Council of Canadian Academies
Conseil des académies canadiennes

REPORT IN FOCUS

May 2009

The Sustainable Management of Groundwater in Canada

Canadians and their industries use enormous quantities of water, among the largest in the world in *per capita* terms and more than double the European average. 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 drinking water, and more than 80 per cent of the country's rural population relies on groundwater for its entire water supply. 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.

Almost 10 million Canadians depend 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 is a critical resource that Canadians often treat as 'out of sight, out of mind,' but it is now gaining visibility due to a growing number of threats that include rampant urbanisation, intensification of agriculture, contamination from diverse sources, burgeoning energy production and climate change. Canadians have already seen that groundwater quality and quantity problems incur enormous costs on society. This was underlined by the tragic groundwater contamination in Walkerton, Ontario, 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.

Despite the social, economic, and ecological value of groundwater, Canada's legislative framework and institutional capacity for groundwater management have yet to fully mature. While much of the knowledge required for the sustainable management of groundwater exists, this knowledge is not uniformly applied and there are aspects for which scientific understanding remains seriously underdeveloped. This is not an acceptable state of affairs in view of the many current and emerging stresses on Canada's groundwater resources that are discussed more fully in a subsequent section.

Canada has not yet experienced catastrophic over-usage or contamination of its groundwater resources on a national scale. While local and regional problems have arisen, there is no national crisis. So why worry about groundwater, and why now? The answer is that Canada is experiencing increasing stresses on groundwater, but is still in the enviable position of being able to proactively implement the policies and management practices that can prevent future potential calamities similar to those experienced all too often in other parts of the world. Furthermore, public attitudes in Canada have been evolving, with an increasing emphasis on environmental values. Never before has the quality and availability of water been of greater importance to Canadians.

Figure 1 — Monitoring well with satellite telemetry equipment.
Courtesy of William Cunningham.

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Charge to the Panel

The trends and stresses summarised in this report underline the need to pay greater heed to Canada's precious water resources, both above and below the ground. Water is 'the driver of nature' and it is therefore imperative that Canada's hydrosphere be managed sustainably. To this end, the federal government, through Natural Resources Canada, asked the Council of Canadian Academies (the Council) to appoint an expert panel to assess 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 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?

To address these questions, the Council assembled a diverse group of leaders in the science of groundwater, as well as experts in the social, economic, and legal aspects surrounding sustainable groundwater management. The expert panel was assisted in their deliberations by a large number of submissions from authorities across Canada in response to a Public Call for Evidence posted on the Council's website. A great deal of valuable advice was also received from 18 expert reviewers appointed by the Council to comment on the penultimate draft of the report.

Figure 2 — Installing a groundwater-monitoring well.
Courtesy of the Oak Ridges Moraine Groundwater Program.

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SUMMARY OF KEY MESSAGES

Almost 10 million Canadians depend 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. While Canada has not yet experienced widespread over-usage of groundwater, there have been a number of cases where severe local or regional problems have arisen. Canada is still in the enviable position of being able to proactively implement policies and management practices that can prevent the kind of groundwater crises experienced in many other parts of the world.

This report addresses the question "What is needed to sustainably manage groundwater in Canada, from a science perspective?" The answer requires first an appropriate definition of groundwater sustainability — in this case through a set of goals to be achieved; then an identification of the key gaps in knowledge and capacity that need to be filled. These gaps are only partly scientific and technical; sustainable management of groundwater also depends on governance that is less fragmented than is the case today, better integrated across jurisdictions, and well equipped to apply the latest knowledge and methods in groundwater science.

The report addresses three themes — goals, gaps and governance — in considerable detail. The following summarises the panel's broad conclusions for each theme. Detailed findings are outlined in the present document and more fully in the panel's report.

Defining Sustainability

The concept of groundwater sustainability developed by the panel encompasses five interrelated goals: three that involve primarily the physical sciences and engineering, and two that are essentially socio-economic in nature. These goals are:

- 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

The achievement of groundwater sustainability requires a careful analysis and balancing of the five goals. A comprehensive sustainability framework for groundwater has not yet been implemented in Canada. Adoption by federal, provincial and local jurisdictions of such a framework, based on the goals outlined above, would be valuable in guiding efforts to improve the understanding and management of groundwater.

Building the Knowledge and Capacity to Manage Groundwater

- Sustainability requires that groundwater and surface water be characterised and managed as an integrated system on a watershed or groundwatershed scale within the context of the full hydrological cycle. This approach should guide the collection of data and would be the appropriate basis for assessing cumulative impacts and the effects of large-scale phenomena like climate change.
- Due to the infancy of research examining 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.
- Poor groundwater quality is usually due to human activity, such as intensive agriculture, mineral extraction, contaminated legacy sites, or poor quality control in many rural wells. The ability to address these stubborn issues requires a better understanding of the relevant groundwater science and the economic and other behavioural incentives that cause the contaminating activities to persist.
- In most provinces, the use of models by regulatory agencies lags behind state-of-the-art application. Thus, as government authorities embrace sustainable groundwater allocation strategies, there is a need to improve their capacity to employ catchment-scale groundwater management models.
- There is currently 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.
- There is a need for more data on virtually all aspects of groundwater that are relevant for sustainable management. The collection, maintenance, and management of groundwater data, as well as ready access to these data, should be a priority for action. 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 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. To this end, the cooperative Groundwater Information Network (GIN) needs further support.

Improving the Governance of Groundwater

- An adequate base of scientific knowledge is necessary, but not sufficient, for the sustainable management of groundwater. 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.
- Existing high-level governance frameworks such as *The Canada Water Act* (1970); *The Federal Water Policy* (1987); and *The Canadian Framework for Collaboration on Groundwater* (2003) have either been little-used or have failed to produce clarity in the divisions of responsibility for groundwater management. There is a need for a more clear-cut, formally stated division of duties among the various levels of government.
- In many jurisdictions, the management of water is fragmented, with groundwater and surface water, as well as water quality and quantity, being treated independently. The integration of these responsibilities would foster sustainability.
- Groundwater management is best achieved at a local level through a regional municipality or a watershed authority, but this approach will only be successful when accompanied by sufficient financial and human resources, together with a requirement to take action and report on progress.
- An enhanced understanding of the value of groundwater's contribution to Canada's economy, environment, and society could promote more efficient decision-making. Current groundwater allocation methods in Canada rarely use market-based incentives despite considerable evidence suggesting that a greater implementation of economic instruments such as water prices, abstraction fees, and tradable permits has the potential to promote sustainable groundwater use.
- 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 measurements for the key dimensions of groundwater sustainability in order to guide management and to chart progress.

GROUNDWATER IN CANADA — AN OVERVIEW

Canada is fortunate in having enormous resources of fresh water. Almost 900,000 km^2 or eight per cent of the nation's total area is covered with fresh surface water. Total annual fresh-water use in Canada for all purposes (domestic, agricultural, industrial, and in connection with thermal power generation) is estimated to be about 1,500 m^3 per capita.[1] Normal household use of about 330 litres per person per day, on average, accounts for less than 10 per cent of total use. Data on the uses of groundwater specifically (within the use of fresh water overall) are limited and dated. Estimates from the mid-1990s suggest that groundwater accounts for roughly four per cent of fresh-water use in Canada, about double the share of a decade earlier.[2]

Groundwater discharges into streams, wetlands and lakes and thus often fills a critical role in sustaining sensitive aquatic species.

