of the position and identification of private wells.

Appendix 3: Major Recommendations of Canadian Reports on Groundwater Resources

This appendix lists excerpts of recommendations from major reports in Canada on the subject of groundwater. Many of the cited documents deal with water generally, and recommendations of less relevance to groundwater have been omitted.

By and large, these findings have not been fully implemented. It is also important to note that while many reports over the years have been geared towards provincial governments, we have limited this appendix to major policy-oriented reports directed primarily to the federal government, though many of the recommendations will be relevant to, and have implications for, provincial and local water management and policy.

FEDERAL WATER POLICY (1987)

Context: In the 1987 Federal Water Policy, the Government of Canada committed to a number of actions such as developing national guidelines for groundwater assessment and protection and measures to achieve appropriate groundwater quality in transboundary waters. The policy remains largely unimplemented.

Author: Officials from Environment Canada.

Recommendations

Water Pricing

The federal government is committed to the concept of 'a fair value for water.' To implement this concept in federal policies, programs and initiatives, the federal government will:

- endorse the concept of realistic pricing as a direct means of controlling demand and generating revenues to cover costs;
- develop new water-efficient technologies and industrial processes that minimise costs, and encourage water conservation and improved water quality;
- undertake, support and promote joint federal-provincial examination of the costs and pricing of water for both consumptive and non-consumptive water uses; and
- encourage the application of pricing and other strategies, such as the beneficiary/polluter pays concept, to encourage efficient water use.

Science Leadership:

In recognition of the national leadership role it must play in this endeavour, the federal government will:

- conduct and encourage the undertaking of physical, chemical, biological and socioeconomic investigations, which are directed to current and emerging issues;
- establish research advisory mechanisms with broad representation from scientific and applied research clientele, to advise on program needs and priorities;
- develop and maintain, with the provinces and territories, water data and information systems directed to improving the knowledge available for managing Canada's water resources;
- promote cooperative federal-provincial endeavours when the objectives are of joint interest;
- undertake and support research and technological development and transfer efforts;
- encourage opportunities for nongovernmental technological development, and the growth of a private sector water conservation industry; and
- foster international cooperation in scientific and technological research and development and in data and information collection systems.

Integrated Planning

In support of its commitment to this strategy of integrated, long-term planning for the development and management of water and related resources, the federal government will:

- adhere to integrated water resource planning in areas of federal jurisdiction, and in interjurisdictional waters subject to federal-provincial-territorial agreements, in order to ensure that all values are given full consideration;
- encourage, on the basis of a watershed, or other appropriate spatial unit, the integration of water management plans and objectives with those of other natural resource interests — fisheries, forestry, wildlife, mining, hydro power, and agriculture — to reflect the unity of natural processes and the interdependence of uses and users in that spatial unit;
- establish and apply evaluation criteria to all federally sponsored projects to ensure their compatibility with federal goals respecting water management, based on an appreciation of the values of water and related resources;
- ensure that all significant national and international water-related development projects, which are supported or initiated by the federal government or for which federal property is required, are subject to the Federal Environmental Assessment and Review Process, so that potential adverse environmental and socioeconomic effects can be identified and, to the extent possible, mitigated;
- ensure the participation or cooperation of all relevant coordinating and regulatory agencies; and
- encourage and support opportunities for public consultation and participation in the integrated planning.

Legislation

To these ends, the federal government will renew, consolidate or otherwise strengthen the application of existing federal legislation, so as to:

- produce legislative provisions to address interjurisdictional water issues relating to levels, flows and quality;
- control and manage toxic chemicals throughout their entire life cycle — from production to disposal;
- establish water quality standards and guidelines to better protect human health and the diversity of species and ecosystems;
- encourage existing mechanisms like the Prairie Provinces Water Board and develop others to address potential provincial-territorial and interprovincial water conflicts; and
- ensure the effectiveness of regulatory measures through the provision of appropriate enforcement and compliance measures.

