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Water Science and  
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## Environnement Canada

Groundwater Quality in Canada: Linking Science & Policy

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# GROUNDWATER QUALITY IN CANADA: LINKING SCIENCE & POLICY

A.S. Crowe and K. Schaefer

## ABSTRACT

Over ten million Canadians rely on groundwater for drinking water. In the past, Canadians have assumed groundwater provided an ample supply of water free of contaminants. However, recent contamination events and media coverage have lead to heightened public awareness and concern over the vulnerability of this resource. This heightened awareness is challenging governments at all levels to respond with better and more effective programs and policies to protect groundwater quality, and to ensure we have the essential science to guide these programs. In March 2002, in response to concerns about groundwater quality in Canada, the Canadian Council of Ministers of the Environment sponsored the workshop *Linking Water Science to Policy: Groundwater Quality*. The workshop presented the results of new research and management practices to senior policy personnel, and provided a mechanism for leading scientists and water managers to contribute expert input to Canadian water programs. This paper presents the key scientific research and policy needs for 11 key groundwater issues identified by the workshop.

# LA QUALITÉ DES EAUX SOUTERRAINES AU CANADA : FAIRE LA JONCTION ENTRE LA SCIENCE ET LA POLITIQUE

A.S. Crowe et K. Schaefer

## RÉSUMÉ

Plus de dix millions de Canadiens tirent leur eau potable de sources d'eaux souterraines. Jusqu'à présent, les Canadiens ont toujours présumé que les réserves d'eaux souterraines leur fournissaient un abondant approvisionnement d'eau salubre. Mais de récents épisodes de contamination qui ont fait la manchette des médias ont amené le public à prendre conscience de la vulnérabilité de cette précieuse ressource. Les gouvernements de tous les paliers doivent prendre acte de cette nouvelle sensibilité et mettre en œuvre des programmes et des politiques plus efficaces pour protéger la qualité des eaux souterraines en mobilisant les ressources scientifiques nécessaires. En mars 2002, en réponse aux préoccupations exprimées au sujet de la qualité des eaux souterraines au Canada, le Conseil canadien des ministres de l'environnement a parrainé un atelier intitulé *Science de l'eau et politiques : Qualité des eaux souterraines*. Cet atelier communiquait aux principaux décideurs les résultats des recherches récentes et des nouvelles pratiques de gestion, et a fourni aux scientifiques et aux gestionnaires des ressources hydriques les moyens de contribuer à l'élaboration des programmes canadiens sur l'eau. Ce document fait état des principaux besoins en matière de recherche et de politiques autour de 11 grands enjeux liés aux eaux souterraines, tels qu'identifiés au cours de l'atelier.

## **NWRI RESEARCH SUMMARY**

### **Plain language title**

How to ensure that the best and current science is actually being used to aid in regulatory and policy decisions.

### **What is the problem and what do scientists already know about it?**

Following several events that impaired drinking water quality in Canada, CCME wanted to know if there are currently any policy and/or science gaps that may limit federal, provincial and municipal governments' ability to protect groundwater resources used as a source of drinking water. CCME sponsored a workshop that invited leading Canada's eminent groundwater scientists to address 11 key groundwater quality issues facing Canadians. They provided an overview of the current state of science, what we don't know and what current scientific knowledge can be used to immediately improved the regulations and policy designed to protect and improve Canada's groundwater quality for drinking water.

### **Why did nwri do this study?**

This study was undertaken in response to the May 2001 request from CCME to hold expert workshops on water quality issues in Canada, including groundwater quality.

### **What were the results?**

Scientists are willing to work with regulatory and policy personnel to ensure that the best available science is being appropriately used when developing policy and regulations related to the protection and management of Canada's groundwater. Currently there is a 10-20 year time lag before the current science is actually incorporated into regulations and policy.

### **How will these results be used?**

The results of the workshop, and its reports and papers will be used both to guide federal provincial and municipal personnel in what regulations and policy is required to protect groundwater quality, and to ensure that the best and current science is actually being used to aid in regulatory and policy decisions.

### **Who were our main partners in the study?**

CCME.

## **SOMMAIRE DES RECHERCHES DE L'INRE**

### **Titre en langage clair**

Comment faire en sorte que l'on puise aux meilleures connaissances scientifiques pour prendre des décisions en matière de réglementation et de politique.

### **Quel est le problème et que savent les chercheurs à ce sujet?**

À la suite de plusieurs événements qui ont mis en péril la qualité de l'eau potable au Canada, le CCME a voulu déterminer quelles lacunes politiques et/ou scientifiques risquaient de restreindre la capacité des gouvernements et des administrations municipales de protéger les ressources en eaux souterraines utilisées comme source d'eau potable. À cette fin, le CCME a parrainé un atelier au cours duquel d'éminents spécialistes des eaux souterraines du Canada ont abordé 11 grands enjeux liés à la qualité des eaux souterraines auxquels font face les Canadiens. Ils ont pu ainsi faire le point sur l'état actuel de la science, préciser les lacunes de nos connaissances, et déterminer quelles connaissances scientifiques actuelles peuvent nous aider à améliorer immédiatement la réglementation et les politiques visant à protéger et à accroître la qualité des eaux souterraines utilisées comme source d'eau potable au Canada.

### **Pourquoi l'INRE a-t-il effectué cette étude?**

Cette étude a été entreprise à la suite d'une demande soumise en mai 2001 par le CCME pour qu'on organise des ateliers d'experts sur les grands enjeux liés à la qualité de l'eau au Canada, et notamment la qualité des eaux souterraines.

### **Quels sont les résultats?**

Les scientifiques sont prêts à collaborer avec les responsables chargés de la réglementation et de l'élaboration des politiques pour faire en sorte que les meilleures connaissances scientifiques existantes soient utilisées dans l'élaboration des politiques et des règlements concernant la protection et la gestion des eaux souterraines du Canada. À l'heure actuelle, il faut encore 10 à 20 ans avant que les connaissances scientifiques à jour soient incorporées aux règlements et aux politiques.

### **Comment ces résultats seront-ils utilisés?**

Les résultats de l'atelier, de même que les rapports et mémoires qui y ont été présentés aideront les fonctionnaires fédéraux, provinciaux et municipaux à déterminer quels règlements et politiques sont nécessaires pour protéger la qualité des eaux souterraines et à faire en sorte que les données scientifiques les plus à jour soient réellement utilisées pour prendre des décisions réglementaires et politiques.

### **Quels étaient nos principaux partenaires dans cette étude?**

CCME.

# GROUNDWATER QUALITY IN CANADA: LINKING SCIENCE & POLICY

A.S. Crowe and K. Schaefer

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## ABSTRACT

Over ten million Canadians rely on groundwater for drinking water. In the past, Canadians have assumed groundwater provided an ample supply of water free of contaminants. However, recent contamination events and media coverage have lead to heightened public awareness and concern over the vulnerability of this resource. This heightened awareness is challenging governments at all levels to respond with better and more effective programs and policies to protect groundwater quality, and to ensure we have the essential science to guide these programs. In March 2002, in response to concerns about groundwater quality in Canada, the Canadian Council of Ministers of the Environment sponsored the workshop *Linking Water Science to Policy: Groundwater Quality*. The workshop presented the results of new research and management practices to senior policy personnel, and provided a mechanism for leading scientists and water managers to contribute expert input to Canadian water programs. This paper presents the key scientific research and policy needs for 11 key groundwater issues identified by the workshop.

## INTRODUCTION

Canada is a country rich in water resources. Throughout much of the country, Canadians have often taken a clean and plentiful supply of water for granted. However, recent events, such as drought in western Canada, beach closures along the shores of the Great Lakes, low lake-levels, and groundwater contamination from the Fraser River valley in B.C. to the Sydney Tar ponds in Nova Scotia have changed people's attitudes about the abundance and safety of Canada's water.

