Linking Water Science to Policy: Groundwater Quality

A CCME sponsored workshop

March 21 and March 22, 2002

Toronto

CCME Linking Water Science to Policy Workshop Series: Groundwater Quality

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Workshop Context and Overview

The Canadian Council of Ministers of the Environment (CCME) provides a forum for federal, provincial and territorial governments to cooperate on priority environmental issues. Because of concerns about water quality and the value placed on water by Canadians, CCME has made water quality one of its top priorities.

One active CCME initiative is directed at ensuring that CCME members, and policy and decision makers in particular, are up-to-date on the latest science with respect to various water quality issues. CCME also wanted to provide an opportunity for its members to give input to the scientific community on water quality-related research priorities.

CCME identified an initial list of three priority areas for information exchange:

1. water quality impacts of agricultural practices;
2. groundwater quality; and
3. water quality issues related to water reuse and recycling.

It was agreed that Environment Canada's National Water Research Institute (NWRI), on behalf of CCME, would organize a series of workshops where leading scientists would be invited to present the latest science related to the above issues. The targeted audience would include CCME members' representatives, and other federal, provincial and territorial departments, as well as stakeholders. The meetings would be designed to foster a two-way dialogue where policy and program personnel could get the recent science to help them make better decisions, and allow them an opportunity to help shape the research agenda based on their needs and priorities.

This is the report from the second of the workshops, held March 21 and 22, 2002, and co-chaired by NWRI and the British Columbia Ministry of Water, Land and Air Protection. The workshop was attended by about 60 science and policy experts from provincial and federal environment and agriculture departments, other federal departments, universities, and private agencies. A tremendous success, these workshops have set the standard as a ground-breaking enterprise in building a substantive, much-needed and ongoing dialogue between the scientific and policy-making communities.

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We have attempted to capture the salient points of these presentations and the discussion that followed. Any errors or omissions are due to our oversight and not that of the workshop presenters or discussants. The views and opinions expressed in this workshop report are those of the presenters.

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Executive Summary

Introduction

Ten million Canadians rely on groundwater for drinking water. Groundwater also provides vital water supplies for agriculture and major industries involved in manufacturing, mining and petroleum production. Groundwater is an integral component of the hydrologic cycle interacting with streams, lakes, wetlands and supporting their ecosystems. Tragic events involving groundwater quality in Canada have heightened public awareness and concern over the vulnerability of this precious resource. This heightened awareness is challenging our institutions to respond with better and more effective programs and policies to protect groundwater quality, and to ensure we have the science essential to guide these programs.

The Canadian Council of Ministers of the Environment (CCME) is the major inter-governmental forum in Canada for discussion and joint action on environmental issues of national and international concern. In the fall of 2001, in response to concerns about water quality in Canada, CCME initiated a workshop series, *Linking Water Science to Policy*, on priority water quality issues. Organized by Environment Canada's National Water Research Institute with provincial co-chairs, the series communicates the results of new research and management practices to senior decision makers and policy makers, and provides a mechanism for scientists and water managers to contribute expert input to Canadian water programs.

The second workshop in this series - *Groundwater Quality* - was held March 21 and 22, 2002, bringing together about 60 science and policy experts from provincial and federal environment and agriculture departments, other federal departments, universities, and private agencies. Presentations by eminent groundwater scientists, panel discussions, and plenary sessions took place on the state of groundwater quality knowledge, and linking the science with policy. Scientific topics ranged from an overview of groundwater flow and contaminant transport processes to the nature of fractured rock environments, roles of aquitards, impacts of agriculture, petroleum production, municipal, and mining activities on groundwater, pathogens, natural sources of contamination, chemical spills, and aspects of risk assessment and watershed management. This report synthesises the workshop's scientific presentations and ensuing panel discussions on policy and program issues. Related groundwater initiatives, workshop observations on science-policy linkages, and thoughts on maintaining dialogue are also highlighted.

Science Updates and Policy Perspectives

Fractured Rock Environments - There is considerably more variation in the aquifer properties and groundwater flow conditions within fractured rock environments than in porous media. This variation can have a significant impact on migration of chemical and biological contaminants. Bacteria and viruses in particular, can migrate widely and rapidly from relatively small sources. 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. Characterizing contaminant migration frequently requires significantly more resources than equivalent problems in porous media. Plans for wellhead protection and groundwater management zones must incorporate the complexities of the fracture framework.

Natural Groundwater Contamination - Not all substances in groundwater are harmful to human health are man-made substances. Naturally occurring elements and compounds, such as arsenic, fluoride, salinity, are often present in groundwater at concentrations above CCME's Canadian Water Quality Guidelines (CDWG). Various natural processes and human water-use practices can enhance release of these substances into groundwater, and often lead to high concentrations. From a policy perspective, the most important issue is for municipal, provincial and federal government agencies to be pro-active in locations where concentrations of naturally occurring substances are above CDWG. Being pro-active should include obtaining background groundwater quality data prior to groundwater use; implementing regulations that restrict or control well drilling in high risk areas; implementing more rigorous programs for testing rural wells over time; and issuing health advisories.

Clay Barriers - Clays can be an effective barrier to the movement of contaminants from surface into groundwater. Naturally deposited clays at or near ground surface are increasingly being used in groundwater protection programs to justify aquifer and well protection from surface contamination. Man-made clay liners in water disposal/storage areas are used to limit migration of contaminants to groundwater. From a policy perspective, we cannot assume that clays will always be an effective barrier; natural and engineered clay barriers can become fractured and these fractures present pathways for contaminant movement. Fully characterizing clays at depth to determine if fractures exist and will develop over time is critically important.

Pathogens in Groundwater - 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. Improved techniques to identify the source and type of microbiological contamination in well water are needed. Groundwater supplies at most risk from contamination from pathogens are those relying on shallow wells, wells improperly constructed, wells completed in aquifers under the direct influence of surface water, and wells improperly maintained. Pathogens generally do not travel large distances through fine-grained sediments (clay, silt, sand), but can travel considerable distances through fractured rock and gravel. From a policy perspective, protection of water supplies should focus on a multi-barrier approach that includes improved waste management practices, application of effective well construction standards, establishment of set-back distances from sources of pathogens specific to various geological material; and more advanced monitoring techniques.