Public Awareness

In order to promote public awareness and participation in programs and initiatives to improve and protect Canada's water resources, the federal government will:

- ensure that the public is consulted and that its views are considered in all major federal water management decisions;
- encourage public participation and initiate, develop and deliver a national water conservation awareness program;
- encourage the efforts of provinces and non-governmental organisations in public information and awareness; and
- ensure public access to information on the extent and health of water resources through appropriate means, including a State of the Environment reporting system.

Applying the Policy

At the federal level, the government will:

- ensure the effective coordination of federal water policies among federal departments and agencies;
- ensure a regular review of the water-related policies and programs of all federal departments to assess the degree to which these policies and programs are supportive of federal water policy;
- reconcile the water policy positions of all federal departments to promote a coordinated and thoughtful federal approach;
- ensure amendments or additions to federal water policy as appropriate; and
- apply the Environmental Assessment and Review Process to examine federally sponsored water-related developments and projects.

To achieve effective implementation of the policy, the federal government has designated the Interdepartmental Committee on Water (ICW) as the focal point for coordinating the policy among federal departments and agencies. As part of its responsibility, ICW will produce an annual report on the overall implementation of federal water policy, on the strengths and weaknesses of that policy's delivery and on areas for future examination; it will also serve as a focal point for explaining federal water policy and for providing integrated information on all aspects of that policy; and coordinate such interdepartmental studies as may be necessary to fulfil its terms of reference, and constitute subcommittees as may be appropriate to address particular problems or issues related to water policy.

At the federal-provincial-territorial level, the adoption and application of policy goals and strategies will be encouraged through:

- existing and improved federal-provincial coordinating mechanisms and bilateral arrangements, which include: consultation and information exchange so as to encourage compatible water policies and cooperative programs through forums such as the Water Advisory Committee of the Canadian Council of Resource and Environment Ministers (CCREM);
- support for formal and informal consultative or advisory committees to deal with either a single issue or a range of water problems;
- intergovernmental agreements for cooperative programs with all provinces/territories; and
- special agreements to respond to a particular water problem or issue in one or more of the provinces or territories.

Groundwater Contamination

The federal government is committed to the preservation and enhancement of the groundwater resource for the beneficial uses of present and future generations. To meet this commitment, the federal government will:

- develop, with provincial governments and other interested parties, appropriate strategies, national guidelines and activities for groundwater assessment and protection;
- conduct research and undertake technological development and demonstration projects in response to groundwater problems;
- develop exemplary groundwater management practices involving federal lands, responsibilities, facilities, and federally funded projects;
- develop measures to achieve appropriate groundwater quality in transboundary waters; and
- provide information and advice on groundwater issues of federal and national interest.

Drought

The federal government is prepared to support provincial initiatives directed to managing water supplies to realise their full value and to resolving real and potential problems associated with droughts. To this end, the federal government will:

- encourage and promote water demand management approaches and conservation technology with a view to extending the use of limited supplies;
- undertake, support and promote research into improving understanding of drought;
- encourage the development and dissemination of water conservation technologies and practices to promote the best use of current supplies; and
- encourage an integrated approach to planning and managing the augmentation and allocation of water supplies.

Water Data and Information Needs

The federal government is committed to maintaining cooperative data programs with the provinces and territories in the interest of understanding and managing the resource for the common good. To this end, the federal government will:

- work with the provinces and territories to produce reliable and timely data and information on the quantity, quality and variability of the nation's water resources;
- encourage the extension of data programs into the North and generally remote areas;
- maintain and promote the use of a range of national water databases, as well as a comprehensive directory of water-related data and sources of such data and information;
- encourage the integrated planning of information-gathering systems;
- augment certain data holdings on, for example, water use, water pricing, or groundwater, when they are needed to deal with new issues;
- undertake and promote new technology appropriate for general use across Canada; and
- implement cost-recovery policies for data and information, recognising that basic data constitute a common good.