The change in attitudes has been especially dramatic when it comes to Canada's groundwater resources. Ever since the tragic events leading to groundwater contamination in the drinking water of the town of Walkerton, Ontario, in May of 2000, the quality of groundwater as a source of drinking water has become a national issue. The media more frequently reports on potential threats to groundwater contamination, actual events, and government reaction. The public's concern and loss of trust is demonstrated by a dramatic rise in the sale of bottled water and demands for government action. All levels of government have made groundwater protection and drinking water safety a major policy focus through increased regulations, monitoring, and testing. But, when it comes to governments actually implementing procedures to ensure that Canada's groundwater is adequately protected four basic questions are frequently asked:

1. Is our current scientific knowledge sufficient to identify and solve existing problems?
2. If, not, what are the science deficiencies, and how can we address this?
3. What will be the emerging groundwater contamination issues of the future?
4. Are current and proposed policies and regulations backed by sound science?

There is a growing consensus that to ensure that science better informs the decision-making process, researchers and policy/program managers need to interact routinely. There is, however, little practical guidance on how this should be done and even less experience with specific mechanisms that better link these two groups. The Canadian Council of Ministers of the Environment (CCME) is the major intergovernmental forum in Canada for discussion and joint action on environmental issues of national and international concern. CCME is comprised of environment ministers from the federal, provincial and territorial governments. CCME has made water a top priority, and in May of 2001 identified five main areas for exchange of information: (1) agricultural impacts on water quality; (2) groundwater quality; (3) water recycling and reuse, (4) wastewater treatment for small communities; and (5). water quality monitoring.

This paper presents the key scientific research and policy needs identified during the CCME-sponsored workshop *"Linking Water Science to Policy: Groundwater Quality"*. The goals of this workshop were to present current research findings to policy and decision makers; ensure scientific research is meeting the needs of the policy community; identify future research needs; help establish research priorities; and determine a process for ongoing information sharing and communication. Or in more basic terms: (1). what do we currently know; (2) what don't we know; (3) what science is required; (4) what policy is required; and (5) how do we communicate it. Presentations on specific issues of groundwater quality by eminent groundwater scientists, panel discussions, and plenary sessions on the state of groundwater knowledge and linking the science with policy took place. Also included were overviews of several key initiatives involving groundwater quality taking place across Canada, and perspectives on groundwater quality from the municipal sector and the United States.

## SCIENCE UPDATES & POLICY PERSPECTIVES

Eleven key groundwater quality issues requiring national attention were identified during the workshop. An overview of the state of science with respect to each issue was presented by a scientific expert in the field (Table 1). The following is a summary of each issue.

**Table 1. Key groundwater quality issues and speakers.**

gw quality issue	speaker
1. fractured rock environments	Kent Novakowski, Queen's University
2. natural contaminants	Carol Ptacek, National Water Research Institute
3. clays as barriers	Jim Hendry, University of Saskatchewan
4. pathogens	William Woessner, University of Montana
5. agricultural impacts	Dick Coote, Agricultural Watershed Associates
6. rural and municipal issues	David Rudolph, University of Waterloo
7. DNAPL and LNAPL spills	Jim Barker, University of Waterloo
8. mining and metals	David Blowes, University of Waterloo
9. petroleum industry	Kevin Parks, Alberta Geological Survey
10. risk assessment	Leslie Smith, University of British Columbia
11. Canadian groundwater quality surveys	Garth Van der Kamp, Environment Canada



## Fractured Rock Environments

### Background

Groundwater is commonly perceived as coming from sand and gravel deposits. However, there is another groundwater environment from which many Canadians obtain their groundwater: fractures in sedimentary rock (e.g., limestone, dolostone, sandstone) or crystalline rock (e.g., granite). Fractured rock is used as a source of groundwater when there is little overburden or the overburden has little capacity for an adequate supply of groundwater. Groundwater may be obtained from a single fracture or multiple fractures if the density of fractures is large. Fractured rock aquifers contain both horizontal and vertical fractures. Even though the thickness of fractures may be very small (<1 mm), they can have a significant water-carrying capacity. Typically, the rock surrounding a fracture will produce little water.

### Issue

The differences in structure of porous media and fractured rock aquifers are reflected in significant differences between them, including: (1) groundwater flow and groundwater availability; (2) transport and extent of contamination; (3) mathematical and physical characterization; and (4) our knowledge of groundwater flow and contaminant transport. This means that fractured rock environments cannot be treated in the same manner as porous media aquifers, and the basic and common principles upon which our knowledge of groundwater flow and contaminant transport in porous media resides cannot be applied to fractured rock.

### What we know

Within the scientific community, it is well known that fractured rock aquifers are very different than porous media aquifers, and hence must be treated differently. Unfortunately, groundwater consultants and regulatory personnel generally do not use this knowledge; they treat fractured rock environments as porous media. This may be due, in part, to a lack of knowledge among practitioners about groundwater flow and contaminant transport in fractured rock. But it is also because knowledge of groundwater flow and contaminant transport within the scientific community is similarly limited. A fair amount of knowledge is available on groundwater flow and contaminant transport within a single fracture. The effects of diffusion of contaminants into and out of the adjacent rock mass (matrix diffusion) are also known. Hence, we can track and predict the movement of contaminants over short distances (in the order of metres).

### What we do not know.

At the present time, there are only a small number of groups in government and university actively conducting research on the hydrogeology of fractured rock. The majority of that research is directed toward understanding contaminant migration and development of remedial technologies, with very little attention given to sustainable development and wellhead protection in bedrock aquifers. In addition, a considerable number of fundamental processes such as groundwater-surface water interaction, sorption of organic contaminants, transport of agricultural chemicals and bacteria, and mixing and dispersion of contaminants in complex fracture networks remain poorly understood.

Our knowledge of the structure and continuity of fractures is limited. Hence, we cannot accurately predict the movement of contaminants within a single fracture over limited distances. We are not able to predict the flow of groundwater and transport of contaminants within fracture networks. Our lack of knowledge and understanding of groundwater flow and contaminant transport in fractured rock means that our attempts to remove or remediate contaminants within a fractured rock environment are essentially not achievable at this time.

#### Policy perspective

From a policy perspective, the single most important issue is the recognition that management of groundwater resources in fractured rock cannot be conducted in the same way as for sand and gravel aquifers. Because of the complexity, characterization of contaminant migration requires significantly more resources than equivalently scaled problems in porous media. Site managers must recognize this need and recognize that the potential success of eventual site clean-up is significantly diminished in comparison to porous media. Plans for wellhead protection and groundwater management zones must incorporate the complexities of the fracture framework, and components such as recharge, discharge and consumptive use in a flow system having low storativity and very high groundwater velocity.

### **Natural Groundwater Contamination**

#### Background

The absence of human impact on the groundwater regime does not guarantee that the quality of groundwater will meet Canadian Drinking Water Guidelines (CDWG) for human consumption. There are many naturally occurring substances in groundwater, and in many instances concentrations may be present above CDWG. Some may present a risk to human health when at elevated concentrations, including arsenic, mercury, selenium, lead, fluoride, nitrate, sulfate, and uranium. Others (iron, manganese, chloride, calcium, magnesium, hydrogen sulphide) only present esthetic problems, and are no risk to human health at concentrations typically encountered in groundwater. However there is public perception that if the water does not look or smell good it is unsafe to drink.

#### Issue

Not all substances found in groundwater that are harmful to human health are anthropogenic substances. Naturally occurring elements and compounds are often present in groundwater at concentrations above CDWG. Various natural processes and human water-use practices can enhance release of these substances in groundwater, and often lead to high concentrations.

#### What we know

We know that naturally occurring substances are commonly found in groundwater in domestic wells throughout Canada at concentrations above CDWG. The presence of naturally occurring substances in groundwater and their concentrations are directly related to the composition of the soil, sediment and rock through which the groundwater flows. Arsenic at concentrations above CDWG is a common and well-documented problem in domestic wells throughout Canada. Concentrations of arsenic in some groundwater supplies in Canada exceed concentrations that have been the focus of international concern in undeveloped nations. High concentrations in

groundwater are linked to till (Alberta, Saskatchewan), shale (N.B., N.S., Saskatchewan), and igneous and metamorphic rock (Ontario, Saskatchewan, B.C., Newfoundland, and elsewhere). Elevated concentrations of uranium have been reported in wells in southwestern N.S., N.B., Ontario, and in Saskatchewan. Radon has been reported in parts of Ontario, Saskatchewan, and Alberta. Salinity above CDWG has been reported along the Niagara Escarpment in Ontario, and throughout Alberta and Saskatchewan. High sulfate concentrations are commonly reported in all provinces due to pyrite oxidation and by gypsum dissolution.