Agricultural Impacts on Groundwater - Across Canada, analyses of groundwater from rural wells commonly exhibit nitrate, bacteria and/or pesticide contamination. Little is known about the toxic effects of multiple pesticides, or the impact of long-term exposure to concentrations of nitrate or pesticide that are elevated but below CDWG. Because of the regional nature of groundwater contamination from agricultural activities, groundwater protection and research have to be conducted on a large regional or watershed scale. Policy should focus on improving water quality guidelines and testing protocols for individual rural wells; regulations governing water quality standards and frequency of testing are applied only to municipal water treatment systems. Improved agricultural practices, such as developing an environmental farm plan for all large and small operators, are required. Placement, construction, maintenance, and especially abandonment of individual wells can only be controlled through clearer regulations and inspection.

Rural and Municipal Issues - The threat to groundwater quality from urban sources of contamination will increase as urban areas expand into rural areas traditionally serviced by wells. Manure or pesticide spreading on the land surface is particularly a problem if undertaken close to an improperly constructed or inappropriately located municipal well or well field. Pro-active land-use practices and zoning regulations are critical and should include: wellhead protection areas; source (recharge) zone protection; best management practices; and zoning restrictions, all of which should be adopted on a regional or watershed scale to be effective. Research should be directed at improving techniques and models that better integrate groundwater-surface water and land-use linkages at a regional or watershed scale. This research will help to define the size of area requiring protection more accurately.

Spills - Chemical leaks or spills frequently involve organic substances that do not readily dissolve in water (known as Non-Aqueous-Phase-Liquids or NAPLs). Groundwater contamination by these chemicals has garnered considerable attention because, first they pose a significant risk to human health at very low concentrations, and secondly they may be a source of groundwater contamination above CDWG for decades. There are numerous sites throughout Canada where these spills have contaminated groundwater, including gasoline stations, dry cleaning stores, petroleum refineries, chemical plants, wood-preserving plants, waste disposal facilities, and industrial sites. Regulatory and remediation issues with respect to these substances must advance together. Technology to remove/destroy some of these substances is advancing without a clear understanding of what remedial goals are to be met. Regulatory and policy personnel must be aware of both the technical limitations of cleaning a site and the potentially enormous costs involved in detection, remediation and monitoring. Polices are needed to determine who pays the cost of remediation, especially at abandoned sites, and to force the responsible party to clean up the site.

Mining Industry Issues - There are over 90 active metal mines and over 10,000 abandoned mines across Canada. The waste rock and tailings at these sites can introduce into groundwater, high concentrations of acid, sulfate and metals several orders of magnitude above CDWG. The waste sites can be a source of groundwater contamination for 10s to 1000s of years. The processes controlling release of metals into groundwater and generation of acidic groundwater within mine wastes are well known and sufficient to assess adequately the impact of mining on groundwater quality. We know much less about the processes that neutralize this acidity and attenuate metals in groundwater. In general, little is known about existing and potential groundwater quality problems at abandoned mine sites across Canada. Guidelines should be revised to ensure that groundwater quality is protected in the vicinity of mines. Installation of monitoring wells to detect groundwater quality problems should be a routine component of waste management strategies for active mines. Guidelines are also required for abandoned mines, especially in the selection of appropriate groundwater remedial technologies.

Petroleum Industry Issues - The greatest threat to groundwater quality from the petroleum industry stems from the legacy of over a century of exploration, development, and refining (improperly abandoned exploration boreholes, drilling sumps, flare-pits and spills), less stringent environmental standards of the past, and aging facilities (production and disposal well seals, plugs, and casing, pumps, pipelines, storage tanks). As an example, little is known about the long-term integrity of concrete seals and steel casing in the hundreds of thousands of abandoned wells across Canada. There is a need for ongoing supported surveys of baseline conditions and ongoing monitoring of groundwater quality in both conventional petroleum producing areas and non-conventional energy developments to ensure that once exploration and development occurs, groundwater quality is not impaired.

Risk Assessment - Computer models that simulate groundwater flow and contaminant transport are invaluable tools to aid in the assessment and protection of groundwater quality. Unfortunately, there is typically considerable uncertainty in the predictions from a computer model because of the inherent uncertainty in the parameters input into the model. In spite of the complexities of computer models, for the most part they do not include a quantitative determination of prediction uncertainty. Uncertainty analysis offers a means to quantify the probability of error in a computer simulation or prediction due to these uncertainties. Although uncertainty analysis is being used by groundwater scientists, it is rarely used in the regulatory decision-making process for risk assessment. Regulatory agencies should require that uncertainty analysis be adopted in the decision-making and policy process with respect to assessment and prediction of groundwater quality.

Rural Well Water Quality in Canada - Numerous surveys of well water quality throughout Canada consistently show that pathogens represent by far the most common well water contaminant. 20% to 40% of all rural wells have coliform bacteria occurrences in excess of CDWG. Nitrate concentrations exceed CDWG in about 15% of rural wells. By contrast, pesticides exceed CDWG in only about 0.1% of rural wells. The suitability and effectiveness of source area protection measures for preventing well water contamination by pathogens, nitrate and other contaminants require more investigation. Surveys show that potentially far more Canadians are at risk from bacteria in wells than from industrial contaminants, yet more resources and attention are given to the latter. Finally, a thorough national review of the results of all existing well water quality of surveys is needed, followed by detailed studies aimed at reducing threats to health due to contaminated well water.

Groundwater-related Initiatives and Perspectives

Canadian Framework for Collaboration on Groundwater - A National Ad-hoc Committee on Groundwater has developed a Framework focused on: acquiring a high standard of groundwater information and knowledge; improving communications and collaboration among all groundwater stakeholders; establishing effective linkages of groundwater information systems; providing a resource base accessible to all levels of government and stakeholders; and fostering national consistency with respect to groundwater standards, guidelines, qualifications of professions and drillers, and training. It is a working document that will help provide access to the current science and technology in support of policy design and regulations.