GROUNDWATER ISSUES AND RESEARCH IN CANADA (1993)

Context: This report, commonly referred to as the 'Cherry Report,' comments on the federal government's activities with respect to groundwater in Canada. The report, prepared by an eight-member Task Force appointed by the Canadian Geoscience Council,[52] identifies problems and describes areas where improvements can be made on the part of the federal government with respect to groundwater knowledge and management activities. The 1993 report's overall conclusion states that "Canada needs to make major advances in areas such as groundwater inventory, protection and research in order to achieve responsible and effective management of this important freshwater resource." The Cherry task force also concluded that "it is reasonable to expect that within the next three years the federal government should show significant progress with the implementation of these recommendations."

Author: The report was prepared by an eight-member Task Force appointed by the Canadian Geoscience Council. The Task Force included:

John A. Cherry, Chair
Donald W. Pollock, Vice-Chair
H. Douglas Craig
R. Allan Freeze
John E. Gale
Pierre J. Gélinas
Robert E.J. Leech
Stephen R. Moran

Recommendations:

1. Establishment of Linkages, Partnerships and External Review

The federal government should establish an interdepartmental (federal) Groundwater Task Force to (i) clearly identify, coordinate and communicate groundwater issues and problems within the federal government and (ii) establish functioning partnerships and linkages between federal departments and between the federal government and other elements of Canadian society that deal with groundwater

52 The Canadian Geoscience Council was formed in 1972 at the request of the Science Council of Canada to promote the role of the earth sciences in the early strategies of the resource-based federal department of Energy Mines and Resources and the growing Canadian economy in general. In a time when Canadians had limited knowledge of our earth sciences, the Council recommended in 1971 "Provincial departments of education should promote the teaching of earth sciences in secondary schools". (Background Study for the Science Council of Canada, 1971 available at the Canadian Federation of Earth Sciences website.) More recently, the Council has led numerous task forces addressing federal earth science policy issues such as funding for geological surveys. In 2007, the Council became the Canadian Federation of Earth Sciences.

issues. This effort should involve directly the following federal ministries: Environment, Energy Mines and Resources, Agriculture, Health and Welfare, Fisheries and Oceans, National Defense [sic] and Industry Science and Technology.

There is a critical need for an overall federal strategy that encompasses all pertinent ministries, with their plans responding to the overall strategy.

This Federal Groundwater Task Force should appoint an Advisory Panel comprised primarily of leading groundwater specialists from outside the federal government, to provide guidance and insight so that bureaucratic impediments are minimised.

2. Establishment of Regional Centres for Groundwater Studies

The federal government should establish regional centres for groundwater studies with priority given to the immediate establishment of a centre in the Atlantic Region and second priority to a centre in the Prairie Region.

The Atlantic Centre: …should foster groundwater research by M.Sc. and Ph.D. students, primarily ones enrolled in universities in this region, thus providing continuing education opportunities for groundwater professionals employed in government and industry in the region.

Prairie Region Centre: What is needed now is the establishment of strong institution-to-institution partnerships and linkages (federal, provincial and universities) and some augmentation in research funding (federal and provincial) for initiation of research in important topic areas not currently being studied in the region, such as wetlands and mine-environment problems.

3. Education of Groundwater Professionals

The federal government should include mechanisms that foster advanced education of groundwater professionals in all of its groundwater research activities, whether the activity involves provision of research funds to universities, or the research is conducted primarily in-house.

4. Groundwater and the Canadian Mining Industry

Existing federally sponsored research efforts pertaining to (i) mine-environment problems and (ii) the use of groundwater in the exploration for new mineral deposits should provide improved research opportunities, and expanded partnerships between the various segments of the Canadian research community working on mine-environment and mineral-exploration problems.

These improvements should involve research groups in Energy Mines and Resources (Mineral and Energy Technology Sector and the Geological Survey of

Canada), Environment Canada, industry and academia. The progress of this research should be monitored closely by relatively independent panels or committees to ensure that the achievements are commensurate with the considerable expertise that now exists in Canada for this type of research.