Human groundwater-related activities can cause geochemical changes that also can lead to elevated concentrations of natural substances that under natural conditions would not be above CDWG. Irrigation in arid areas of Canada, such as the southern Prairies and the interior of B.C., can release natural salts such as halite, gypsum, and anhydrite, and increase the salinity of groundwater. In coastal areas such as of P.E.I., N.B. and B.C., extensive pumping of groundwater can lead to advancement of seawater inland and contamination of wells; the landward encroachment of seawater cannot be reversed. In many cases simply pumping groundwater from a well can alter the chemistry of the aquifer material and the groundwater adjacent to a well. In the Prairies, pumping of domestic wells can cause oxidation of pyrite in tills and coal seams, leading to increased concentrations of sulfate. In N.B., pumping from municipal wells has caused river water to infiltrate through aquifers resulting in increased levels of manganese.

#### What we do not know

There has not been a national assessment of naturally occurring groundwater contaminants or a comprehensive assessment of how human activities are affecting levels of naturally occurring substances. A number of recent surveys on arsenic in groundwater indicate a high percentage of wells produce groundwater that greatly exceeds recommended guidelines. These surveys suggest that the occurrence of unacceptable levels of arsenic in groundwater may be much more widespread than previously anticipated. Water quality guidelines for arsenic recently have been lowered in the U.S. If Canada adopts this lower standard, even broader regions of the country will need to rely on alternative water supplies or advance treatment systems.

There are many instances throughout Canada where it is suspected that commercial, industrial, or resource development activities have caused deleterious changes in the groundwater quality. Without knowing natural background concentrations of naturally occurring substances, it is difficult to know the extent that these human activities have caused, or even if these activities have actually affected groundwater quality at all.

#### Policy Perspective

Municipal wells are generally well regulated, water quality is regularly tested, and standards are enforced. If CDWG are exceeded, the well is no longer used. Domestic wells are not as well regulated with respect to the frequency of water quality testing, or water quality standards that must be met. Many provinces are undertaking programs to test groundwater quality in domestic wells, and revising guidelines and regulations relating to well construction, well placement, influence of surface water/runoff, etc. However, there are no regulations to enforce closure of a domestic well due to contaminants exceeding CDWG. It is up to an individual well-owner to decide what water quality they will tolerate. As a result, many domestic wells throughout Canada

supply groundwater for drinking where concentrations are above CDWG. In areas where it is known that there are concentrations of naturally occurring substances above CDWG, health advisories should be issued to all home owners, especially before wells are installed. Also, small treatment systems are available for a domestic well owner that could be used to reduce levels of contaminants; but there are no regulations enforcing their use. Programs need to be put in place for testing groundwater from domestic wells over time (not just when well is drilled). Restrictions on drilling wells, or regulations on controlling the depth of a well could be implemented in areas of known high concentrations.

Baseline data on natural groundwater quality are needed before development occurs, both to determine if natural groundwater quality is being affected by human activities, and to predict how human activities will change natural groundwater quality (e.g., increased dissolution, saltwater intrusion, redox change mobilizations). If the problem is due to natural levels, then all we can do is use expensive treatment systems. If problems are related to the human activities, then we can restrict land-use activities, or change the activities to protect or restore groundwater quality.

### **Clay as Barriers to Contaminant Transport**

#### **Background**

Clay is used as a barrier to prevent contaminants from moving into groundwater. Clay is widely used as an engineered barrier at landfills, hazardous waste disposal sites, manure storage sites at hog farms or cattle farms, mine tailings ponds, brine waste from potash extraction, etc. Naturally occurring clay deposits at or near ground surface are also widely recognized as an effective barrier to the downward movement of contaminants, especially in rural settings. Areas with thick and widespread clay deposits are often selected as sites for waste disposal areas.

#### **Issues**

Clay can be an effective barrier to the movement of contaminants from surface into groundwater. But natural and engineered clay barriers can become fractured and these fractures present pathways for contaminant movement. Hence, if the clay barrier contains fractures, the barrier may not effectively prevent contamination of groundwater.

#### **What we know**

Based on current research it appears that nonfractured natural clay-rich deposits and engineered clay liners can provide a barrier to minimize the potential for groundwater contamination from certain diffuse and point-source contaminants to underlying aquifers. But we know that fractures are common in clay and these fractures act as a pathway for contaminant transport. Nonfractured clay does not prevent the movement of contaminants; it only slows the movement of contaminants. However, because the principle mechanism for transport in nonfractured clay is diffusion, contaminants will only move <1 mm per year. Chemical and biological reactions should, in most cases, further slow the migration of many inorganic and organic contaminants.

We also know that clay deposits can also act as a long-term source of groundwater contamination if the contaminants enter the clay. Contaminants at waste disposal/storage sites will move into the clay barrier by diffusion. Contaminants from spills, etc. can also diffuse into natural clay

deposits. Once the contaminant has been removed from outside the clay, the contaminant, which entered the clay, will migrate out of the clay into an aquifer by the same diffusion mechanisms by which the contaminant entered the clay. Hence, because diffusion is a slow process, this outward diffusion of contaminants may act as a source of contaminants for decades or longer.

Recent research has identified areas of increasingly important knowledge regarding the impacts of these reactions on contaminants in clays. For example, initial studies indicate: (1) migration of some metals through these clays can be enhanced by sorption onto mobile dissolved organic carbon; (2) in-situ biological reactions may have no measurable impact on attenuation of contaminants in the clays; and (3) bacteria should not migrate through nonfractured clay, but bacteria will move through fractures in clay.

#### What we do not know

For a complete understanding of the effectiveness of natural clay barriers, critical areas of future research include: (1) defining the extent of fracturing in regionally extensive clays; (2) quantifying the degree of impact of biological reactions on contaminant migration; (3) quantifying the interactions between dissolved contaminants and the clay-rich matrix material and its impact on the migration of contaminants; and (4) characterizing the distribution of bacteria in clay.

Unfortunately research in clay environments is technically difficult and very costly. It is difficult to locate fractures in clays, especially at depth. It also takes a very long time to characterize the hydrogeological environment of clays because flow and transport through clay are extremely slow. Hence, few studies have been undertaken in clays. Naturally occurring stable isotopes can be used to determine where fractures are likely to be present in clay, and where diffusion is the dominant transport mechanism. Isotopes of water (deuterium and oxygen-18) are indicative of atmospheric conditions when water first diffused into the clay.

#### Policy Perspective

Information on mechanisms controlling transport of contaminants through clays can be transferred to policy makers and the public with some degree of certainty. However, given the early stages of research into biological and chemical reactions and the impacts of those reactions on contaminant transport, it would not be appropriate to transfer similar conclusions about most biochemical and chemical reactions. Given the characteristics of these clay materials and the time- and equipment-intensive nature of the research, sufficient time to reach valid conclusions will be the defining factor of success in this area of research.

Engineered clay barriers at waste disposal/storage sites are also known to contain fractures, and hence they fail to contain contaminants. Many of these waste disposal sites are known to be leaking and causing groundwater contamination. Therefore, before using clays at waste disposal/storage facilities, or undertaking land-use practices that require a barrier to groundwater contamination, we must fully characterize clays at depth to determine if fractures exist.

## **Pathogens in Groundwater**

### Background

Bacteria are not the only organism that can contaminate groundwater. Those that pose a threat to human health are collectively known as pathogens, and include bacteria, viruses and protozoa. Pathogens are the most prevalent contaminant in water causing illness. In the past there has been little public concern about pathogens in drinking water utilizing a groundwater source because very few municipalities have been affected by pathogens.

### Issue

Little is known about the transport and persistence of pathogens in the subsurface. Most studies have focused on bacteria, and very few have investigated transport and fate of viruses and protozoa. The behaviour of viruses and protozoa in groundwater is very different from bacteria.