CCME Canada-wide Water Quality Data Referencing Network - At present, there is no established nation-wide network for water quality monitoring in Canada. Water quality monitoring efforts are often fragmented, monitoring of some key issues and stressors is lacking, and existing distributed programs and their data/information are not synthesized to form integrated regional or national pictures. A CCME Action Plan on Water is building a common vision towards a *network of networks* approach for water quality monitoring in Canada. This network will be an association of distributed water quality monitoring networks and programs, run by multiple jurisdictions and partners, and contributing to a national water quality information database.

Canadian Water Network - The Canadian Water Network's (CWN) mission is to ensure Canada's leadership role in management and sustainable use of water resources, in protection of human and aquatic ecosystem health, and in sustaining economic growth in the water technology and services sector. The principal role of the CWN is to foster an integrated, coherent and national vision for water management and provide the sound research foundation needed to contribute effectively and objectively to national policy deliberations and development of regulations. The Network was formed in November 2001 and includes themes in the areas of wastewater management, safe drinking water, infrastructure, development, groundwater, and governance, among others.

A Municipal Perspective - The Federation of Canadian Municipalities (FCM) created a national policy - water options team to influence federal regulations, budgets (including groundwater), and drinking water quality. Its key focus has been on watershed management. FCM supports delineation of watershed boundaries, as well as identification of land use activities that could affect surface and groundwater quality, to improve risk management strategies. Participation by all levels of government is needed to ensure that infrastructure is adequately funded, national standards for water quality are provided, and operator training is improved. FCM advocates the need to improve land use planning to reduce the negative impact on water quality.

A U.S. Perspective - The objective of the U.S. Water Science and Technology Board (of the NRC) is to improve the scientific and technological basis for resolving important questions and issues associated with the efficient management and use of water resources. The Board frequently uses Blue Ribbon Panels to help bring together top scientists to address timely issues. Main messages include: sound policy development needs high quality science; blue ribbon panels are helpful in solving problems; the "carrot and stick" approach to funding is useful in guiding research towards priority problem areas; the large scale of difficult water-related problems necessitates a multi-disciplinary approach; and the paradigm shift towards green technologies provides significant industrial opportunity for Canada.

Linking Science and Policy

Throughout the two-day meeting, recurring themes or observations appeared in the area of better linking groundwater quality science with policy development and program management. They included:

Improving communication between government decision-makers and academia - Improving communication is increasingly important because the bulk of the research effort and expertise in the groundwater quality area in Canada now rests largely in academia. Ultimately both researchers and policy/programs managers need to put more effort into ensuring science is considered in the decision-making process. The attendance of this workshop clearly demonstrated that the academic scientific community is willing to participate with policy and decision makers.

Policy should keep pace with evolving science - Workshop participants argued there is currently sufficient scientific knowledge and technology expertise to make significant improvements to groundwater management in this country; problems like Walkerton should not occur. However, for various reasons, the results of some 20 years of groundwater quality research in Canada, for the most part, do not seem to make its way easily to decision-makers.

Repositories of scientific information - To help "get the science out," there is a need for repositories of organized scientific information on groundwater quality. This should be updated with time so that it is readily available for decision-making.

Expert panels for quick decision-making - Typically, researchers and policy developers are on different time tracks. In Canada, there appears to be no existing mechanism to initiate groundwater quality research in priority areas required for policy making. Blue Ribbon Panels are frequently used in the U.S. to help fund research in priority areas of policy development. Expert panels need to be explored more aggressively in Canada.

Policy and program research needs should be better articulated - The groundwater quality research community is essentially unaware of what research decision-makers need. Groundwater quality policy and program initiatives in government should be more regularly communicated to researchers. Scientific research to support policy issues could be encouraged by making research funds available for specific policy needs.

Implementation of the multi-barrier approach - To protect rural groundwater, and drinking water supplies in general, implementation of the multi-barrier approach was viewed as an important proactive management strategy.

Maintaining the Dialogue

This workshop has served as a first step by the CCME in building a substantive, much-needed, ongoing dialogue between the scientific and policy-making communities in the groundwater quality area. This, and all workshops in the science-policy series, have been designed to ensure that issues of key importance to CCME are considered in a timely fashion, that leading-edge science was presented to, and discussed by, a variety of interested parties, and that a process be developed for continuing information sharing and communication.

Workshop delegates were extremely supportive of the need for continued information exchange and dialogue between the science community and policy/program managers in the area of groundwater quality. As this report is being produced, the CCME is considering options for maintaining and, indeed, expanding on the dialogue initiated during the workshop. Workshop participants were also insistent that future initiatives for maintaining the dialogue also include recent policy initiatives and programs, across the country, directed at improving or maintaining groundwater quality.

Summary of Research Needs and Policy Perspectives

For quick reference, the following table summarizes the key research needs and policy issues identified in each of the science themes addressed at the workshop.

Summary of Research Needs and Policy Perspectives

Research Need	Policy Perspectives
Fractured Rock Environments	
■ Sustainable development and wellhead protection in fractured bedrock aquifers. ■ Groundwater-surface water interaction; sorption of organic contaminants; transport of agricultural chemicals and bacteria; mixing and dispersion of contaminants in complex fracture networks. ■ Structure and continuity of fractures to better predict the movement of contaminants within fracture networks over great distances.	■ Recognize that groundwater flow in fractured rock environments will be considerably different than in sand and gravel aquifers, and therefore managing resources will be considerably more difficult. ■ Can be expensive to understand complexity in characterizing contaminant migration, relative to porous media. Consequently, the success of eventual site clean-up can be significantly diminished in comparison to porous media. ■ Plans for wellhead protection and groundwater management zones must incorporate the complexities of the fracture framework and a flow system with low storativity and very high velocity.
Natural Groundwater Contamination	
■ National assessment of naturally occurring groundwater contaminants and how human activities are affecting levels of naturally occurring substances. ■ Effects of long-term exposure to levels of natural contaminants below Canadian Drinking Water Guidelines (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. ■ Initiate programs for testing groundwater from domestic (rural) wells over time (not just when a well is drilled). ■ Explore restrictions on drilling wells, or regulations on controlling the depth of a well in areas of pervasive problems, as done in other jurisdictions. ■ Obtain baseline data on natural groundwater quality before development occurs.
Clay as Barriers to Contaminant Transport	
■ Defining the extent of fracturing in regionally extensive clays. ■ Quantifying the impact of biological reactions on contaminant migration. ■ Describing the impact of facilitated transport of contaminants (e.g., metals) by dissolved organic carbon. ■ Quantifying the interactions between dissolved contaminants and the clay-rich matrix material and the resulting impact on the migration of potential contaminants; characterizing the distribution of bacteria in clay.	■ The existence of natural clay deposits at surface may not always indicate that a barrier to contaminant transport exists. Fractures are common in natural clay deposits and can act as a pathway for contaminant transport to aquifers. ■ Before using engineered clay barriers for waste disposal/ storage facilities, or undertaking land-use practices that require a barrier to groundwater contamination, fully characterize clays at depth to determine if fractures exist.
Pathogens in Groundwater	
■ Pathogen transport and survival, especially with respect to viruses and protozoa, including the development of computer simulation models.	■ Recognize that bacteria are the most prevalent contaminant causing illness in rural wells;