The primary use of groundwater in Canada varies regionally, from municipal purposes in Ontario, Prince Edward Island, New Brunswick, and the Yukon, to agricultural purposes such as livestock watering and irrigation 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. The portion of the population dependent on groundwater for domestic needs ranges widely, from 100 per cent of the population in Prince Edward Island to about a quarter of Alberta's population. It follows that any consideration of water in Canada will have a strong regional dimension.

The provinces, as resource owners and regulators, have the primary legal jurisdiction over groundwater. There is an increasing trend for provinces to delegate groundwater management responsibilities to local governments and multi-stakeholder bodies, such as watershed authorities. Local governments are involved in groundwater management in cases where groundwater is a source of municipal water supply, and also in controlling land-use practices that have the potential to contaminate 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, including a responsibility for First Nations. The federal jurisdiction includes boundary and transboundary waters shared with the United States. The federal government also contributes significantly to the development of knowledge about groundwater through the Geological Survey of Canada and various agencies that address groundwater issues that relate, for example, to the environment, health, agriculture, and fisheries, as well as through federal support of university-based research. Finally, there are several areas, such as agriculture and environment, where responsibility is shared by the Government of Canada and the provinces.

SOME CHARACTERISTICS OF GROUNDWATER

The total volume of groundwater, worldwide, is estimated very roughly to be about 100 times the volume of surface water in rivers and lakes. (Reliable estimates of the amount of groundwater in Canada do not exist.) Contrary to what may be common intuition, groundwater does not exist as a subterranean river or lake except in the very rare situations associated with cave formation in limestone. 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. Groundwater flow rates are typically much slower than those of surface water. This gives rise to much longer residence times for groundwater and, consequently, to some unique management issues. In particular, 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.

Groundwater discharges into streams, wetlands and lakes and thus often fills a critical role in sustaining sensitive aquatic species. In fact, groundwater and surface water are inextricably interconnected in the hydrological cycle; there is really just one store of available fresh water. Groundwater-resource development must therefore consider impacts both on the groundwater itself and on the surface-water regime.

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 important 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; and
- long groundwater-flow paths and natural filtration through subsoil media, which can achieve substantial contaminant removal.

GOALS FOR THE SUSTAINABLE MANAGEMENT OF GROUNDWATER

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. Today's much broader concept of 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 natural systems and human uses in the future. Adopting a comprehensive view of sustainability, the panel developed a conceptual framework, based on five interrelated goals, to help identify what science is needed to underpin sustainable management of groundwater in Canada. This framework is depicted in Figure 3.

A comprehensive sustainability framework for groundwater has not yet been implemented in Canada.

The first three goals relate primarily to the physical sciences and engineering domains, while the other two are mainly socio-economic. The question of what constitutes 'significant' in the context of the first three goals — i.e., sustainability requires that there not be a significant impact on groundwater quantity, quality or ecosystem support — involves judgement and is ultimately a societal decision that should be informed by scientific knowledge and sustainability principles. The mechanisms by which society determines what is acceptable are encompassed in the last two goals, which aim to achieve economic and social well-being and to ensure application of good governance.

Sustainability requires that groundwater and surface water be characterised and managed as an integrated system.

Based on the evidence reviewed by the panel, it appears that no jurisdiction in Canada has yet adopted a comprehensive sustainability framework for groundwater. Adoption by federal, provincial and local jurisdictions of such a framework, based on goals along the lines of those set out here, would be valuable in guiding efforts in groundwater management.[3]

GOALS FOR GROUNDWATER SUSTAINABILITY

- **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 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.
- **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 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.

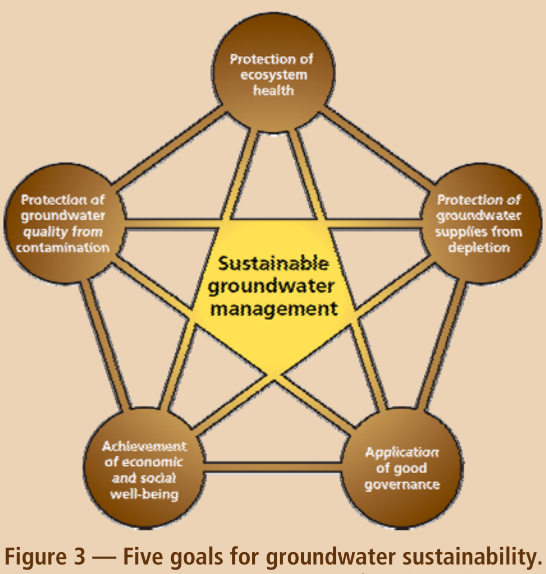

Figure 3 — Five goals for groundwater sustainability.
Council of Canadian Academies, 2009.

CASE STUDIES

The panel has prepared a number of case studies to illustrate a range of situations where groundwater management can be considered in light of the five proposed sustainability goals. Capsule 'abstracts' of these cases will be found throughout this summary.

CHALLENGES IN ACHIEVING THE SUSTAINABILITY GOALS

Sustainability requires that groundwater and surface water be characterised and managed as an integrated system in a drainage basin or groundwater basin. This systems approach to assessing the sustainability of water-resource development requires consideration of all 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, reinforcing the notion that each of the five sustainability 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.

Protection of groundwater supplies from depletion

Sustainable groundwater management must seek to prevent continuous, long-term declines in regional groundwater levels. Water-table elevations that reach a new equilibrium position are generally acceptable, provided the third goal, namely protecting ecosystem viability, has been adequately respected. To date, there are few examples of excessive groundwater depletion on a large scale in Canada, although localised examples do exist.[4] There can be serious economic consequences from excessive depletion. Greater costs for pumping, and possibly for treatment, are expected if groundwater has to be extracted from ever-deeper aquifers because of increasing water-level declines. Declining storage levels also reduce the buffer provided to municipal and agricultural users during droughts.

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. In addition, responsible agencies need to assign a high priority to the collection of data on groundwater allocations, actual withdrawals, and volumes discharged or reused.

Protection of groundwater quality from contamination

Sustainability requires that groundwater quality must not be compromised by significant degradation of its chemical or biological character. While poor groundwater quality may arise from naturally occurring constituents in the aquifer matrix, contamination 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 and fertilizer application. In urban settings, large-scale industrial activities, transportation networks, sewer-system leaks and small-scale commercial operations may contribute to the problem. In coastal settings, groundwater management must account for the protection of aquifers from seawater intrusion, especially as sea levels rise in the changing climate. Impacts on groundwater 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.

Poor groundwater quality is usually due to human activity and is a reflection of local land use.

Groundwater quality is protected through drinking-water and aquatic-ecosystem protection, pollution control and prevention, and environmental assessment laws. Water-borne disease is nevertheless a potentially serious problem associated with degraded water quality. As of March 31, 2008, there were 1,859 boil-water advisories in effect in Canada as reported by the Canadian Medical Association (the number of advisories attributable to groundwater is unknown). Fortunately, fatalities caused by water contaminated with microbial pathogens are now rare in Canada. The Walkerton tragedy in 2000 does not demonstrate that groundwater is inherently unsafe for drinking water supplies. Rather, it shows that a systemic breakdown of governance can occur with water supplies from any source, whether groundwater or surface water.