5. Groundwater and Wetlands

The federal government should assess the state of knowledge of Canadian wetlands, including of the role of groundwater in wetlands hydrology, ecology and human impacts. It should then sponsor research aimed at filling the main gaps in knowledge of our wetlands ecosystems.

6. Establishment of a Groundwater Protection Office

The federal government should establish an Office For Disseminating Information About Groundwater Protection.

7. Contaminated Sites / Orphaned Sites Programs

The federal government should incorporate appropriate mechanisms and expertise for assessing groundwater and groundwater contaminant pathways into the Federal-Provincial Contaminated Sites Program and federal government programs pertaining to contaminated sites/environmental audits on federal lands. This would provide for sound decision-making with regard to prioritising sites and allocating funds for groundwater control or cleanup.

8. Identification and Hazard Assessment of New Contaminants in Groundwater

The federal government should assess the occurrence and degree of hazard associated with those types of groundwater contaminants that occur with significant frequency in Canadian groundwaters but which are not detected in the routine analyses of groundwater samples and which are not included in current federal or provincial water quality criteria or drinking water objectives.

The goal of this assessment should be the development of an information base that will provide for progressive updating of federal-provincial water quality guidelines and objectives in a manner appropriate for and relevant to groundwater resources.

9. National Standards for Groundwater Information Storage and Retrieval

The federal government should develop national standards and sponsor demonstration projects for computer storage, retrieval and display of groundwater information.

The federal initiative should develop minimum national standards for storage, retrieval and display of groundwater information by:

- providing a framework for appraising the new hardware and software systems that have recently entered the commercial marketplace for management and modelling of subsurface data;
- assessing the experience of Canadian provinces and other countries in managing groundwater information; and
- undertaking demonstration projects of appropriate technologies in cooperation with the provinces.

10. Aquifer Delineation and Groundwater Resource Characterisation

The federal government should establish a system of Groundwater Resource Inventory and Aquifer Characterisation Agreements with the provinces with the goal of achieving a specified minimum level of knowledge of the groundwater resources in each of the provinces and the Canadian North.

The Agreements could be modelled on the Mineral Development Agreements whereby the federal government provides incentive funding and the provinces conduct the investigations, in some cases in cooperation with federal agencies.

11. A Groundwater Information System for Land-Use Planning and Groundwater Protection

The federal government should develop, through research and field testing, a groundwater information system for land-use planning and groundwater management and protection.

For scientific information on groundwater to be used effectively in the context of land-use planning, water management and environmental protection, including groundwater protection, the information must be compiled and available in a form appropriate for such multidisciplinary use.

12. Inclusion of the Groundwater Environment in the State of the Environment Report

The federal government should include an assessment of the state of the groundwater environment in the next issue, and all future issues, of the 'State of the Environment Report'.

13. Priorities for Internal and External Federal Research

Groundwater research groups in the federal departments, primarily Environment Canada, Energy Mines and Resources and Agriculture Canada should develop research facilities that complement, in general, those that already exist in universities in Canada. Federal in-house research should emphasise those projects requiring long-term monitoring, or other forms of work not well suited for undertaking by non-federal research organisations. Priority should also be placed on research

projects intended to provide answers to problems that are anticipated to arise in the future (anticipatory research).

14. Groundwater and Transportation

The federal government should assess the impacts of distribution of fuel for transportation on groundwater and initiate a federally coordinated effort to reduce these impacts by application of more cost effective remedial measures derived from research and development.

15. Groundwater and Agriculture

The federal government should initiate a systematic research program led by Environment Canada and Agriculture Canada to determine the impacts of Canadian agriculture on groundwater quality and to determine the degree to which adverse effects can be reduced through reasonable changes in practice.

16. Groundwater and the Great Lakes

The federal government in cooperation with the Province of Ontario should expand research efforts directed at determining the influence of groundwater and groundwater-borne contaminants on water quality and ecological systems in the Great Lakes.