Summary of Research Needs and Policy Perspectives (cont.)

Research Need	Policy Perspectives
■ Contaminant loading and movement in groundwater from large livestock operations. ■ More knowledge about the types of bacteria in wells and aquifers.	■ About 30% of rural domestic wells exhibit bacterial contamination, and wells most at risk are shallow wells in highly permeable aquifers (gravel, fractured rock). ■ 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. ■ Establish guidelines for viruses, protozoa, non-coliform bacteria
Agricultural Impacts on Groundwater	
■ Large regional or watershed scale assessments that better integrate the link between watershed characteristics, surface hydrology, groundwater, meteorology, soil properties and farm management practices. ■ Toxic effects of long-term exposure to concentrations of nitrate or pesticide below the CDWG. ■ Rural family long-term exposure and resistance to pathogenic bacteria ■ Survivability of bacteria in groundwater and wells, and strategies to prevent their survival. ■ The impact of potentially large loads of contaminants (especially manure), and how far these contaminants will travel in groundwater.	■ Nitrates above CDWG a problem in about 15% of rural wells. ■ Pesticides above CDWG rarely detected; in less than 0.5% of rural wells. ■ Potential for groundwater contamination from agricultural sector will increase. ■ All growers and producers (both small operators and intensive livestock operations) should be required to complete and follow an Environmental Farm Plan. ■ Policy/regulation is needed to address water quality guidelines, to improve groundwater testing protocols, and to develop regulations on minimum well construction and maintenance for individual rural wells. ■ Develop CDWG for multiple pesticides in drinking water.
Rural and Municipal Issues	
■ Assessment of the magnitude of the diverse groundwater quality impacts occurring in both rural and urban environments. ■ More accurately defining the size of area that requires protection. ■ Improved techniques and models to assess integrated groundwater-surface water and land-use interrelationships at a regional or watershed scale.	■ The threat to groundwater quality from urban sources of contamination will increase as urban areas expand. Proactive land-use practices and zoning regulations are critical. Land-use practices should include (1) wellhead protection areas, (2) source (recharge) zone protection, (3) best management practices, and (4) zoning restrictions, all of which should be adopted on a regional or watershed scale in order to be effective. ■ Placement, construction and especially abandonment of wells must be directed through clear regulations and enforcement. ■ Improved information on the extent and location of improperly abandoned wells.

Summary of Research Needs and Policy Perspectives (cont.)

Research Need	Policy Perspectives
Mining and Metals	
■ Understand processes controlling acid neutralization and metal attenuation in mine waste. ■ Establish methodology to scale laboratory tests to field scale. ■ Develop long-term prediction models for contaminant generation in mine waste and release to groundwater.	■ Release of metals, sulfate, and acidity from mine waste to groundwater at levels orders of magnitude above CDWG can continue for 100s to 1000s of years. ■ Waste closure must be engineered to prevent the movement of water and oxygen into waste rock and mine tailings. ■ Effluent from waste sites must be treated. ■ Guidelines to protect groundwater at waste sites, including monitoring, remedial technologies. ■ Realistic bonding to cover site closure and potential long-term problems. ■ Database of active/abandoned sites, level of chemical stability, etc. needs to be developed.
Spills	
■ Improve technology and field methods that can precisely locate NAPLs (Non-Aqueous-Phase-Liquids) in the subsurface. ■ Quantification of the extent to which and how DNAPLs (denser contaminants) can penetrate downward into aquifers. ■ Improve our understanding of the composition of spilled or leaked NAPLs. ■ Develop techniques to locate and destroy deep DNAPLs.	■ The regulatory and remediation issues with respect to DNAPLs should advance together; technology to remove/destroy DNAPLs is advancing without a clear understanding of what remedial goals must be met. ■ Scientists and regulatory/policy personnel are frequently asking the same questions: how much DNAPL must be found and remediated? Is 100% removal required, or is 90% sufficient? 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. ■ Policy personnel could be involved in the validation and demonstration of emerging technologies as a potentially useful approach to transfer scientific awareness and the state of technology. ■ Regulatory and policy personnel must be aware of both the technical limitations to cleaning a site and the potentially enormous costs involved in detection, remediation and monitoring.
Petroleum Industry Issues	
■ Assess long-term integrity of pipelines, exploration borehole seals and abandoned well cement plugs and steel casing. ■ Assess the scale of groundwater contamination should integrity of petroleum wells in an old oil or gas field fail. ■ Assess the effectiveness of natural attenuation processes in all Canadian environments to remediate spills.	■ The threat to groundwater quality from all aspects of past activities (from exploration, through field production, storage, transportation, and refining/petrochemical production) represents a major challenge to governments and industry. ■ Little is known about the long-term integrity of concrete seals and steel casing in the hundreds of thousands of abandoned wells across Canada, yet the associated costs of ensuring abandoned wells are secure or remediating contaminated aquifers, is immense.

Summary of Research Needs and Policy Perspectives (cont.)