Case Study: Orange County, California

By the 1950s, irrigation had lowered the water table below sea level, and salt water intrusion from the Pacific Ocean had reached about eight kilometres inland. The Orange County Water District was subsequently created to protect and manage the basin. Injection wells raised the water table using a mixture of deeper groundwater and secondary effluent to prevent further saltwater intrusion. Engineered wetlands for the natural attenuation of increasing upstream effluent loading in the Santa Ana River improved river water quality, and a series of levees encouraged infiltration to artificially recharge the basin aquifers. In Orange County, hydrogeological understanding, coupled with engineering solutions, has overcome the problem of groundwater use in excess of natural recharge so the basin can sustainably provide more than half of the water used within the District.

Protection of ecosystem viability

Groundwater discharge to streams maintains 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. Pumping groundwater from shallow aquifers usually leads to reduced groundwater discharge to streams. There is inevitably a trade-off between the socio-economic benefits of increased water supply for human uses and the ecological benefits of stable outflow to groundwater discharge areas. An assessment of groundwater-discharge requirements for ecosystem viability must ensure that: (i) relevant surface-water features are incorporated into the groundwater understanding when estimating the discharge of groundwater to surface-water bodies, and (ii) 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 or quality (including temperature) a major conceptual and measurement challenge. In fact, there is currently no standard methodology for incorporating instream flow protection into laws and regulations, although a number of provinces are examining ways to address this gap.

Governance processes seek to balance the human benefits of groundwater extraction with the ecosystem benefits incurred by maintaining adequate stream baseflow and wetland habitats. While methods to value the human benefits are readily available and well understood, the mechanisms to assign value to the ecosystem benefits derived from groundwater are poorly understood and incomplete. In order to equitably balance ecosystem and socio-economic needs, comparable procedures are necessary in both domains to quantify the value of water.

The mechanisms to assign value to the ecosystem benefits derived from groundwater are poorly understood and incomplete.

Achievement of economic and social well-being

Sustainable-management policies that maintain water levels, stream baseflow rates and wetland habitats provide direct economic benefit. Groundwater also has value far beyond its worth as a resource owing to its spiritual, cultural and aesthetic value. A better understanding of the value of groundwater's contribution to Canada's economy, environment, and society could promote more-effective 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 users' valuation specifically of groundwater.

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. 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, might 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 (achievement of economic and social well-being) might nevertheless be used to justify such a decision. The application of such a rationale, which some would question, is illustrated in the Denver Basin case study.

Case Study: Denver Basin, Colorado

A lack of available surface-water rights and accelerated urban growth has resulted in extensive development of the Denver Basin aquifers. The State of Colorado agreed that it was acceptable to mine the 'non-tributary' aquifers in the basin by taking out more water than was being recharged, even if negative consequences resulted. (Non-tributary groundwater is essentially isolated from surface water.) Colorado has knowingly compromised future groundwater availability with current use to enable development in areas of the Denver Basin that have no alternative water supply at this time. As water levels decline, the cost may rise to a point where it is no longer economically feasible to mine the aquifers. The hope is that additional options for water supply will develop in the future.

There is 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.

Still, current groundwater allocation methods in Canada rarely use market-based incentives; e.g., 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.) The principal challenges facing the use of economic instruments in water management include: 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 many industrial and domestic sectors, the application of available technology, in addition to further research, is needed to improve the efficiency of water use. Economic incentives, and in some cases regulations, may also need to be considered to encourage efficiency.

Application of good governance

Water governance encompasses the range of processes through which interests are articulated, input is received, decisions are implemented, and decision-makers are held accountable. Governance is distinct from water management, which is the operational activity of regulating water. Governance involves more than the activities of any particular 'government,' and extends to public, private, and civil-society actors.

An enhanced understanding of the value of groundwater's contribution to Canada's economy, environment, and society could promote more efficient decision-making.

Criteria for good water governance commonly take into account: inclusivity, participation, transparency, predictability, accountability, and the rule of law. While an adequate base of scientific knowledge is clearly necessary for good governance, it is not sufficient. Many of the greatest challenges lie in the domain of institutional and political factors, including fragmented and overlapping jurisdictions and responsibilities, competing priorities, traditional approaches, and long-established ways of thinking.

Good governance in the context of sustainable water management clearly involves both quantity and quality. Current legal frameworks nevertheless treat these two aspects separately: water laws regulate access, allocation and water quantity; health, environmental and sector-specific laws regulate water quality. There are several situations in which the legal protection of groundwater quantity and quality could be improved: specifically, protecting instream flows; addressing nitrate contamination and other agricultural impacts; preventing general groundwater contamination; and assessing, when issuing a groundwater licence or permit, the cumulative impacts of activities that affect groundwater and dependent ecosystems.

Stronger enforcement of existing regulations is part of implementing good governance and would contribute significantly to sustainable groundwater management. Most in need of improvement in this regard are accurate and timely reporting of all licensed groundwater withdrawals; adherence to strengthened water-quality monitoring requirements; provision of complete documentation of geology in connection with well construction and well abandonment; and timely adherence to requirements for contaminated site clean-up and restoration.

Case Study: Abbotsford-Sumas Aquifer

This aquifer straddles the Canada-US border southeast of Vancouver. Agricultural contamination of the aquifer, originating in British Columbia and transported to Washington State, has been documented since the 1970s. Provincial and state agricultural regulations include mandatory nutrient management plans. Four groups, involving all levels of government and stakeholders, seek to coordinate scientific studies and provide public information. Industry groups encourage best management practices. Nevertheless, nutrient loadings have recently increased. An improved governance model is needed to ensure financial stability for coordinating bodies; to see that decisions are implemented; and to establish equity among participants as a means of encouraging commitment.

Over the years there have been several initiatives to create high-level frameworks that would facilitate the good governance of Canada's water resources. *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 jointly designate water quality management agencies. It has seen little use recently, but could play a beneficial role in groundwater management in the future. 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. This policy remains largely unimplemented. In 2003, an ad hoc committee of stakeholders issued *The Canadian Framework for Collaboration on Groundwater*, encouraging 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, including the assumption of responsibilities for follow-up actions.

KNOWLEDGE AND CAPACITY NEEDED TO ACHIEVE GROUNDWATER SUSTAINABILITY

Groundwater studies must aim to address the 'flow system,' from area of recharge to area of discharge. 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 components that, when managed in an integrated manner, should lead to credible forecasts of groundwater behaviour in a sustainable-management context (see Figure 4). These are:

- An understanding of the geological framework through which the groundwater flows;
- A quantitative description of the hydrogeological regime, including the extent of major hydrogeological units and parameters such as hydraulic conductivity;
- An appropriate groundwater-flow model; and
- A comprehensive water database (including geology and groundwater data as well as current stresses such as extraction, climate, and streamflow).

In jurisdictions where groundwater managers have not instituted the four-component approach recommended here, or its equivalent, the roadblocks appear to be one or more of (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 data.