### What we know

The size of the aquifer pore space act to filter the pathogens. The pore spaces of fine silt and clay ( $<0.3\ \mu\text{m}$ ) will not permit the movement of bacteria ( $1 - 5\ \mu\text{m}$ ) or protozoa ( $4 - 14\ \mu\text{m}$ ), but will permit the movement of some viruses ( $0.02 - 0.9\ \mu\text{m}$ ). Pore spaces in sand ( $5\ \mu\text{m}$ ) will permit movement of some bacteria and viruses. The pore spaces in gravel ( $>100\ \mu\text{m}$ ) and aperture spacing in fractures ( $>10\ \mu\text{m}$ ) could easily permit the movement of most pathogens. Widespread contamination of groundwater by pathogens leaching through clayey and silty soil is rare.

Pathogens will be carried by moving groundwater. Hence, the higher the groundwater velocity (e.g., gravel, fractures, close to a pumping well), the faster the pathogen transport. But pathogens favour attachment onto the aquifer material rather than freely moving with groundwater flow. This limits their extent and rate of spreading and lowers their concentrations in groundwater. Only under very favourable conditions will pathogens migrate over large distances (10s to 100s of metres). Also, cooler groundwater temperatures favour the survivability of pathogens.

The primary source of bacteria contaminating groundwater is fecal waste and waste systems (manure, biosolids, septic systems). The pathways for pathogens to enter groundwater include leaching through the soil to the water table with infiltration, direct flow through fractures from surface to the water table in bedrock or till, as contaminated runoff entering poorly constructed or maintained wells and unplugged boreholes, or via direct transport from subsurface wastewater disposal sites to wells. Groundwater supplies at risk from contamination from pathogens are those relying on (1) shallow wells, (2) improperly constructed wells, (3) wells completed in aquifers under the direct influence of surface water, and (4) wells improperly maintained.

### What we do not know

We know that many wells are contaminated by bacteria, but we do not know what type of bacteria. We also do not know much about viruses and protozoa in wells. It is not known how many wells are contaminated by bacteria actually moving from the aquifer into the well, versus contamination by bacterial sources originating in the well itself.

It is very difficult to relate laboratory results to actual field conditions because the physical,

chemical and biological complexity in the real world cannot be fully duplicated by a laboratory test. There have been few controlled field studies to investigate how a pathogen moves through groundwater systems and how long it survives. Hence, we do not have a good understanding of pathogen transport and survivability in aquifers and wells, especially with respect to viruses and protozoa. Research may require the development of new tools and techniques for sampling, detecting and characterizing pathogens for which no standard tests are currently conducted.

There are no widely accepted or comprehensive computer simulation models for the transport and fate of pathogens in groundwater that would allow us to accurately predict and assess the transport and fate of a variety of pathogens under a range of field conditions.

#### Policy Perspective

The threat to rural groundwater supplies will increase in the future as the sources of pathogens increase. Because pathogens generally do not travel large distances through fine grained sediments (clay, silt, sand) protection of water supplies should focus on (1) well construction and (2) waste management practices. Policy must support the development and enforcement of a multi-barrier approach for protecting rural groundwater supplies from pathogens that includes addressing (1) waste-management procedures, (2) improved water-quality guidelines, (3) aquifer sensitivity analyses, (4) regulations for septic systems and set-back distances, (5) source-water monitoring, (6) groundwater quality/well testing, and (7) minimum well construction and maintenance standards.

Current water-quality regulations and guidelines are based only on coliform bacteria. Not all bacteria behave the same, and viruses and protozoa have much longer survival rates. Studies have shown that viruses and bacteria have different transport characteristics; at some field sites, viruses are transported farther than bacteria, and at other sites bacteria are transported farther than viruses. Therefore, water-quality guidelines and regulations based only on coliform bacteria are inadequate for the protection of drinking water from viruses and protozoa.

Water-quality regulations and testing frequency for wells are focused on municipal systems; no similar regulations for water-quality testing of individual wells exist. Groundwater that contains contaminants at levels above CDWG that are not acceptable from municipal systems is frequently being used as drinking water from individual wells in rural areas. Policy is needed to address water-quality guidelines, groundwater testing, and regulations on minimum well construction and maintenance for individual rural wells.

### **Agricultural Impacts on Groundwater**

#### Background

Many agricultural activities can have impacts on both groundwater quantity and groundwater quality that will, in turn, affect the viability of agricultural activities. Agricultural growers and producers tend to be sensitive to groundwater quantity and quality issues, and will be the first to feel the impact of changes to groundwater quality due to contamination for several reasons. First, most depend on groundwater of good quality for livestock watering and irrigation. Second,

approximately 90% of Canada's rural residents rely on groundwater for their domestic needs. Third, they are responsible for their own water needs because they maintain their own wells.

#### Issue

Contamination of groundwater and wells due to agricultural activities is common in all agricultural regions of Canada. Across Canada, analyses of groundwater from rural wells commonly exhibit one or more of the contaminants nitrate, bacteria and/or pesticides.

#### What we know

The types of groundwater contaminants from agricultural activities can be divided into three main categories: nitrate, bacteria, and pesticides. Nitrogen is added to soil to sustain crop production. Nitrate concentrations above CDWG are common across Canada; surveys indicate that about one third of wells in agricultural areas contain nitrate concentrations which exceed CDWG. But these surveys show that there is little change in the frequency in the number of wells exhibiting nitrate contamination over time.

Pesticides (both single and multiple) are occasionally detected in groundwater and wells in areas of local use, but rarely at levels near or above CDWG. The pesticides detected generally reflect local use, and thus detections and concentrations are highly variable from region to region. Most high concentrations in groundwater are due to improper disposal, cleaning equipment, spills, etc.

The primary sources of bacteria in groundwater in agricultural regions are manure spreading on fields, runoff from waste disposal sites, and septic systems. Given the characteristics of bacteria, it is not likely that widespread bacterial contamination of an aquifer by bacteria leaching from the surface will occur. It is more likely that bacterial contamination of wells is due surface runoff entering wells that are improperly constructed, poorly maintained, or inappropriately located, than from bacterial contaminated groundwater moving from an aquifer into the well. Well surveys show the frequency of wells with bacteria has increased between 1954 and 1992. However, there is no direct link between groundwater/well contamination by bacteria and specific agricultural practices.

#### What we do not know

Our knowledge about contaminants and their transport and persistence in groundwater is based on research that is focused very narrowly on site or field scale studies. Research is required on a large regional or watershed scale, and needs to integrate relationship among watershed characteristics, surface hydrology, groundwater, meteorology, soil properties, farm management practices, etc. Included should be studies to assess the discharge of contaminated groundwater into streams and wetlands adjacent to agricultural land.

CDWG focus on a single pesticide; we do not know the toxic effects for multiple pesticides. In fact for some pesticides there are no CDWG. Also, we do not know how safe long-term exposure to nitrate or pesticide concentrations below CDWG. We know that many wells are contaminated by bacteria, but we do not know what type of bacteria. We also do not know if rural families that have long-term exposure to pathogenic bacteria are more likely to be resistant to these bacteria than those not frequently exposed. We need more research into the survivability of bacteria in



groundwater and wells, and develop strategies to prevent their survival. Research into farm practices that could reduce or prevent groundwater contamination (e.g., the maximum environmentally sustainable input of nitrate to groundwater in agricultural areas) is needed.

A major concern is that the livestock industry is shifting from small livestock farms or mixed livestock-crop farms to intensive operations. For example, in Ontario the number of registered hog producers dropped from 20,000 in 1980 to 4,200 in 2002, but the total number of hogs produced has actually increased by approximately 5%. The impact on groundwater of potentially larger loads of contaminants within a smaller area and the distance these contaminants will travel are not known. Of particular concern is the spreading of manure in sensitive groundwater recharge areas, near surface waters, and near operational or abandoned wells.

#### Policy Perspective

Generally we have sufficient knowledge to define agricultural best management practices relating to soil conservation practices, waste management procedures, and pesticide/fertilizer applications that could prevent future groundwater contamination. Our level of knowledge about the types of contamination, their source, their transport and persistence in groundwater is good.

As the agricultural industry continues to move towards more intensive livestock operations, the potential for groundwater contamination will increase from increased production of substances that we know about (e.g., nitrate, bacteria) and those we do not know about (e.g., pharmaceuticals, viruses). All growers and producers (both small operators and intensive livestock operations) should be required to complete and follow an Environmental Farm Plan. All wells should be tested regularly for nitrates, bacteria and pesticides.