17. Groundwater and Heavier-Than-Water Industrial Liquids

The federal government should ensure that within the framework of Canadian groundwater research there is research directed at heavier-than-water industrial organic liquids to a level commensurate with the degree to which these liquids are a problem at contaminated/orphaned sites in Canada.

Research is needed to better understand the long-term environmental impacts of these chemicals and to develop and assess better approaches for site investigations and cleanup.

18. Groundwater Contamination Benefit-Cost Analysis and Risk Assessment

The federal government should sponsor research aimed at improving methods for determining the risk to human health and the environment as a whole of various types of occurrences of groundwater contamination.

19. Socio-Economic Values of Groundwater

The federal government should sponsor research on the socio-economic aspects of groundwater resources in Canada.

Socio-economic studies are needed to provide a better framework for decision-making in contaminated sites programs, in development of groundwater protection

programs, and in assessment of options for provision of new or expanded water supplies for communities that need more water for growth or to replace contaminated supplies.

20. Development and Commercialisation of Canadian Groundwater Technologies

The federal government should aggressively promote the development and commercialisation of Canadian technologies for groundwater monitoring, extraction and remediation so that the Canadian groundwater industry will have enhanced competitiveness in the world marketplace.

21. Report on the Canadian Groundwater Industry and Groundwater Research and Development

The federal government should produce in 1994 a comprehensive report on the capabilities and status of groundwater research and development in Canada and on the Canadian groundwater industry, comprising the manufacturing and service sectors including groundwater drilling, monitoring, treatment and remediation as well as the consulting sector. This report should be updated at three year intervals.

22. Enhancement of International Opportunities for the Canadian Groundwater Industry

The federal government should intensify its efforts and improve coordination of its activities directed at enhancing opportunities for the Canadian groundwater industry to engage in commercial activities outside Canada, particularly in rapidly developing market regions such as eastern Europe, the Pacific Rim, and Central and South America.

IJC: PROTECTION OF THE WATERS OF THE GREAT LAKES: FINAL REPORT (2000)

Context: "This is the Final Report of the IJC to the governments of the United States and Canada concerning protection of the waters of the Great Lakes. It was submitted in response to a February 10, 1999, Reference from the governments to undertake a study of such protection. This Final Report incorporates and, where appropriate, updates the Commission's Interim Report of August 10, 1999. It also extends and, in some cases, modifies the conclusions reached and recommendations made in the Interim Report" (IJC, 2000).

Author: International Joint Commission.

Recommendation VII. Groundwater

Governments should immediately take steps to enhance groundwater research in order to better understand the role of groundwater in the Great Lakes Basin. In particular, they should conduct research related to:

- unified, consistent mapping of boundary and transboundary hydrogeological units;
- a comprehensive description of the role of groundwater in supporting ecological systems;
- improved estimates that reliably reflect the true level and extent of consumptive use;
- simplified methods of identifying large groundwater withdrawals near boundaries of hydrological basins;
- effects of land-use changes and population growth on groundwater availability and quality;
- groundwater discharge to surface water streams and to the Great Lakes, and systematic estimation of natural recharge areas; and
- systematic monitoring and tracking of the use of water-taking permits, especially for bottled water operations.

In recognition of the frequent and pervasive interaction between groundwater and surface water and the virtual impossibility of distinguishing between them in some instances, governments should apply the precautionary principle with respect to removals and consumptive use of groundwater in the Basin.

REPORT OF THE COMMISSIONER OF THE ENVIRONMENT AND SUSTAINABLE DEVELOPMENT (2001)

Context: In 1995 the Office of the Auditor General of Canada was given a specific environment and sustainable development mandate. It was established through amendments to the *Auditor General Act* that created the position of Commissioner of the Environment and Sustainable Development. According to the website of the Office of the Auditor General, "the Commissioner of the Environment and Sustainable Development provides parliamentarians with objective, independent analysis and recommendations on the federal government's efforts to protect the environment and foster sustainable development. The Commissioner conducts performance audits, and is responsible for assessing whether federal government departments are meeting their sustainable development objectives, and overseeing the environmental petitions process."