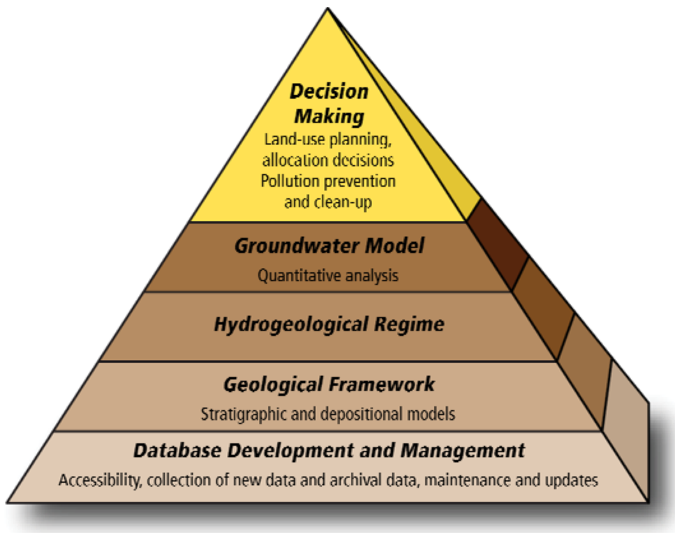

Figure 4 — Science requirements for groundwater sustainability.
Council of Canadian Academies, 2009.

Understanding the geological and hydrogeological context

Developing a sound understanding of the subsurface geology is one of the most critical steps in managing groundwater. 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. The next requirement is to understand the groundwater-flow system through analyses of hydraulic head measurements, pumping test results and other relevant hydrogeological data. With quantitative estimates in hand, calculations can be made of hydrogeologically important parameters such as flow velocities, bulk-flow rates, water budget components, and discharge rate to streams.

An adequate base of scientific knowledge is necessary, but not sufficient, for the sustainable management of groundwater.

Many such studies have been carried out by local and provincial agencies over the years, but little integration of the information on a national scale has taken place. The last comprehensive assessment of Canada's groundwater resources was published in 1967. Efforts are currently underway to establish a National Groundwater Inventory and, in that regard, the Groundwater Mapping Program managed by the Geological Survey of Canada has undertaken to assess 30 key regional aquifers. The collaborative assessments are intended to broaden knowledge on recharge, discharge, estimation of sustainable yield; quantify aquifer vulnerability at a regional scale; and provide provincial and local groundwater managers with the data and information needed to make informed land-use and groundwater-allocation decisions (see the following case studies of Basses-Laurentides and Oak Ridges Moraine). By 2006, only nine of the 30 aquifers had been assessed. At the current rate of progress 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.

Use of models

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. Properly calibrated models help to prioritise data-collection activities and provide a method for forecasting future conditions under various development scenarios. 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.

Case Study: Basses-Laurentides, Québec

The northward expansion of Montréal has meant that regional municipalities need to become better equipped to account for groundwater resources in their land-use decisions. Four municipalities formed a partnership with the Geological Survey of Canada, the province, and local universities to improve scientific knowledge of the regional aquifers. This cooperative approach overcame the otherwise prohibitive cost of collecting the field data necessary to understand the hydrogeological system and develop a numerical model to simulate groundwater-pumping scenarios, thus showing how science contributes to decision-making in water-resources management. A detailed groundwater study produced maps that can be used by the municipalities to manage land use proactively and resolve conflicts among users. It is expensive to conduct such detailed studies, and the financial commitment of governments has not been sufficient to reproduce such studies wherever they may be needed in Canada.

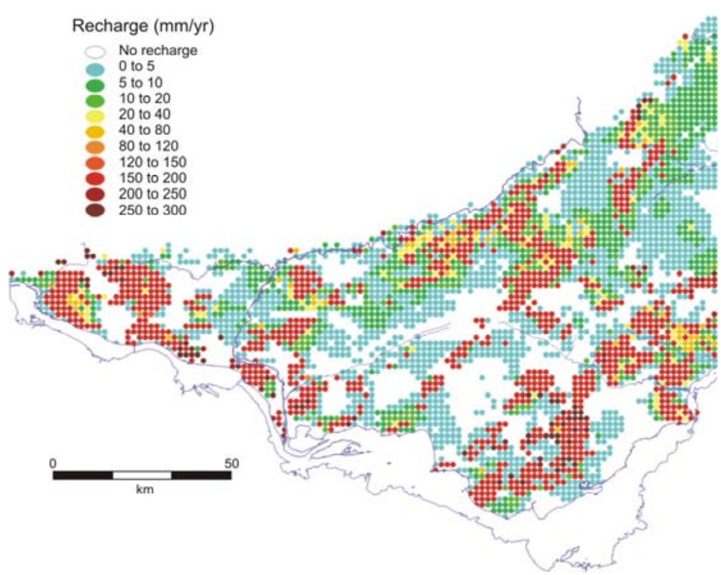

Figure 5 — Spatial distribution of recharge for the fractured rock aquifers of the Basses-Laurentides.
Courtesy of Andréanne Hamel, 2002.

Case Study: Oak Ridges Moraine Area, Ontario

The Oak Ridges Moraine is located immediately north of Toronto and extends from the Orangeville area to Trenton. The northward expansion of communities has rapidly changed land use, with impacts on groundwater quality, quantity and baseflow to streams. Several municipalities and conservation authority agencies in the moraine area have pooled resources to collectively manage groundwater. They operate within a framework based on a robust geological understanding (building on work of the Geological Survey of Canada), numerical groundwater-flow modelling, and a data management system. Each of these components is continually updated so that the elements of the framework are 'living.' The program also maintains a strong linkage to the planners so that local land-use decisions, which typically have the most impact on groundwater resources, are informed with the groundwater knowledge generated by the framework's elements. Limitations have been placed on development in important recharge areas.

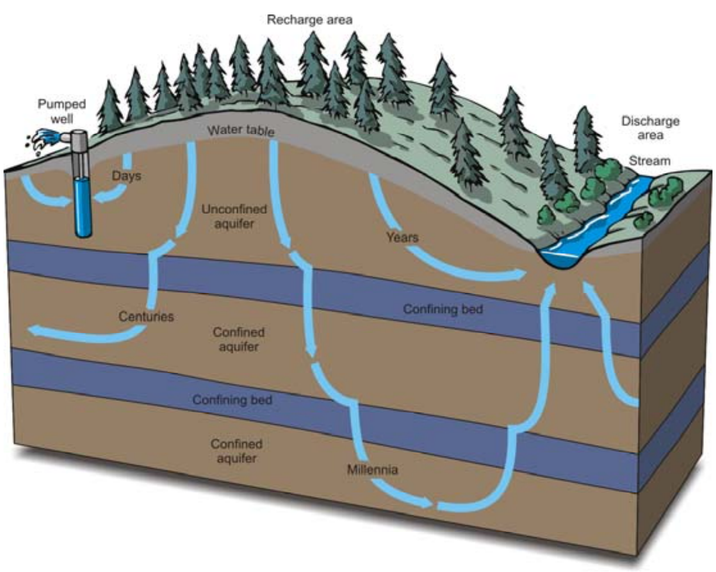

Figure 6 — Simplified local, intermediate, and regional flow system schematic.

Adapted and reproduced with permission from the U.S. Geological Survey.

The use of models by provincial regulatory agencies varies from province to province, but in most cases lags behind state-of-the-art application. 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. The panel strongly endorses the development of effective modelling platforms by government agencies. The most effective uses of numerical groundwater models are those in which the requirement 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.