In some jurisdictions, regulations permit the burial of animal by-products from abattoirs in rural areas with no consideration of potential groundwater contamination, especially local wells. For example, in Ontario, the only restriction is that the waste must be covered with at least two feet of soil; there is no restrictions on the soil texture of the disposal pit or even if the water table is intersected at the base of the pit. Because of the volume of material (10s of tonnes per week), and the potentially hazardous nature and associated threat to human and livestock health of some of these animal by-products (including blood, brains and spinal column, burial, disposal practices should be restricted to incineration, composting, rendering plants, or disposal at proper landfills. Burial in an abattoir's backyard or in a shallow pit within a rural area should be banned.

There are regulations governing water-quality standards and frequency of testing for municipal water treatment systems. However, no similar regulations for individual wells exist. Groundwater having poor quality and contaminant levels above CDWG that would not be acceptable for municipal systems is frequently used as drinking water from individual wells. Policy is needed to address water quality guidelines, to improve testing protocols for groundwater, and to develop regulations on minimum well construction and maintenance for individual rural wells.

## **Rural and Municipal Issues**

### Background

Non-agricultural residents and activities dependent on groundwater include single-owners, small subdivisions, municipalities (from villages to large cities), and recreational areas (seasonal residences, campgrounds, parks, resorts, etc.). Urban expansion into traditional rural and agricultural areas presents a threat to groundwater quality for both rural and urban residents, from activities such as landfills, existing/abandoned industrial sites, sand/gravel pits, fuel storage/retail sites, lawn chemicals, deicing salts on roads, cemeteries, residential septic systems, and land spreading of municipal sludge. Also, municipalities that depend on groundwater tend to locate their groundwater well field in rural areas away from possible urban sources of groundwater contaminants. In many cases, urban development has expanded into these well fields, thus introducing urban sources of groundwater contaminants not prevalent in rural settings.

### Issues

An increasing non-agricultural population not only depends on groundwater as a reliable source of good quality water, but also may impact on groundwater quality. Competition for groundwater resources (e.g., farm wells vs. municipal wells) and the resulting detrimental impact on groundwater quality (pesticides in municipal wells and road salt in farm wells) will increase.

### What we know

Urban development throughout Canada is expanding rapidly into areas that have been traditionally rural or agricultural. The areas most at risk are where significant urban growth is occurring, and where municipalities rely on groundwater as their primary supply source of drinking water. For municipalities dependent on groundwater as their source of water, expansion into areas occupied by their municipal well fields has impaired groundwater quality as new sources of urban contaminants (road salt, industry, etc.) develop over well fields. The solution is either to switch to an expensive surface water system such as constructing costly pipelines to bring water from a large lake or river, impose wellfield protection programs, or move the well field further into rural areas which may be susceptible to agricultural contaminants.

Urban development is accompanied by increased volumes of municipal and industrial waste that is typically disposed in rural areas. Abandoned and unknown landfills and hazardous waste sites present a threat to groundwater quality for both urban and rural residents. For example, locating supply wells (both individual and municipal wells) near unknown waste disposal sites. Disposal of increased volumes of municipal biosolids by spreading over the surface of agricultural lands, may result in deterioration in the quality of groundwater and surface water.

Agricultural activities may impact on municipal water supplies. Manure or pesticide spreading is especially a problem if undertaken close to an improperly constructed or inappropriately located municipal well field. Spreading of manure has been documented to impact municipal supplies.

The proportion of urban areas that is impermeable and a dense network of storm drains reduce or prevent groundwater recharge to underlying aquifers. This causes dramatic reductions in natural

replenishment of aquifers (less groundwater for supply wells), reductions in replenishment of streams as groundwater baseflow, and a decrease in groundwater and stream water quality. Such problems in the Oak Ridges Moraine area north of Toronto has resulted in restriction on development to protect groundwater and surface water recharge areas.

Wellfield protection program objectives are achieved through both an integrated watershed management approach, and coordination of scientific knowledge, planning, assessment, public information programs, and enforcement. A variety of monitoring networks to aid in assessment and planning are being implemented. Various activities within a well field protection area are controlled within a series of zones surrounding a well or well field. The aerial extent of each zone is defined by the capture area for wells being pumped, reflecting that different contaminants persist, travel, and pose risks differently (e.g., petroleum products, bacteria, road salt).

Watershed-scale investigative approaches and advanced modelling tools have improved our assessment of risks to groundwater quality in both rural and urban environments. Our increased understanding of the transport and persistence of many critical contaminant species in the groundwater environment has improved our ability to predict the fate of these contaminants, their potential impact on groundwater supplies, and means to mitigate the problem.

#### What we do not know

Better land-use management practices and zoning policies will reduce threats to groundwater quality. But more research is needed to define accurately the area that requires protection. Better assessment techniques and models are required to assess integrated groundwater-surface water-land-use practice relationships at a regional or watershed scale.

Although it is widely suspected that improperly abandoned wells (wells not plugged) offer a pathway for contaminants to enter aquifers utilized by both rural and municipal wells, there is very little scientific evidence to support or disprove this concern, let alone assess the extent of the threat posed by the numerous improperly abandoned wells in Canada. A major problem in addressing this concern is that we do not know the location of most abandoned wells. There are probably over 100,000 abandoned wells in Ontario alone, and most were never properly sealed.

#### Policy Perspective

Essentially all municipalities dependent on groundwater have adopted a policy of complete dependence on the treatment of groundwater at the wellhead. This provides no protection from contaminants that are not routinely tested or as yet unknown, or that are not removed through treatment systems. Source protection must be adopted as a critical element in long-term groundwater management strategies for both municipalities and rural residents. Management strategies, such as those in N.B. and N.S., that include both wellhead protection and modification to land-use practices have had proven results in protecting groundwater quality.

Land-management practices and regulations have to be adapted to encompass urban, rural, and agricultural activities, and developed in consultation with all residents, stakeholders, researchers, and government agencies. These land-use practices, including (1) wellhead protection areas, (2) source (recharge) zone protection, (3) best management practices, and (4) zoning restrictions,

must be adopted on a regional or watershed scale in order to be effective. Long-term groundwater management requires consideration of evolving land use practices and water requirements in both rural and urban settings. Implementing these practices may require a philosophical change within municipalities and local governments with respect to how they view development: put the protection of well fields and recharge areas ahead of the economic value of land development.

Placement, construction and especially abandonment of wells need to be directed through clear regulations and inspection. Typically in Canada, wells are registered when drilled but are not registered when abandoned. We will not realize that contaminants are entering an aquifer via an improperly abandoned well until a local source well is contaminated or health problem emerges.

## **Mining and Metals**

### Background

Metal mining has traditionally been a major resource industry in Canada. Although the number of active metal mines has remained essentially the same during the past decade, there has been a trend toward larger mines that produce more waste. The mining and metal processing industry has produced an estimated 350 million tonnes of waste rock during the mining operation, 510 million tonnes of sulfide tailings during the ore processing stage, and 55 million tonnes of waste during the smelting and metal finishing. Typically groundwater contaminants from mine site wastes include metals (iron, nickel, zinc, copper), sulfates and acid generation.

### Issue

There are probably over 10,000 abandoned mines across Canada. The waste rock and tailings at these sites can introduce high levels of sulfate, metals and acid contamination into groundwater. Unless waste sites are protected from oxidation and metal release, they represent a source of serious contamination to groundwater and aquatic ecosystems for 100s to 1000s of years.

### What we know

The processes controlling the release of metals into groundwater and the generation of acidic groundwater within mine wastes are well known. Mine waste (waste rock and tailings) at some sites is expected to generate very high concentrations of dissolved metals (iron, copper, arsenic, etc.) and sulfate in groundwater that are several orders of magnitude above CDWG, and can make groundwater very acidic. Because of the slow rate of oxidation and slow rate of groundwater flow, the waste sites can be a source of groundwater contamination for decades to hundreds of years, and in some extreme cases thousands of years after the mine has closed. Contaminants can travel via groundwater flow hundreds of metres from a mine waste site. Contaminated groundwater typically discharges to surface water (streams, rivers, lakes and wetlands) causing very long-term environmental degradation.