Research Need	Policy Perspectives
Petroleum Industry Issues (cont.)	
■ Define baseline hydrogeological investigations in coal-bed methane and exploration frontier areas to be able to recognize and track groundwater contaminants. ■ Determine if thermal projects, such as the steam injection for enhanced recovery of heavy oil, is mobilizing natural contaminants in groundwater and fracturing, and hence compromising the integrity of, overlying confining layers. ■ Improved characterization of the hydrologic connection between disposal formations and shallow aquifers/surface water. ■ Determine if brackish water from coal-bed methane production should be disposed to surface water (if salinity is sufficiently low it could be a resource), or injected into the subsurface.	■ There is a need for ongoing government-supported surveys of baseline conditions, and ongoing government-supported monitoring of groundwater chemical quality to determine if groundwater contamination within conventional petroleum fields is occurring, and to determine the long-term and cumulative environmental impacts of the oil-sands mega-projects. ■ Reliance on natural attenuation or current technologies for remediating contaminated sites may not effective in all Canadian environments.
Risk Assessment	
■ Improved knowledge of the amount of data required to adequately characterize a system in order to reduce uncertainty to an acceptable level. ■ Develop user-friendly quantitative tools for uncertainty analysis that would encourage and simplify their use by the regulatory community (e.g., few, if any, push-button software packages are available). ■ Encourage emerging research in the development of more powerful techniques for mapping spatial variability in hydrogeological parameters, and in the quantification of prediction uncertainty that can be attributed to errors in data model structure.	■ Although there is typically considerable uncertainty in the predictions from a computer model because of the inherent uncertainty in the parameters that are input into the model, this uncertainty can be accommodated within the decision making process through risk assessment. ■ Regulators must encourage project proponents and their consultants 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 is likely to involve trade-offs with model complexity. ■ Where feasible, computer modeling should move beyond deterministic calculations adopting a conservative bias, sensitivity studies, or practical worst-case evaluation.
An Overview of Rural Well-Water Quality in Canada	
■ Improve techniques to identify the source of microbiological contamination of well water (surrounding groundwater versus the well itself). ■ Improve understanding of whether nitrate contamination is increasing in extent and depth of aquifers. ■ Suitability and effectiveness of source area protection measures for preventing well water contamination by pathogens, nitrate and other contaminants. ■ Nation-wide review of documented cases where discharge of contaminated groundwater has had a significant impact on surface water and aquatic ecology.	■ In the context of public health, the widespread contamination of well water by pathogens in Canada is a concern (approximately 30% of rural wells). ■ A national survey of well water quality is needed. ■ Shallow wells close to the water table in highly permeable aquifers (sand, gravel, fractured rock) are at much greater risk to contamination from surface contaminants than deep wells. ■ Poorly constructed or maintained wells are at high risk of contamination. ■ Need nationally consistent standards for well construction, pump installation, well abandonment, licensing of drillers.

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Chapter 1.

Introduction

Water is a key component of the modern Canadian economy: it is a fundamental resource for food production, plays an important role in virtually every modern industrial process and many recreational activities, and is essential for urban development. It is critical to the health and survival of plants, animals, and people. In Canada, water is generally plentiful and clean; however, it is sometimes locally or regionally polluted. Pollution enters surface and groundwater from industrial and municipal discharge, in runoff and seepage from land managed for agriculture or forestry, and from deposition of airborne pollutants. Impacts of pollution include threats to drinking water in certain areas, closures of shellfish harvesting areas on the Atlantic and Pacific coasts, loss of part of the Great Lakes fishery, reduced ecosystem diversity, and fewer recreational opportunities.

The Canadian Council of Ministers of the Environment (CCME) has identified water quality as a priority issue because of recent concerns about water quality and the important value placed on water by Canadians. CCME is the major inter-governmental forum in Canada for discussion and joint action on environmental issues of national and international concern. The Council is made up of environment ministers from the federal, provincial and territorial governments. CCME works to promote cooperation on and coordination of inter-jurisdictional issues (e.g., waste management, air pollution, water and toxic chemicals) and to provide a forum for cooperation in developing and maintaining the scientific information base required to support sound environmental decision making. In response to concerns about protection of groundwater quality, CCME recently sponsored a workshop on potential activities that may affect groundwater quality, the state of scientific understanding of groundwater, and linking this scientific knowledge to policy.

Ten million Canadians rely on groundwater for their drinking water supplies. Groundwater also provides vital water supplies for agriculture and major industries involved in manufacturing, mining and petroleum production. Groundwater is an integral component of the hydrologic cycle interacting with streams, lakes, wetlands and supporting their ecosystems. Several events involving groundwater quality in recent years such as the Walkerton tragedy have heightened public awareness and concern over the vulnerability of this precious resource. This heightened awareness challenges our institutions to respond with better and more effective programs and policies to protect surface and groundwater quality, and ensure we have the science essential to guide these programs.

This paper provides an overview of the CCME sponsored workshop *Linking Water Science to Policy: Groundwater Quality* held on March 21 and March 22, 2002, in Toronto (Appendix 1). The goals of the workshop were to present current research findings to policy and decision makers; ensure this research is meeting the needs of this user community; identify future research needs; help establish research priorities; and determine a process for ongoing information sharing and communication.

Approximately 60 representatives from local, provincial and federal departments, universities, and private agencies attended the workshop, where presentations by eminent groundwater scientists, panel discussions, and plenary sessions on the state of groundwater knowledge and linking the science with policy took place. Scientific topics ranged from an overview of groundwater flow and contaminant transport processes to the nature of fractured rock environments, roles of aquitards in protecting aquifers, impacts of agriculture, petroleum production, municipal, and mining activities on groundwater quality, pathogens in groundwater, natural sources of contamination, chemical spills, and aspects of risk assessment and watershed management. Also included here are summaries of several key initiatives involving groundwater quality taking place across the country, and perspectives on groundwater quality from the municipal sector and the United States.

Chapter 2.