Numerical models do not provide unequivocal answers to issues in groundwater management, but rather 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. As a consequence of uncertainty, modelling needs to be viewed as an ongoing process. The 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. Early decisions will thus reflect a precautionary approach, but as uncertainty narrows, management decisions can be made with greater levels of confidence. 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. 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 must therefore relate to the context of sustainability for a given situation.

While Canada does not need a comprehensive national groundwater database, it is important to agree on a structure and set of best practices…to facilitate the sharing of data among the provinces and between the provinces and the federal government.

Looking forward, the multiple goals of sustainable groundwater management can be expected to require new types of sophisticated models that can: (i) better capture the interaction between groundwater and surface water; (ii) integrate hydrogeological phenomena with economic variables; (iii) provide a detailed account of contaminant transport; and (iv) couple together the atmosphere, land-surface hydrology and groundwater to enable better assessment of the impacts of land-use change and of climate change and variability. The development and refinement of models of these types are active areas of research in which Canadians continue to make significant contributions.

Collection and integration of groundwater data

There is a critical lack of data on groundwater 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 parts 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 needed to produce a less-fragmented picture of groundwater use in Canada.

Case Study: Big River Basin, Rhode Island

Increasing water demand in the area of the Big River basin forced water managers to turn to groundwater. Previous investigations showed that groundwater could not be developed without reducing streamflow, but what pumping rates could be sustained without unacceptable reduction? The United States Geological Survey, in collaboration with State water managers, developed a simulation-optimisation model for the basin to determine the relation between minimum streamflow criteria and groundwater withdrawals. Repeated simulations permit the 'testing' of different hydrological stresses, such as the effects of various well locations. Minimum streamflow rates were varied in a series of model runs to test several management criteria. Incorporation of the hydrological system into 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.

The level of resources dedicated to systematic water-related data collection has generally failed to keep pace with the demands of development and in some cases has declined over the past 20 years; e.g., the number of stream gauges in Canada has declined from 3,600 to about 2,900. Some proactive provincial programs have nevertheless emerged, including the 2001 Ontario Provincial Groundwater Monitoring Program and the Ontario Clean Water Act.

Examples of the shortcomings of groundwater data collection include the following:

- Although all provinces and local agencies have ongoing water level monitoring programs, the number of observation points is generally insufficient. Furthermore, 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.
- Provincial water well records usually fail to capture the 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.
- 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.

The collection, maintenance, and management of groundwater-related data, and ready access to these data, should be a priority for action across the country.

Systematic efforts to assemble groundwater-related data into readily accessible information management systems have been limited. Although many hydrogeological data are collected, there are few efforts to assemble them into a collective database to improve understanding of groundwater. Moreover, the lack of an integrated data-management effort continues to result in considerable loss of valuable groundwater-related data principally collected in various reports and research studies carried out by consulting firms, universities, and non-governmental agencies. The collection, maintenance, and management of groundwater-related data, and ready access to these data, should be a priority for action across the country.

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 practices and a design 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) is developing standards for data management to facilitate sharing of information.[7] Groundwater monitoring at all levels needs to be more strongly supported, and a platform for sharing data, such as the GIN, should be further developed through federal-provincial cooperation.

Building the needed human capabilities

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 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 can generate positive outcomes by combining available resources into a single, geographically focused, vertically integrated management approach.

There is currently 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.

As more rigour is applied to managing groundwater in Canada, there will be an increasing call for relevant science and management skills. This suggests that there will be a growing demand for 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.

ADDRESSING KEY CHALLENGES TO GROUNDWATER SUSTAINABILITY

In the course of its work, the panel considered the many issues facing groundwater science and management in Canada in light of the five sustainability goals introduced earlier. What follows are brief summaries of the panel's findings as regards some of the actions that might be taken to address specific challenges to groundwater sustainability.

Population growth and urbanisation

The concentration of population in urban areas is forecast to increase from 80 per cent of Canadians today to 87 per cent of a larger population by 2030. Population growth and urbanisation usually lead to encroachment 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. Urban concentration also increases the risk of contamination of groundwater due to the threat of chemical contamination from waste water and microbial contamination from surface sources. As water demands increase with population growth, areas with limited groundwater resources will seek supplemental water, often in the form of surface water piped from larger lakes; e.g., in southern Ontario, 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 transfer and pipeline-related costs.

Coordinated action from provincial and local governments is needed to protect groundwater recharge zones and to minimise the adverse impacts of potentially harmful land uses. This coordination is vital because the stresses from urban growth and associated infrastructure needs are felt directly at the local level, while regulatory authority is shared with the provincial government.

In cases where groundwater investigations preceded land-use development, the products of hydrogeological studies, including aquifer mapping, characterisation and modelling, were effective in integrating groundwater concerns into the land-use management process. 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.

Case Study: Regional Municipality of Waterloo, Ontario

Groundwater management in the rapidly growing Regional Municipality of Waterloo offers important insight into the complexities of applying groundwater policies, in practice, at the municipal level. Unlike most other municipalities of its size, the Regional Municipality is almost entirely supplied by groundwater and has evolved many sustainable management practices. Owing to the region's long and diversified industrial history, water managers must contend with numerous legacy sites and their associated groundwater contamination. The Regional Municipality encourages water efficiency, but growth pressures require additional wells possibly supplemented with an aquifer storage and recovery system. A pipeline from Lake Erie is a possibility in the long term. Because of the geological complexity of the aquifers, projections of sustainable yield are uncertain. Development pressures in recharge areas add to the difficulties of predicting future groundwater availability. The effects of current withdrawals on ecosystem health are uncertain, and the specific criteria for maintaining ecosystem viability and integrity are poorly developed.

Intensification of agriculture

Agriculture is a major user of water in Canada. There is a growing interest in the environmental sustainability of agriculture, including the importance of groundwater in the context of irrigation, soil salinity and water contamination by nitrogen compounds and pathogens. Nitrates in groundwater potentially pose a threat to the health of infants and, because of transport through the hydrological cycle, create the threat of adverse effects in receiving waters that contain aquatic species.

The risk of nitrate contamination has increased due to regional increases in fertilizer use, livestock numbers, and legume crop acreages. For example, it is suggested that the nitrate in water leaching from agricultural land throughout Canada increased by about 25 per cent between 1981 and 2001. Despite widespread awareness of the problem, there has been little success in significantly reducing the incidence of nitrate contamination. If best management practices were more widely adopted by agricultural producers, there would be grounds for more optimism that the risk of nitrate contamination could be reduced, though success to date has been limited. This is illustrated, for example, by the panel's case studies of the Prince Edward Island and Abbotsford-Sumas aquifers. Further efforts are needed to address the technical, regulatory and economic factors that are responsible. Finally, stronger enforcement and regulatory regimes may be needed, along with adequate incentives and information programs.

Coordinated action from provincial and local government is needed to protect recharge zones and to minimise the adverse impacts of potentially harmful land uses.

Protecting the quality of groundwater

It is estimated that more than four million Canadians, mostly in rural or suburban areas, rely on private (as opposed to municipal) water supplies that are mostly sourced from groundwater. There is no national program for tracking how many private wells are subject to contamination but it is estimated that 20 to 40 per cent of all rural wells have either nitrate concentrations or coliform bacteria occurrences in excess of drinking water guidelines. When testing is conducted on private wells in Canada, it typically reveals a situation that would be unacceptable for a regulated municipal water supply.