The design of many mine disposal sites is determined by geotechnical factors rather than groundwater quality issues. Therefore, waste rock piles need to have engineered closure of the waste in order to prevent the migration of the contaminants from the waste into the groundwater flow regime. Effluent that exceeds water quality guidelines emanating from these waste sites must be collected and treated. The conventional practice of placing vegetation on top of tailings

does not prevent sulfate oxidation, and hence, will not reduce the release of metals and acidity to groundwater. Barriers that prevent oxygen from entering tailings must be installed over the tailings shortly after deposition to prevent the oxidation reactions. About 10 to 15 years after the deposition of the tailings, treatment systems should be installed to address the water moving into and through the tailings because of its high levels of sulfate, metals and acidity.

#### What we do not know

Although we have considerable knowledge about the processes that lead to generation of metals and acidic conditions in groundwater from mine waste, we know much less about the processes that neutralize this acidity and stop (attenuate) metals from being released into groundwater. Cost effective technologies are required to prevent the oxidation and release of metals and acidity to groundwater. Our knowledge of the flow of water through tailings and the geochemistry of tailings is better than our understanding of flow through waste rock and metallurgical waste.

Treatment technologies are currently available including both conventional collection and treatment of contaminated water. However, these are expensive and potentially ineffective. Innovative technologies are currently being developed and assessed, such as passive in-situ treatment systems (permeable reaction barriers). Further support and research are required to develop cost effective technologies to treat mine waste effluent, including acid neutralization.

Laboratory tests provide insight into the processes occurring at a waste site and can be used to predict levels of contaminants entering the groundwater flow system. However, because there is no widely accepted method of scaling from small-scale laboratory tests to full-scale site behaviour, there is a problem with applying the results. At the same time, long-term predictive models for contaminant release need to be developed to provide insight into contamination problems at a mine site and to assess potential remedial technologies.

#### Policy Perspective

Some federal and provincial guidelines relating to mine wastes from active mines have recently been revised and this should lead to better protection of groundwater quality. Guidelines should also be revised in other jurisdictions. Installation of monitoring wells to detect groundwater quality problems should be a routine component of guidelines and waste management strategies for active mines. Guidelines are also required for the selection of appropriate remedial technologies where groundwater has become contaminated at abandoned mines.

Because of the large number of active and abandoned mine sites throughout Canada, and the large volume of mine waste at each site, reclamation costs are expected to be tremendous. The reclamation cost for the active mine sites in Canada is estimated to be \$3 - \$5 billion alone. The estimated cost for all the abandoned sites is unknown. However, estimated costs of some abandoned mines currently being reclaimed are as high as \$200 million for a single site. It is recommended that during the operation period, government require that the mining companies set realistic bonds for funds to be used to cover the costs of the closure of the mine site and the potential long-term problems that may occur after the site has been abandoned; current bonds (where required) only cover a fraction of the actual costs.

## LNAPL and DNAPL Spills

### Background

Groundwater contamination by Non-Aqueous-Phase-Liquids (NAPLs) has been a major concern throughout the world because of their widespread production and use, and because they pose a significant risk to human health at very low concentrations. There are numerous sites throughout Canada where NAPL spills have contaminated groundwater. Most sites are quite small, such as a gasoline station or a dry cleaning store. Other sites are larger, such as a petroleum refinery, chemical plant, wood-preserving plant, waste disposal facility, and an industrial site. Some contaminated sites, such as False Creek site in Vancouver in B.C., the waste disposal site at Ville Mercier in Quebec, the former CWML site at Smithville in Ontario, and the Sydney Coke Oven and Tar Ponds at Sydney in Nova Scotia, have caused such severe contamination of groundwater supply for numerous people, that they have attained widespread media and public attention through Canada.

### Issue

NAPLs pose a long-term and serious threat to groundwater because they are difficult to detect, difficult to remove, take 10s to 100s of years to dissolve, and they pose a significant risk to human health at extremely low concentrations. Because of the potential health threats from drinking groundwater contaminated with NAPLs, it is imperative that groundwater be protected from NAPLs and if contaminated, the groundwater be remediated.

### What we know

Based on the history of chemical use, we can anticipate the presence of NAPLs. For example, trichlorethene (TCE) is typically found near dry-cleaning facilities, and benzene is common at gas stations. However, in most cases the exact location of the NAPL source may be difficult to find. Analysis and delineation of the dissolved chemical plume can be used to aid in locating the NAPL. LNAPLs are easier to find because they float on the water table and are not as deep. DNAPLs, on the other hand, sink further into the subsurface, making their detection more difficult. Even without knowledge of the source, a key issue is the control of the dissolved plume.

The technologies for controlling the dissolved plume are at various stages of development. These technologies available for this task include: pump and treat, in-situ permeable reactive barriers, and natural attenuation. Of these three technologies, the second and third options are still in the developmental stage. For LNAPLs, because the contamination tends to be shallower, remediation of both the source and dissolved contaminant plume is a reasonable goal. For DNAPLs, complete remediation of both the DNAPL source and the dissolved contaminant plume seems remote at most sites. It is difficult to impossible to locate precisely the DNAPL source due to the fact that DNAPLs penetrate deeper into the subsurface, and move and spread through a heterogeneous and fractured subsurface environment. Thus, although excavation of shallow soil contaminated with DNAPL is often practical, excavation of deep sources of DNAPL is not practical. Moreover, research in DNAPL remediation is still in its early stages.

We know concentrations of dissolved NAPLs are generally very low, However, because CDWG for most of these NAPLs are very low, even small concentrations of NAPLs in groundwater can

pose a threat to human health if contaminated groundwater is used as a source of drinking water. Even if the NAPL source is very small, because of the slow dissolution it can cause widespread contamination at levels above CDWG for many years or decades.

#### What we do not know

We do not have the technology or field methods to precisely find NAPLs in the subsurface. With respect to DNAPLs, the extent to which DNAPLs can penetrate downward into an aquifer and how natural heterogeneities and fractures determine the direction of movement and spreading are not well known. Drilling and sampling programs generally miss the pure-phase NAPL because the NAPL can be confined to a small area, often less than 1 m<sup>3</sup>. With DNAPLs, even if the source is located, it will be nearly impossible to remove all of the DNAPL because we lack cost-effective and practical DNAPL removal or in-situ destructive technologies.

In addition to this, we frequently do not know the composition of the NAPL that has spilled or leaked. Thus, making it difficult to know what to look for, or to know where to look, or to know if remediation has removed all of the contaminants. For example, gasoline may contain other chemicals, such as MTBE. In this case, the various components (e.g., MTBE and benzene) will move at different rates, and undergo natural degradation at different rates. Remediation of the BTEX components of gasoline will not include MTBE.

#### Policy Perspective

Dealing with both regulatory and remediation issues with respect to DNAPLs is a priority and must advance together. Technology to remove/destroy DNAPLs is advancing without a clear understanding of what remedial goals must be met. Although there are gaps between our current level of scientific knowledge and its application to regulations and policy, there are many areas where scientists and regulatory/policy personnel are basically asking the same questions: How much DNAPL must be found and remediated? If we cannot find the source, should we spend enormous funds to try to remediate the aquifer? How will policy and regulatory personnel balance the costs, long-term commitments, and potential risks or lack of risk to human health? If all contaminants at a site can be removed will anyone ever drink this groundwater? Regulators, policy people, industry and researchers should be brought into partnership to evaluate and demonstrate remediation technologies, outcomes, costs and policy implications at a few controlled field sites. Policy personnel should be involved in the validation and demonstration of emerging technologies for NAPL remediation.

Regulatory and policy personnel must also be aware of both the technical limitations to cleaning a site and the potentially enormous costs involved in detection, remediation and monitoring. For example, the costs of remediation at Ville Mercier in Quebec, Sydney in Nova Scotia, and Smithville in Ontario could be as high as \$30,000,000 to \$700,000,000 each. In some cases it may be impossible to find the source of the NAPL, especially if the source is very small, and thus it will never be possible to completely remediate the site even if millions of dollars are spent. While regulatory agencies are correct to place emphasis on planning and prevention of pollution, there still needs to be policies in place to ensure responsible parties clean up contaminated groundwater.