Science Updates and Policy Perspectives

For each of the topic areas, the report section is organized by the following subheadings: background; main issue; what we know (regarding scientific understanding); what we do not know; policy perspective; and additional resources. Material for these sections came principally from workshop speakers and comments and questions posed during the session discussion period. In some sections, the workshop editors included additional information to maintain consistency in the breadth and content of material among such a diverse selection of topic areas. We hope this format results in a useful and comprehensive resource for those seeking specific information on the status of scientific understanding, research needs and related policy issues.

2.1 An Introduction by Dr. Robert Gillham, FRSC, O.C.

The expression "out of sight – out of mind" is very appropriate when one considers groundwater. Indeed, while close to ten million Canadians rely on groundwater as a source of potable water, it is usually only seen as it emerges from a faucet, and is brought to public attention only when there are problems associated with quantity or quality. It is not surprising, therefore, that the general perception of groundwater is far from complete and frequently inaccurate.

The range of physical and chemical conditions of groundwater far exceeds those of surface water. Velocities can range from centimetres per decade to hundreds of metres per day, chemical conditions can range from near rainwater to salinities greater than seawater, and ages can range from hours to tens of thousands of years. While several decades ago it was thought groundwater was largely immune to the effects of anthropogenic activity, it is now recognized that this is far from the case. Thus, evaluating a particular groundwater resource as a supply for domestic use and instituting policies to protect future quantity and quality of the resource require knowledge of various interacting processes.

The rate of groundwater flow is controlled largely by the permeability of the geologic material through which the water flows and by the hydraulic gradient. Thus, supplies for domestic use are generally situated in highly permeable materials such as sand, gravel and fractured rock. The natural chemistry of groundwater is controlled largely by age and by dissolution of the geologic materials through which the water flows. Contaminants can enter groundwater by a variety of means, but most commonly from sources at the ground surface. The major processes that influence migration of contaminants include advection, dispersion, physical filtering, sorption, precipitation, and biological transformations. The dominant process(es) in a particular situation depends upon the geological conditions, geochemical conditions and chemical and biological characteristics of the particular contaminant. As a consequence, some contaminants, though highly toxic, are essentially immobile and do not pose a risk, while others can move, in effect, at the velocity of the water and thus, can represent a significant risk.

Groundwater is a natural resource of substantial size and economic value. Though it is generally of high quality, as with other natural resources, groundwater requires management and protection. The science of contaminant migration in groundwater is relatively new; nevertheless, great advances in knowledge have been made over the last three decades. For cost effective management, it is important this knowledge be recognized and applied in developing appropriate management policies.

2.2 Fractured Rock Environments

Background

Groundwater is commonly perceived as coming from sand and gravel deposits. These are also known as "porous media" because there is considerable space or pores between individual sand grains and stones, and the pores are well connected.

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 where 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

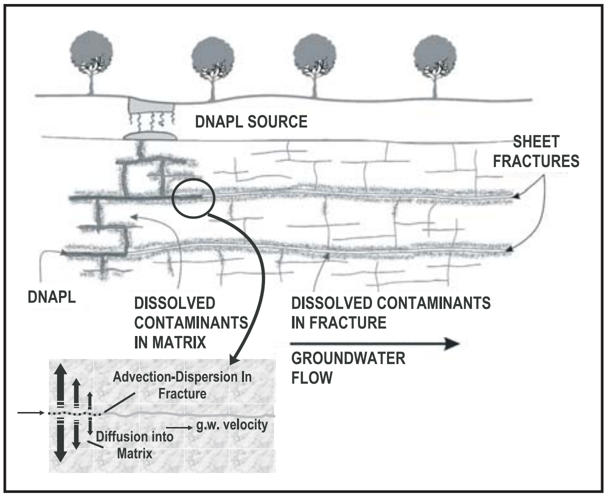

Fig. 1. Complex transport of a DNAPL contaminant through a fractured bedrock aquifer; advective flow through the fracture, diffusion into the rock matrix.

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.

Fractured rock aquifers are common in every region of Canada. For example, the Carboniferous Basin within the Maritime provinces, the carbonate aquifer of the St. Lawrence Lowlands in southwestern Quebec, the Cambridge carbonate aquifer in Ontario, crystalline rocks in Ontario, carbonate aquifer underlying the Red River Valley/Interlake Region of Manitoba, and the Cretaceous sedimentary rocks in Alberta. Within these regions, rural water supplies are obtained from wells drilled into limestone, dolostone, sandstone and shale. Unfortunately, the quality of groundwater in fractured rock aquifers is often naturally poor due to high concentrations of sulfate, methane, or salts.

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 generally cannot be applied to fractured rock.

Differences with respect to groundwater flow and storage.

In most bedrock aquifers, groundwater migrates through discontinuities (i.e., fractures and joints) in the rock. The unfractured rock mass adjacent to the fracture is often of very low hydraulic conductivity and moderate to low porosity. In crystalline rock, the primary porosity may be as low as 0.05%, but a typical sand aquifer usually has a porosity of 30% or greater. Thus, the volume of water stored in fractured bedrock aquifers is often orders of magnitude less than that stored in more porous media. Consequently, sustained pumping for municipal supply or even for domestic usage from fractured bedrock will draw groundwater from greater distances. In some areas, response to aggressive pumping in carbonate aquifers has been observed at distances of several kilometres from the pumping well. This response has two implications. First, bedrock aquifers have a limited supply for sustained removal of groundwater and are often more susceptible to well interference and over consumption than porous aquifers of equivalent scale. Second, the zone in which we must protect the recharging water from contamination may be significantly larger than for porous aquifers.

Because the majority of moving groundwater passes through discrete fracture planes that occupy a very small percentage of the total volume of rock, the speed at which the water migrates is very rapid. For example, typical rates of groundwater migration in a sand aquifer may be in the order of 0.01 to 5 m/day, whereas groundwater velocities ranging from 1 to 100 m/day are commonly observed in the fractures pervading the dolostones of southern Ontario. Hence, contaminant transport may be relatively fast.

There is considerably more variation in transmissivity, hydraulic conductivity, and porosity within a single fractured rock aquifer than a porous media aquifer because of the irregular distribution of fractures and fractures size. Thus, in order to determine the hydrogeological properties of a fractured rock aquifer and groundwater velocity, we need to determine the distinct properties of its individual fractures.