Case Study: Prince Edward Island

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. This action is giving water managers time to better understand the potential impact of such extractions on fresh-water and estuarine ecosystems. Meanwhile, groundwater and surface-water quality in Prince Edward Island have been negatively impacted by widespread nitrate contamination from agriculture and to date no sustainable management solutions have been developed. The promotion of the 'good governance' sustainability goal appears to be reflected in the terms of reference of the recently appointed provincial Commission on Nitrates in Groundwater. The relatively non-fragmented jurisdictional environment in Prince Edward Island should provide a good test case in Canada for better integrated management of groundwater and surface water.

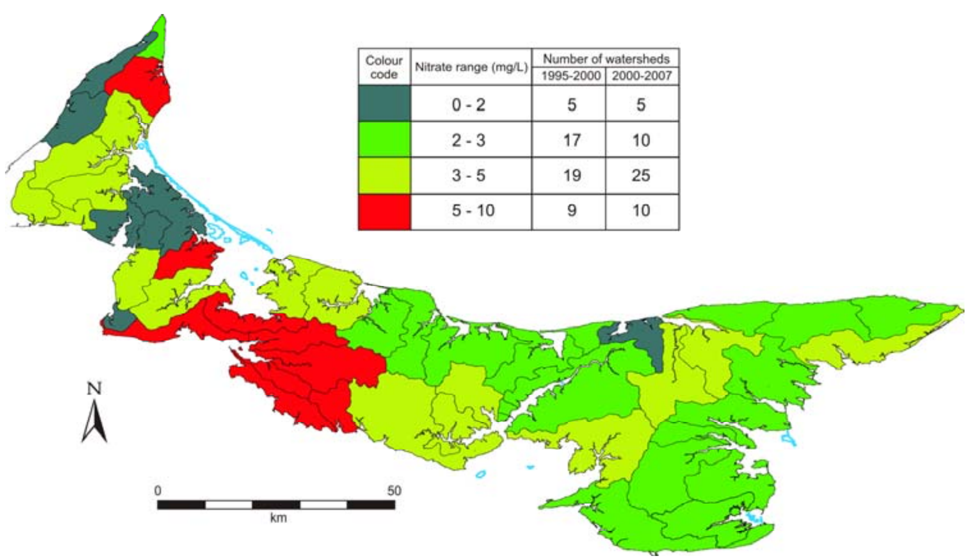

Figure 7 — Mean nitrate concentration in groundwater based on domestic water well data.
Reproduced with permission from Savard and Somers, 2007.

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 small community wells, including in First Nations communities, remains unacceptable. 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 focussed 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. 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. Wellhead and source-water protection plans depend on the technical ability to map capture zones. But available data are often insufficient to properly delineate source-protection zones, especially in complex aquifer settings. Since the required technical ability 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. Better geological understanding is clearly needed to improve the accuracy of models used to delineate the source-protection zones.

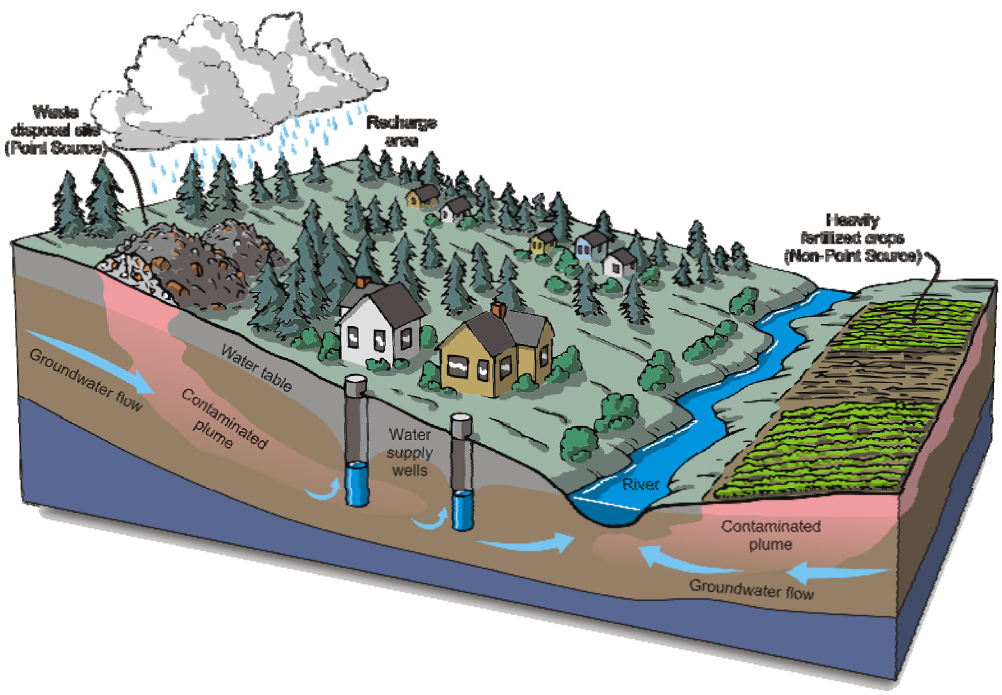

Figure 8 — Plumes of pollution from point and non-point sources of pollution.
Adapted and reproduced with permission from Environment Canada, 2008.

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.

There is considerable disparity in the requirement for, and 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. Assessments of groundwater monitoring must distinguish between regional monitoring of background water quality and site-specific monitoring of known or suspected groundwater contamination. The design of monitoring-well networks that are effective and cost efficient for either purpose is a difficult task and further research is required in this area. 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.

Many of the most challenging hurdles lie in the domain of institutional and political factors.

Regulators have made progress towards limiting point-source pollution from industries. In contrast, best management practices to control non-point-source pollution from agriculture or urban run-off have had limited success. Strengthened regulations or new technical approaches should be explored.

Remediation of contaminated sites

Contaminated sites are areas that have been polluted to a degree that creates a risk to health or the environment. In Canada, it is estimated that there are approximately 5,000 such sites on land owned or controlled by the federal government and 28,000 such sites on non-federal properties. The problem is exacerbated by the fact that concentration limits for many industrial chemicals in drinking water are very low, and thus relatively small releases can contaminate very large volumes of water. While 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, the thousands of legacy sites that remain represent a continuing threat to groundwater quality.

Remedial action is required for sites that have been contaminated by past industrial and military activity, urban development, and leaking underground storage tanks and sanitary sewers. The issue of contaminated site clean-up illustrates the complexity of sustainable groundwater management and the extent of coordination required among different jurisdictions to ensure that existing contaminants are well regulated, emerging contaminants are identified, and disposal sites are judiciously located and maintained to a high standard to minimise damage to groundwater regimes.

Clear groundwater objectives related to allocation and required quality should be defined prior to the approval of new energy extraction projects. These objectives should be based on knowledge of: (i) current hydrogeological systems and their linkages to land and surface-water environments, and (ii) accurate and regularly updated predictions of future cumulative effects. For example, adequate knowledge is currently 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.