## **Petroleum Industry Issues**

### Background

The threat to groundwater quality from all aspects of petroleum industry (exploration, field production, storage, transportation, and refining/petrochemical production) represents a major challenge to governments and industry. Oil and gas exploratory boreholes and production wells are drilled through aquifers used as a source of water for rural residents, municipalities, irrigation, and livestock. Drilling and petroleum processing produce liquid wastes. Pipelines that transport brine, or oil and gas from production wells to storage facilities to refineries, are buried above rural groundwater sources. Contaminants produced in the petroleum industry that pose a threat to groundwater quality include: hydrocarbons, saline formation water, and metals.

### Issue

The greatest threat to groundwater quality from the petroleum industry stems from over 100 years of (1) exploration, development, and refining (improperly abandoned boreholes; drilling sumps; flare-pits; spills), (2) less stringent environmental standards of past times, and (3) aging field facilities (production and disposal well seals, plugs, and casing; pumps; pipelines; storage tanks).

### What we know

Abandoned oil and gas wells, injection wells, and exploration boreholes may act as a pathway for contaminant (oil, gas, saline water) migration from depth to aquifers near surface. The number of abandoned wells and boreholes in producing regions across Canada is immense. It is estimated that there are over 600,000 abandoned oil and gas wells in Alberta alone. If the concrete seal and the steel casing remains intact, there will be little possibility of contamination of shallow aquifers. However, many these wells were abandoned 50-100 years ago, under old (or no) regulations and old technical expertise. Thus, there is concern about the long-term viability of concrete seals within casing and integrity of steel casing to corrosion in old wells.

Oil and gas production from conventional fields, oils sands, and in-situ thermal recovery, typically produces brine that must be disposed through deep disposal wells. Also, the refinery and petrochemical industry produces liquid hazardous wastes that are often disposed by injection through deep wells. Because the formations into which the brine and liquid wastes are disposed are former oil or gas production formations, these are known to have been isolated from overlying formations for millions of years. However, contamination of shallow aquifers may occur if the integrity of casing in the disposal well fails due to corrosion, if the space between the side of the borehole and the casing is not sealed, or if a shallow disposal depth is hydraulically connected to shallow aquifers. Disposal wells in Alberta are very deep (>600 m) and there are no reported instances of a disposed fluid coming up a well. In Lambton County in Ontario, the shallow disposal depth (<300 m) combined with the upward migration of wastes through improperly abandoned petroleum and groundwater wells, caused the contamination of shallow aquifers and the St. Clair River from disposed refinery wastes during the 1960s and 1970s.

A common source of shallow groundwater contamination is accidental spills of brine through leaking pipelines. Accidental hydrocarbon releases can occur from spills during transportation, pipe breaks, leaking storage tanks, flare-pits, and blow-outs. Because these spills are generally



very localized and at surface, they are amenable to remediation by current techniques.

#### What we do not know

We do not know the long-term integrity of pipelines, exploration borehole seals, and abandoned well cement plugs and steel casing. We also do not know the impact or the scale of groundwater contamination should wells in an old field start failing. Contamination by spills of hydrocarbons or brines around legacy oil and gas sites rely on natural attenuation to remediate the sites. We do not know if this strategy is reasonable, or if more aggressive and, hence, very costly remediation techniques should be used. Low-cost bioremediation of petroleum-contaminated and salt-contaminated soil and groundwater in Canadian environments is needed. We need to determine if in-situ thermal projects, such as the steam injection for enhanced recovery of heavy oil, are mobilizing naturally occurring contaminants (e.g., arsenic) and fracturing and, hence, comprising the integrity of overlying confining layers. More research is needed to characterize the hydrologic connection between disposal formations and shallow aquifers/surface water.

#### Policy Perspective

Recognition that little is known about the long-term integrity of concrete seals and steel casing in the hundreds of thousands of abandoned wells across Canada is required. Given that oil and gas production cover very large areas, groundwater contamination may occur at a watershed or regional scale. There is a need for ongoing government-supported surveys of baseline groundwater quality in areas of future exploration and development, as well as ongoing supported monitoring of groundwater quality. Without adequate baseline groundwater knowledge we may not know if energy development is affecting groundwater quality on a regional scale.

Reliance on natural attenuation or current technologies for remediating contaminated sites may not be effective in all Canadian environments, including alpine, boreal forest, permafrost, and tundra. More research on low-cost in-situ (underground) and surface bioremediation techniques is needed. Because of the number and age of localized types of impacts, industry and government should adopt various risk-based methodologies to prioritize sites for active versus passive groundwater remediation. Funds should also be set aside to remediate orphan sites.

#### Risk Assessment

##### Background

Computer models are widely used by the hydrogeological and regulatory communities to simulate groundwater flow and contaminant transport. Computer models are commonly used for, and expected to, provide accurate information about future events. For example, will the contaminant reach a local water-supply well, and if so, how long will it take? The major challenges in constructing accurate models are (1) the real world is too complex for us to simulate every aspect or every detail, (2) typical groundwater and contamination studies have far fewer measurements in time and space than one would expect given the complexity of hydrogeological environments, and (3) how to estimate the values of the parameters and boundary conditions required by the model. All together these factors lead to considerable interpretation, and thus considerable risk of errors and uncertainties in model predictions

### Issue

Computer models that simulate groundwater flow and contaminant transport are subject to considerable uncertainty in their predictions because of the inherent uncertainty in the parameters input into the model. However, this uncertainty can be accommodated within the decision making process through risk assessment.

### What we know

Hydrogeological environments and contaminant sources exhibit considerable variability. In addition to this, we also acknowledge that we will never be able to undertake field studies that can fully characterize a site. This uncertainty in natural systems is transferred to models and thus their predictions. Also, with the advancement of computer technology, there has been emphasis on development and use of more complex computer models to attempt to capture more details of the hydrogeological environment and processes. As computer models become more complex, the number of input parameters required by the model will increase. Subsequently, the degree of uncertainty in the prediction of these more complex models will also increase. Although computer models have increased in complexity, they, for the most part, do not include quantitative determination of prediction uncertainty.

Currently this uncertainty from a computer modelling perspective, is handled through several methods. The first technique is to pretend that uncertainty does not exist because we are able to characterize everything that needs to be characterized; this technique is no longer acceptable. The second technique involves a single prediction with a conservative bias in order to err on the side of safety. A third technique involves two simulations – one based on a “probable worst-case scenario,” and a second based on “best engineering judgement”. In an environmental assessment, the policy issue is how to decide which results are correct.

Uncertainty analysis offers a means to quantify the probability of error in a computer simulation or prediction due to these uncertainties. We have seen significant advances in the conceptual framework for evaluating this prediction uncertainty and incorporating this measure within the decision-making process (risk assessment). Quantitative mathematical methods are now available for undertaking uncertainty analysis within hydrogeological simulations. These uncertainty-analysis tools are being used by groundwater scientists, but currently see limited use in the decision-making process (e.g., regulatory environment). We also know that uncertainties in prediction are not fixed in time but change as models are improved, more data are obtained, and knowledge and experience improve.

### What we do not know

We can quantify uncertainty in a computer model prediction with respect to uncertainty in characterizing a hydrogeological site. However, we do not know how many data are actually required to adequately characterize a site in order to reduce uncertainty to an acceptable level. Obtaining more data will cost more, but at some point, these additional data will no longer reduce the uncertainty. For example, do we need 10 or 100 or 1,000 measurements of K at a site? We know that uncertainty in characterizing a site will lead to uncertainty in a model prediction. But we do not know the degree to which uncertainty of a model prediction is associated with the model itself. For example, how much error is there in the selection of a 2-D versus a 3-D model

for the site? What is the error in selecting an inappropriate contaminant source? Quantitative tools are available to undertake uncertainty analysis, but these tools are not in a user-friendly form that would allow the regulatory community to make widespread use of them.

### Policy Perspectives

Computer models are valuable tools to study groundwater quality issues. However, model predictions often have a high degree of uncertainty associated with them. The present level of knowledge is such that we can evaluate predictions based on uncertainty in our characterization of a site, and can incorporate this knowledge into groundwater quality modelling. However, these techniques have been applied in only a limited number of cases. Because uncertainty analysis offers an invaluable tool to quantify error and uncertainty, this type of analysis should be adopted by those involved in decision-making and policy with respect to groundwater quality.