Because fractured rock aquifers are complex, it is very difficult to characterize groundwater flow and hydrogeological properties of even a single fracture, let alone an entire site or a fractured rock aquifer. Our knowledge and field techniques for characterizing groundwater flow and hydrogeological properties are different from those employed for porous media aquifers, and the mathematics and physics used for porous media aquifers (e.g., Darcy's Law) are not easily applicable to most fractured rock aquifers.

Differences with respect to contaminant transport and persistence

The structure of porous media, within its interconnected pores can give rise to widespread dispersion of contaminants, and the extent of groundwater contamination will increase with increasing distance from the contaminant source in a fairly predictable and well understand manner. In fractured rock, contaminant movement is narrowly restricted to an individual fracture or a few fractures. Hence, although there may be very little lateral spreading in fractured rock aquifers with respect to porous media aquifers, the distance travelled by a contaminant may be considerably greater in the fractured rock aquifers. Fracture networks provide the groundwater pathways in most bedrock aquifers and are often complex, highly heterogeneous, and, in most cases, unpredictable. Horizontal fractures may quickly spread a contaminant, and vertical fractures provide conduits that rapidly move a contaminant from the surface to depth. By following these pathways, the extent of groundwater contamination may be much larger than would occur in porous media. Typically, in most fractured rock aquifers there is one well-connected set of fractures that leads away from the contaminant source through which most of the contaminated groundwater will flow.

Groundwater flow through fractures has a significant impact on the rate of migration of chemical and biological contaminants. Bacteria and viruses, in particular, can migrate at rates equal to the groundwater velocity, resulting in widespread and rapid distribution from relatively small sources (e.g., from surface to local wells). Fortunately, in the case of chemical contaminants, the effect of diffusion of the contaminant transported in the fracture into the adjacent rock (matrix diffusion) initially acts to slow the rate of migration. However, once the contaminated groundwater flows through the fracture, the contaminated rock adjacent to the fracture may become a long-term source of contamination as it slowly diffuses back into the fracture.

When oil-phase contaminants, such as gasoline or chlorinated solvents, or dense non-aqueous phase liquids (DNAPLs), such as PCBs, are introduced into these environments, the resulting distribution is usually complex, difficult to characterize, and even more difficult to remove. Examples of gasoline or diesel contamination in fractured-bedrock aquifers and the contamination of fractured rock by solvent spills are increasingly observed at various locations across Canada.

Many fractured rock aquifers (both sedimentary and crystalline rock) have little overburden to protect them from contaminants in surface water or runoff. Hence, these aquifers are very vulnerable to surface sources of anthropogenic contamination. Capture zones for recharging fractured rock aquifers are much larger than required for porous media aquifers because of limited storage capacity in a fractured rock aquifer. But because there is typically only one major fracture system controlling contaminant transport, the capture zone for contamination is much smaller. When designing wellhead protection zones, we must focus on the smaller contaminant capture zone rather than the large flow-based capture zone. If we are judicious about the capture zones, we can design small wellhead protection zones for fractured rock aquifers.

Table 1: Summary of differences between porous media and fractured rock aquifers.

	Porous Media	Fractured Rock
groundwater flow equation	Darcy's law	Cubic Law
aquifer tests	pumping test	packer test
storage capacity	large storage	little storage
groundwater velocity	lower	higher
well interference	may not be susceptible	more susceptible
predict contaminant migration	possible	very difficult
hydraulic conductivity in a aquifer	narrower range	wider range
porosity in a aquifer	narrower range (25-50%)	wider range (0.05-40%)

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 apply this knowledge, and, as a result, 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.

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2.3 Natural Groundwater Contamination

Background

Groundwater quality is affected by many human activities. However, the absence of human impact on the groundwater regime does not guarantee that the quality of groundwater will meet water quality guidelines for human consumption, livestock water, irrigation, or industrial uses. There are many naturally occurring substances in groundwater, and in many instances concentrations of these substances may be present above water quality guidelines. Some may present a risk to human health when at elevated concentrations, including:

- metals: arsenic, mercury, selenium, lead
- non-metals: fluoride, nitrate, sulfate
- radioactive elements: uranium, thorium
- gases: radon

Other naturally occurring substances that are often above water quality guidelines only present esthetic problems, and are no risk to human health at concentrations typically encountered in groundwater. Although esthetic problems related to taste, colour, and odour do not present a health risk, there is public perception that if the water does not look or smell good it is unsafe to drink. Examples include:

- iron and manganese: staining on plumbing fixtures
- high dissolved solids (especially chloride): taste problems

- calcium and magnesium: hardness in the water
- hydrogen sulfide gas: odour problems

Areas where high concentrations of specific naturally occurring substances exist are found throughout Canada. The presence of a specific element or compound and its concentration in groundwater are directly linked to both the geological material through which the groundwater flows, and the physical, hydrological, and meteorological conditions within the different regions of Canada.

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. These elements and compounds are naturally present in the sediments and rocks forming aquifers. Various natural processes and human water-use practices can enhance release of these substances in groundwater, and often lead to high concentrations.

Occurrence of natural substances

As rain water percolates through the soil zone, it becomes slightly acidic because carbon dioxide, produced by plants and soil organisms, dissolves into the water. This acidity is sufficient to dissolve minerals in the soil and sediment causing various elements and compounds to enter the water. Oxygen in the soil zone can also lead to oxidative reactions. Oxidation of solids such as arsenopyrite can lead to increased concentrations of dissolved arsenic in infiltration waters. The water and its dissolved substances move downward to the water table and enter the groundwater. As groundwater flows through the rocks and sediments forming aquifers, constituents will enter the groundwater through chemical processes such as dissolution, cation exchange, and desorption.

In environments where there is sufficient organic matter, the breakdown of the organic matter by bacteria will consume the oxygen in the groundwater. These reduced levels of oxygen in groundwater will lead to dissolution of metals from their solid oxidized state (e.g., reduction of iron oxide and iron hydroxide to dissolved iron). Bacteria that consume oxygen can also cause sulfate reduction to form hydrogen sulfide gas and generate methane from dissolved carbon dioxide. Trace elements bound to solids such as iron oxides and hydroxides can also be released. Elements such as arsenic can be released through both oxidative and reductive mechanisms.