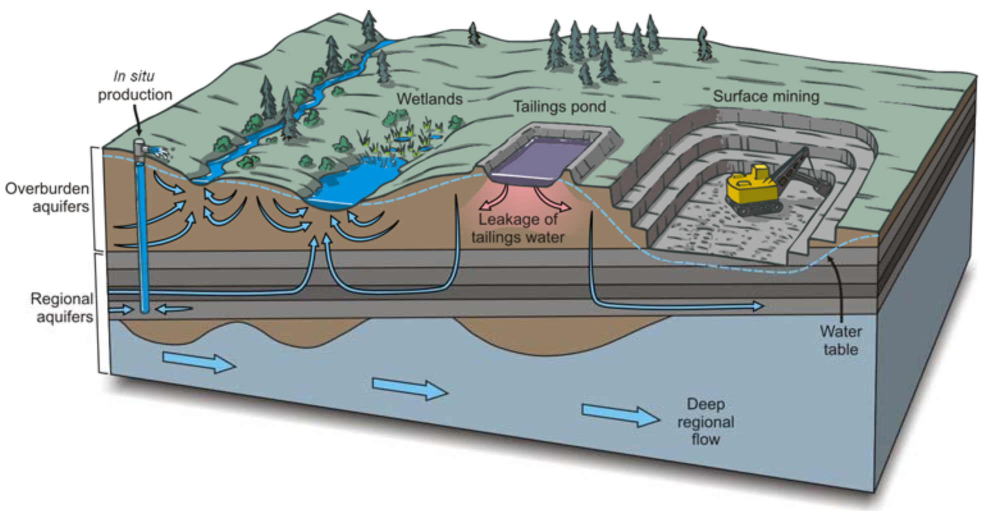

Figure 9 — Schematic diagram of key groundwater issues in the Athabasca Oil-Sands region.
Adapted and reproduced with permission from Alberta Research Council, 2007.

Pharmaceuticals and personal care products have also lately become an issue of concern, particularly in surface water. Though still in the early stages of investigation, the only reported occurrences of pharmaceuticals in Canadian groundwater have been associated with septic-system effluents.

Impact of energy and mining activity on groundwater

Canada's production of energy, metals and minerals is likely to increase in response to the long-term growth of global demand. This will put greater demands on water and is likely to generate increasing volumes of extraction-related wastes. In Canada, there are four particular areas of concern regarding the effect of these activities on groundwater quantity and quality:

- Mining impacts: the generation of effluents from waste rock or mine tailings which, if allowed to migrate freely, degrade the quality of surface water and groundwater;
- Oil-sands impacts: the impacts arising from the extremely large size of the area affected and the large volumes of groundwater and surface water being pumped in the extraction processes. The long-term impact on groundwater is still insufficiently understood, but is likely to be greatest for *in situ* operations;
- Coalbed-methane extraction: the risk of contamination of surface water and other groundwater supplies due to the disposal of extracted groundwater and any associated brines; and
- Geothermal impacts: the risk of degradation of 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 in an open-loop system.

Impact of climate change on groundwater

The Intergovernmental Panel on Climate Change (IPCC) predicts continued warming of the lower atmosphere due to an increased net energy build-up resulting from growing greenhouse gas accumulation. Unfortunately, owing to a lack of definitive studies, there are no specific groundwater conclusions from the IPCC for north temperate zones. Although a complete analysis of the potential effects of climate change on groundwater recharge has not been accomplished for Canada, a number of processes suggest that the recharge of groundwater from snowmelt might decline in southern regions and that episodic summer recharge from intense rainfall events is unlikely to fully compensate for this decline. Since groundwater discharge to streams is generally considered proportional to recharge rates, it is expected that this discharge will decline as water tables drop. These issues, combined with increased withdrawals and evaporation rates due to a warmer climate, will affect both surface and groundwater levels in the coming decades.

Case Study: Athabasca Oil-Sands, Alberta

Oil-sands deposits are relatively close to the surface, so much so that (a) mining operations can damage groundwater regimes and (b) the large tailings ponds, which hold what is left after the oil is separated from the sand, can leach petrochemicals into the surrounding groundwater. *In situ* methods of bitumen extraction consume large volumes of groundwater for steam production. Alberta's regulatory regime has been challenged by the scale and rate of the oil-sands developments. While environmental impact assessments are used in development planning, they are generally limited to the lease area, fail to address basin-scale impacts, and often neglect the cumulative impacts of other operations. Groundwater use in the oil-sands development areas is not sustainable as defined in this report. Regional-scale management may improve the coordination of studies and better account for cumulative impacts on both groundwater and surface water. The efficiency of groundwater use in oil-sands operations also needs improvement.

Climate change will affect groundwater levels through reduced recharge in much of southern Canada, increased 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 on the issues of reduced recharge (particularly in the spring in southern Canada) and increased withdrawals, to ensure sustainability of supplies and to assess impacts on ecosystems. For example, as noted earlier, models that link together atmosphere, land-surface hydrology, and groundwater should be developed to permit better assessment of the impacts of changes in both climate and land use.

Case Study: Prairie Groundwater

The recharge of Prairie groundwater is very restricted; and, with a few exceptions, the provinces do not have sufficiently detailed aquifer management information to fully account for the availability of natural recharge and, thus, for the sustainable yield of aquifers. Accordingly, because unconfined aquifers are very vulnerable to drought, predictive models that couple atmosphere, land surface hydrology and groundwater are needed to provide the basis for water management, especially under climate change. Land uses that favour intensive crop production may be reducing water availability for groundwater recharge, but measurements that can confirm this are lacking. Contamination from oil and gas activity and from intensive livestock operations poses a substantial threat to groundwater quality in certain regions and requires careful monitoring. Although water management is comprehensively organised in provincial governments, further work is necessary to ensure clear lines of communication among groundwater researchers, policy-makers and regulators. Watersheds are the basis for water management in the Prairies, but they do not align geographically with aquifers. Combinations of watershed authorities or cross-tabulation of authorities to form aquifer management authorities would improve management of groundwater substantially.

Transboundary water challenges

Transboundary groundwater tensions have, to date, been rarer than surface water disputes in Canada–US relations. The Abbotsford-Sumas aquifer, which straddles the border between British Columbia and Washington, 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. A comprehensive report on groundwater in the Great Lakes region is anticipated from the International Joint Commission. There are also concerns regarding the adequacy of Canadian laws to protect water from export in bulk. While the debates and bulk export proposals usually involve surface water sources, groundwater is, in principle, not immune from the possibility of diversion or bulk removal.

In many jurisdictions, the management of water is fragmented, with groundwater and surface water, as well as water quality and quantity, being treated independently. The integration of these responsibilities would foster sustainability.

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 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.