Uncertainty analysis with respect to parameter characterization and model error should be encouraged. In practice, building ever more complex models to represent hydrogeological processes is given greater emphasis than the quantitative determination of prediction uncertainty. Where it is feasible, computer modelling should move beyond deterministic calculations adopting a conservative bias, sensitivity studies, or worst-case evaluation. Regulators can encourage project proponents to adopt methods of estimating prediction uncertainties on a more frequent basis when groundwater models are used as tools for managing and protecting groundwater systems. This may involve trade-offs with model complexity.

## **Rural Well-Water Quality in Canada**

### Background

Although, a national perspective on groundwater quality from rural wells has not been undertaken, a compilation of numerous provinces surveys provides a nation-wide perspective. Groundwater analyses from these rural well surveys have focused on three contaminants most prevalent in rural/agricultural areas: nitrates, bacteria and pesticides. However, results from well surveys reflect contamination in wells and not necessarily contamination in aquifers.

### Issue

Numerous surveys of well water quality throughout Canada consistently show that bacteria and nitrates are the most common contaminants in excess of CDWG (10-40% and 15%, respectively, of all rural wells). Pesticides exceed CDWG in less than 0.5% of rural wells. Industrial chemicals, such as trichloroethylene (TCE), have been identified in about 10% of municipal groundwater supplies, but nearly always at concentrations considerably below those CDWG.

### What we know

Bacteria are the most common contaminant detected in rural wells. Well water quality surveys in Ontario (1208 wells), N.B. (583 wells), and Quebec (150 wells) showed that the percentage of wells with fecal coliform exceeding CDWG was 25%, 4%, and 6-36%, respectively. The second most common contaminant detected in rural wells was nitrate. Surveys show the percentage of wells with nitrate exceeding CDWG was 10% of 240 wells in B.C., 6% of 813 wells in Alberta, 17% of 1484 wells in Saskatchewan, 2-19% of 29-119 wells in Manitoba, 13-14% of 1212 wells

in Ontario, and 15-26% of 296 wells in New Brunswick. Pesticides were detected in relatively few rural wells and rarely exceed CDWG. The percentage of wells with pesticide concentrations exceeding CDWG in Ontario was 0.5% of 1300 wells, Quebec was 4.3% of 70 wells (in an area of intense agriculture), B.C. was 0 of 240 wells, Alberta was 0.4% of 824 wells, and Saskatchewan was 0 of 184 wells. These findings for Canada are similar to those for the United States and other countries, thus lending credence to the results.

Naturally occurring trace minerals such as arsenic and fluoride are also of concern, and are likely to become more important as wells are completed at greater depths to bypass contaminated shallow groundwater. In rural wells, occurrences of industrial chemicals are rare. Municipal wells are more susceptible to contamination by industrial chemicals, such as fuels, dry cleaner fluids, solvents, PCB's etc., because the sources of these contaminants are typically located in urban-industrial areas.

By extrapolation from well water quality surveys, it is estimated that about one million Canadians routinely depend on wells that do not meet water quality guidelines for bacteria, and many others are sporadically exposed to such water. However, there are very little data on documented cases of people drinking well water who show symptoms, and hence most statistics are "estimates" or "extrapolated" cases of illnesses. It is possible that not all illnesses are due to a contaminant source (e.g., manure applied to field), problem with the well (e.g., corroded casing), but illnesses could occur due to problems within the water distribution system and treatment systems (e.g., chlorination, leaking pipelines).

Investigations into the contamination of rural-well water consistently show that contamination is often related to poor well location (too close to manure disposal sites or septic systems), poor well construction (lack of grout, leaking casing), poor maintenance (leaving cap off well), surface runoff to a well, or shallow depth of the well. However, for many cases of well water contamination, the source and pathway of the contamination were not obvious.

#### What we do not know

It is not clear how much of the microbiological contamination of well water reflects contamination of the *in-situ* groundwater and how much is related to the wells themselves. We do not know whether nitrate contamination is increasing in extent and depth of penetration. We do not know how appropriate and effective source area protection measures are for preventing well water contamination by pathogens, nitrate and other contaminants. In Canada there are few documented cases of discharge of contaminated groundwater having a significant impact on surface water and aquatic ecology. A nation-wide review of such impacts is needed because we do not know the extent of such impacts and how they can best be prevented. We do not have a national survey of the extent of groundwater quality and well water contamination in Canada. In fact, we do not even have a good up-to-date assessment of groundwater usage in Canada. The last national assessment of groundwater usage was undertaken in 1981.

#### Policy Perspective

In the context of public health, the widespread contamination of well water by pathogens throughout Canada is a concern. The U.S. is proposing to protect drinking water by assuming that

well water cannot be assumed to be safe; it must be proven to be safe. This is a reverse of current assumptions in Canada and the U.S.; currently we assume groundwater is safe to drink unless proven not to be so. Perhaps this perspective should be adopted in high risk areas in Canada. Existing surveys vary widely in scope, purpose and methodology. For example, because one survey may assess high-risk wells in an area of pesticide use, and another survey may randomly test wells throughout a region, the percentage of pesticide detected in each survey will be different. Also, contamination in a well may not reflect contamination in the adjacent well, but an in well source. When interpreting the result of groundwater-quality surveys, care must be taken to ensure that the objects of the survey are considered when interpreting the data and extrapolating the results to a regional aquifer scale. Numerous well water surveys have been carried out in all parts of Canada. What is needed is a critical review of these surveys, followed by studies of: (a) public health studies related to well water contamination, (b) impact of source-area protection measures, and (c) well placement, construction and abandonment practices.

## LINKING WATER SCIENCE AND POLICY PERSPECTIVES

A number of recurring themes or observations appeared in the area of better linking groundwater quality science with policy development and program management. They included:

### *1. Improving communication between government decision-makers and academia. . .*

In Canada the bulk of the research effort in the groundwater quality area now rests in academia. Academics often feel insulated from the government decision-making process, and conversely, policy and program managers are not getting the latest research results they need to help them make better decisions. Government policy and program managers should become explicitly involved with some research projects to build in policy considerations up front in these projects and direct research funding. It must be noted that to strengthen the link between science and policy, the onus rests not only with researchers, but also with practitioners to more aggressively seeking out the science that would strengthen their agency's management strategies.

### *2. Policy should keep pace with evolving science. . .*

In Canada there appears to be a 10-20 year time lag for much of the groundwater quality research to make its way to decision-makers and into regulations. There is currently sufficient scientific knowledge and technology expertise to make significant improvements to groundwater management, and in fact there was sufficient knowledge to have avoided the tragic events of Walkerton, Ontario. The reality is that the current science is often not considered in the development of public policy

### *3. Expert panels for quick decision-making.*

The need for policies, regulations and programs often happens at a rapid pace and require quickly attainable, up-to-date information, including science. In Canada, there appears to be no existing mechanism to initiate priority groundwater quality research for policy making. In the U.S., the Water Science & Technology Board of the National Research Council frequently uses Blue Ribbon Panels to help fund research towards priority policy development areas. Canada should adopt an expert panel approach akin to the U.S. Blue Ribbon Panels.

*4. Policy and program research needs should be better articulated. . .*

The groundwater quality research community is essentially unaware of what research decision-makers need. Researchers are sufficiently flexible, and keen in fact, to accommodate new policy priorities, but these needs could be more clearly and regularly communicated to them. It must be realized though that it will always be challenging for policy makers to identify research needs precisely in advance. There is a need for a concise, regularly updated compilation of groundwater quality policy and program initiatives across Canada for quick reference, or continued groundwater quality science-policy workshops for the purpose of sharing and learning from previous experience.

*5. The Importance of the multi-barrier approach cannot be overstated. . .*

The need for a multi-barrier approach to protect rural groundwater supplies, and subsequently better manage drinking water systems, developed as a key workshop theme. Specifically, improvements in the following areas were repeatedly outlined: land use and waste management practices; source zone and wellhead protection; monitoring and testing; guidelines, regulations and enforcement; well construction and maintenance; education and training; science to support decision-making; and regional/watershed assessments.

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