Author: Commissioner of the Environment and Sustainable Development (at the time it was Johanne Gélinas, who served from August 2000 to January 2007).

Recommendations:
Our findings show that the federal government needs to decide its priorities for freshwater and clarify its commitments to achieving them.

Working with its partners, it needs to develop realistic, scheduled plans with clear accountability; stick to its plans; and provide open and transparent information on results (3.1.30).

3.1.31 Environment Canada should reassess its role and clearly articulate its responsibilities and commitments for freshwater management in the Great Lakes and St. Lawrence River basin, and clarify the commitments expected from other federal departments, especially, but not limited to the following:

- iv. promoting the concept of "a fair value for water" as stated in the Federal Water Policy.

3.1.33 The federal government should develop the information needed to manage freshwater, as follows:

- Natural Resources Canada, together with Environment Canada, should develop enough knowledge of groundwater in the basin to understand its contribution to the availability of surface water — in particular, knowledge of key aquifers, their geology, potential yields, and current withdrawals.

- Environment Canada should develop enough information on the key contaminants in the Great Lakes and St. Lawrence River basin, and on their sources to set priorities for action.

3.1.34 Health Canada should clearly articulate its responsibility for protecting human health in the basin from potential contaminants in drinking water. As part of this it should undertake, in conjunction with the Federal-Provincial-Territorial Subcommittee on Drinking Water if possible, a review of the status of drinking water quality, including its adherence to the guidelines for drinking water quality; the public's access to information on drinking water quality; and the need for nationally enforceable drinking water standards.

CANADIAN FRAMEWORK FOR COLLABORATION ON GROUNDWATER (2003)

Context: The Canadian Framework for Collaboration on Groundwater is an initiative of the Geological Survey of Canada. It was created following two national workshops in 2000 and 2001 involving representatives from all levels of government, academia, and the private sector. The Framework has not officially been endorsed by Natural Resources Canada.

Author: National *Ad hoc* Committee on Groundwater.

Recommendations

With respect to coordination and collaboration mechanisms, we recommend:

- establishing a Federal-Provincial Groundwater Committee (FPGC) to enhance cooperation among all levels of government;
- establishing a Canadian Groundwater Advisory Committee (CGAC), representing various stakeholders, to advise the FPGC; and
- annual reporting of the progress of CGAC and FPGC to stakeholders.

With respect to national cooperative programs, we recommend:

- enhanced funding for groundwater research and inventory;
- undertaking an assessment and inventory of Canada's groundwater resources;
- establishing a groundwater-monitoring 'network of networks';
- identifying critical needs for research on Canadian groundwater issues; and
- promoting linkages between government policy and the research community.

With respect to communication, we recommend:

- programs for raising the public's awareness on their role in protecting groundwater resources;
- providing a knowledge source of groundwater information for groundwater professionals and the public;
- developing and promoting an electronic national groundwater forum; and
- continuing to hold national groundwater workshops every two years.

With respect to performance standard and uniformity across Canada, we recommend:

- advanced training to enhance the knowledge and skills of groundwater professionals, well drillers, and technicians across Canada;
- accreditation for groundwater professionals, well drillers, and technicians across Canada;

- acceptance of provincial accreditation of groundwater professionals, well drillers, and technicians across Canada; and
- developing, promoting, and coordinating guidelines for best-management practices and technology transfer relating to groundwater.

FEDERAL WATER FRAMEWORK (2004)

Context: "The federal government declared water as a sustainable development priority in 2003. A senior-level interdepartmental committee, cochaired by Environment Canada and Health Canada, was given a mandate to develop a Federal Water Framework to address issues related to freshwater quality and quantity. The committee spent time, money, and effort to develop the Federal Water Framework, which was approved by its parent committee at the deputy minister level in February 2004. The Framework begins with a vision: 'Clean, safe, and secure water for people and ecosystems.' Associated with this vision are five ultimate outcomes encompassing the scope of federal activity on water. These outcomes relate to protecting human health through safe drinking water, ecosystem health, sustainable use and economy, hazards and environmental prediction, and the global dimension" (CESD, 2005).