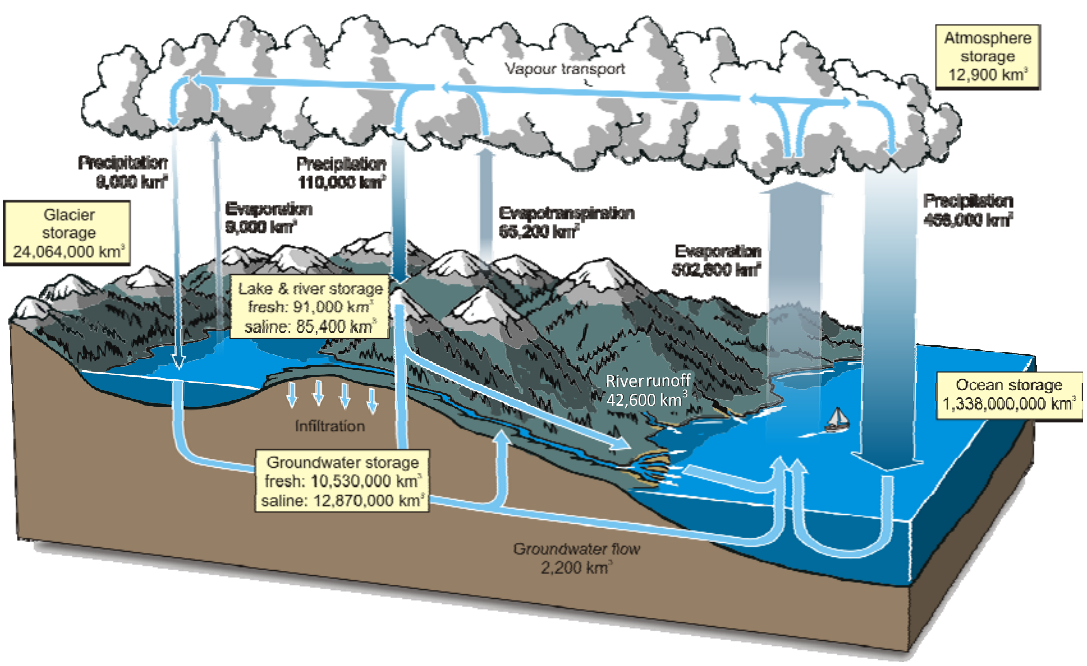

Figure 10 — The hydrological cycle.

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

Case Study: Groundwater in the Great Lakes Basin

Available evidence suggests that groundwater influences in the Great Lakes basin are important for the lakes and inflowing rivers and streams, yet assessment of quantity and quality effects is elusive because of major gaps in measurement and knowledge. While the gaps exist on both sides of the basin, the paucity of information is much more pronounced in Canada. In 2004, the Groundwater Program of Natural Resources Canada began a project to develop a conceptual hydrogeological framework for southern Ontario, which includes the Great Lakes basin. Resource constraints have limited the activity to assessments where considerable data already exist. Only limited surveys and analyses of groundwater in the Canadian portion of the Great Lakes basin had been carried out by the end of 2007. Although much valuable work has been completed by the United States Geological Survey, a comprehensive assessment of the role of groundwater in the Great Lakes Basin and its effects on lake water quantity and quality remains elusive.

Figure 11 — Great Lakes Basin.

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

Cooperation among jurisdictions to foster sustainable management

Considering the interjurisdictional nature of groundwater management, and in light of positive experiences in interjurisdictional cooperation outlined in several case studies in the panel's report, 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, 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.

REPORTING TO CANADIANS ON GROUNDWATER SUSTAINABILITY

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.

A RESEARCH AGENDA

This report has identified a number of topics requiring further research. Action to initiate, accelerate and fund these research activities deserves 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 does not constitute an exhaustive list but represents 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, 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;
- 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;
- Transport, fate and remediation of contaminants;
- Improving the efficiency of water use in many industrial and domestic sectors, particularly in energy production; and
- Design and implementation of pricing and economic instruments to promote sustainable groundwater use.

Sources for Figures

Figure 1 — Monitoring well with satellite telemetry equipment. Courtesy of William Cunningham.

Figure 2 — Installing a groundwater-monitoring well. Courtesy of the Oak Ridges Moraine Groundwater Program. Kassenaar, J. D. C., and E. J. Wexler. 2006. "*Groundwater Modelling of The Oak Ridges Moraine Area*". In *CAMC-YPDT Technical Report #01-06*.

Figure 3 — Five goals for groundwater sustainability. Council of Canadian Academies, 2009.

Figure 4 — Science requirements for groundwater sustainability. Council of Canadian Academies, 2009.

Figure 5 — Spatial distribution of recharge for the fractured rock aquifers of the Basses-Laurentides. Courtesy of Andréanne Hamel, 2002. Hamel, A. 2002. Estimation of Recharge and Groundwater Flow Patterns in Regional Aquifers in South-western Québec, Université Laval.

Figure 6 — Simplified local, intermediate, and regional flow system schematic. Adapted and reproduced with permission from U.S. Geological Survey.

Figure 7 — Mean nitrate concentration in groundwater based on domestic water well data. Reproduced with permission from Savard, M.M., Somers, G., editors, 2007. Consequences of climatic changes on contamination of drinking water by nitrate on Prince Edward Island. Natural Resources Canada, Climate Change Action Fund: Impacts & Adaptation, Contribution Agreement A881/A848, 142 pages; http://adaptation.nrcan.gc.ca/projdb/pdf/109_e.pdf.

Figure 8 — Plumes of pollution from point and non-point sources of pollution. Adapted and reproduced with permission from Environment Canada, 2008.

Figure 9 — Schematic diagram of key groundwater issues in the Athabasca Oil-Sands region. Adapted and reproduced with permission from Alberta Research Council, 2007. "A Regional Water Cycle Approach To Managing Groundwater Resources in The Athabasca Oil Sands Area", edited by Alberta Research Council.

Figure 10 — The hydrological cycle. Adapted and reproduced with permission from United Nations Environment Programme, 2002. Vital Water Graphics. "The World's Water Cycle: Global Precipitation, Evaporation, Evapotranspiration and Runoff." http://www.unep.org/dewa/assessments/ecosystems/water/vitalwater/05.htm.

Figure 11 — Great Lakes Basin. Reproduced with permission from reference map, provided by Earth-To-Map GIS Inc.

Endnotes

1 An Olympic-sized pool contains approximately 2,500 m^3 of water. One cubic metre of water is equivalent to 1,000 litres and is equal to approximately 217 imperial gallons or 264 US gallons. A cubic metre of water weighs 1,000 kilograms, or approximately 2,205 pounds (1 metric tonne).

2 Groundwater accounts for between 20 and 25 per cent of total fresh-water use in the United States.

3 Provincial water laws and policies are increasingly based on sustainability principles. For example, the Ontario Water Resources Act states: "The purpose ofthis 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." Other provincial water laws are also beginning to be guided by sustainability principles. The vision of the Canadian Framework for Collaboration on Groundwater, issued in 2003 by a committee of provincial and federal representatives, is "to ensure a healthy and sustained groundwater resource for all Canadians."

4 For example, 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.

5 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.

6 Hydrogeological models are mathematical descriptions (at varying degrees of complexity) of the factors that determine groundwater flow and contaminant transport.

7 The GIN is a group of federal, provincial and watershed agencies working in partnership with the national GeoConnections program. 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.

This assessment was made possible with the support of the Government of Canada.

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The Council of Canadian Academies supports independent, expert assessments of the science that is relevant to important public issues. The Council is a not-for-profit private corporation, and is supported by a $30 million grant provided in 2005 by the Government of Canada. This "Report in Focus" was prepared by the Council based on the report of the Expert Panel on Groundwater.

Cover photo courtesy of Environmental Agency (UK).