The 2005 report of Commissioner of the Environment and Sustainable Development recommended that Environment Canada, with other federal departments and agencies, should establish clear next steps on what the Federal Water Framework will be used for, particularly in relation to its five ultimate outcomes (CESD, 2005). The CESD deemed the Department's response, excerpted below, to have failed to fully address the specifics of its recommendations.

Environment Canada's Response:

"In September 2004, the Minister of the Environment launched a process to develop a Competitiveness and Environmental Sustainability Framework for Canada (CESF). The purpose of the Framework is to attain the highest level of environmental quality as a means to enhance the health and safety of Canadians, preserve our natural environment, and advance our long-term competitiveness.

"The Federal Water Framework will help to reaffirm federal water policy priorities through the CESF. Some 19 federal departments completed the water framework task to describe their activities along five ultimate outcomes. The Water Framework serves as a tool to assist in identifying strengths and gaps in the departments' activities to address a full spectrum of water issues. Environment Canada will continue to promote the intent of the framework for priority setting and integrating water-related activities across the government.

"As key next steps, outcomes of the Federal Water Framework will be integrated into the broader CESF along the following lines:

Federal Water Framework outcomes	CESF outcomes
Human health	Health and safety of Canadians
Hazards and environmental prediction	
Ecosystem health	Natural environment
Sustainable use and economy	Long-term competitiveness

"The primary strategies for achieving the outcomes of the Federal Water Framework will be used in developing elements of the CESF related to water. A round-table discussion on water through the Deputy Ministers' Policy Committee on Environment and Sustainability will help to reaffirm federal water priorities and align water-related activities across mandates with the CESF. This round-table discussion and the above-noted alignments are planned for the fall of 2005" (CESD, 2005).

Author: A senior-level interdepartmental committee, cochaired by Environment Canada and Health Canada.

Recommendations:

The Framework begins with a vision: "Clean, safe, and secure water for people and ecosystems." Associated with this vision are five ultimate outcomes encompassing the scope of federal activity on water.

These outcomes relate to:

- protecting human health through safe drinking water;
- ecosystem health;
- sustainable use and economy;
- hazards and environmental prediction; and
- the global dimension.

WATER IN THE WEST: UNDER PRESSURE (2005)

Context: The Standing Senate Committee on Energy, the Environment and Natural Resources examined and reported on emerging issues related to its mandate.

Author: The Standing Senate Committee on Energy, the Environment and Natural Resources.

Recommendation 1

The Government of Canada should take the necessary steps to ensure that all of Canada's major aquifers are mapped by 2010. This data should be made available in the national groundwater database and supported by a summary document assessing the risks to groundwater quality and quantity.

Recommendation 2

The Government of Canada should work with industry and with other orders of government to develop a standard methodology for the collection and reporting of water-related data. The Government of Canada should take on the responsibility for the creation of a centralised depository for water statistics.

Recommendation 3

The Government of Canada must restore funding for longitudinal water studies. Such studies are essential to ensuring the sustainability of Canada's water resources.

Recommendation 4

The Government of Canada should bolster its support for the National Water Research Institute and the Prairie Farm Rehabilitation Administration so that these institutions can better address Western Canada's growing water challenges.

Recommendation 5

The Government of Canada should create a National Water Council. This Council, composed of representatives from industry, research institutes and all orders of government, would be tasked with identifying the key water issues that require attention from the federal government and proposing strategies for addressing them.

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Council of Canadian Academies
180 Elgin Street, Suite 1401
Ottawa, ON K2P 2K3
Tel: 613-567-5000
www.scienceadvice.ca