The nature of the geological material through which infiltration and groundwater flow occurs will control the chemical composition of the groundwater as well as the concentrations of the dissolved substances. For example, groundwater flowing through granitic rocks (e.g., the Canadian Shield) or shale is generally acidic, and thus can dissolve and mobilize metals. Carbonate rocks (e.g., limestone, dolostone) will buffer the acidity of groundwater resulting in less dissolution and mobility of metals. Some substances, such as arsenic, are mobile under a broad range of pH conditions.

Human impact on natural groundwater quality

Human activities also can lead to elevated concentrations of natural substances that under natural conditions would not be above CDWG. This occurs indirectly due to groundwater-related activities that in turn lead to geochemical changes that affect natural groundwater quality.

Soils in arid areas of Canada, such as the southern Prairies and the interior of British Columbia, naturally contain salts such as halite, gypsum, and anhydrite. Irrigation can increase the salinity of groundwater because irrigation water infiltrating through the soil will dissolve the salts and transport them downward to the water table far more rapidly than under natural conditions.

In coastal areas, a natural state of dynamic equilibrium is maintained as the discharge of fresh groundwater to the sea prevents the encroachment of seawater into the aquifer. Extensive pumping of groundwater in these coastal areas can reduce the discharge of groundwater and disturb the balance between fresh water and seawater, thus leading to advancement of seawater inland and contamination of wells. The landward encroachment of seawater cannot be reversed. Areas most at risk include coastal areas of Prince Edward Island and the Gulf Islands of British Columbia.

In the southern Prairies, the cultivation of virgin soils has led to increased concentrations of nitrate in groundwater due to the oxidation of plant nitrogen and the leaching of this nitrate to the water table.

In many cases simply pumping groundwater from a well can alter the chemistry of the aquifer material and the groundwater adjacent to a well. For example, pumping can cause oxygen-rich water to pass through bedrock or till containing minerals, which in turn will cause oxidation of various elements. In the Prairies, it is common for pumping of domestic wells to cause oxidation of pyrite in tills and coal seams, leading to increased concentrations of sulfate in wells. In New Brunswick, pumping from municipal wells has caused river water to infiltrate through the city's main aquifer resulting in increased levels of manganese. In many areas of Canada, naturally occurring arsenic is released to groundwater from bedrock and overburden at concentrations above the CDWG. Pumping of wells and drawing down the water table can potentially promote the further release of arsenic.

What we know

We know that naturally occurring substances and compounds 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 geochemical 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 high concentrations in aquifer solids, including till (Alberta, Saskatchewan), shale (New Brunswick, Nova Scotia, Saskatchewan), and igneous and metamorphic rock (Newfoundland, Saskatchewan, British Columbia, Ontario, and elsewhere). Elevated concentrations of uranium have been reported in wells in southwestern Nova Scotia, New Brunswick, north of Kingston in Ontario, and in Saskatchewan. Radon has been reported in parts of Ontario, Saskatchewan, and Alberta. Salinity above CDWG has been reported in domestic wells 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.

What we do not know

Many surveys have been undertaken in Canada to assess groundwater quality in domestic wells. These are generally localized and undertaken in response to a particular concern. Although there is a comprehensive database of groundwater quality analyses throughout Canada, 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 domestic or municipal well owners currently believe that local commercial, industrial, or resource development activities have caused deleterious changes in the groundwater quality. However, without knowing natural background concentrations of naturally occurring substances, in many of these cases it is very difficult to know the extent that these human activities have caused, or even if these activities have actually affected groundwater quality at all. Because groundwater quality is closely related to sediment and bedrock geochemistry, we need to know background natural groundwater quality to determine if a high concentration of a constituent is due to natural conditions or human activity.

In many cases, high concentrations of many natural substances (e.g., metals, arsenic, salinity, hardness, fluoride) can be reduced to levels below CDWG by various treatment methods. For example, reverse osmosis techniques can be used to reduce salinity, remove metals, and remove nitrates. However, CDWG for some elements are lower than that which can be treated by current technology. Also, in some areas, conventional water treatment techniques are unsuitable and there are no cost-effective alternative methods available.

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. Hence, many wells used as a source of drinking water have contaminant levels exceeding standards that would force its closure if it were a municipal well. 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 metals, reduce hardness, or reduce salinity; but there are no regulations enforcing their use. In some regions where conventional treatment systems are not effective, programs should be instituted to develop cost-effective alternative treatment systems.

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 pervasive problems. For example, Wisconsin well regulations will not permit wells to be installed in areas of known high concentrations of arsenic.

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

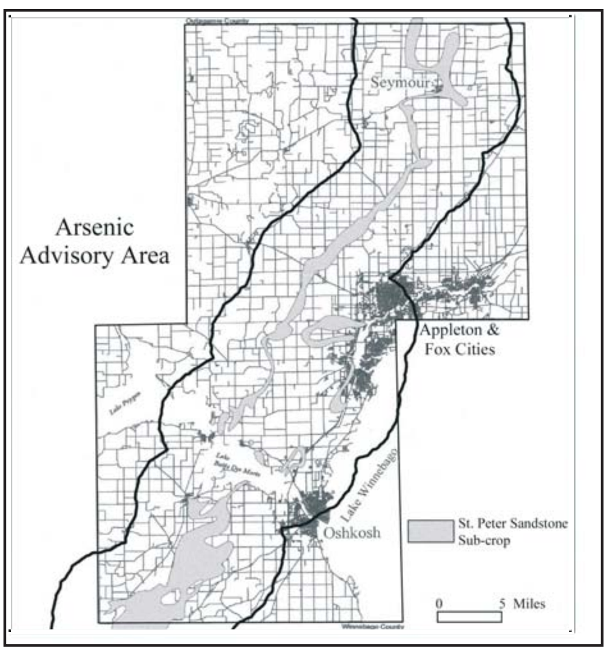

Fig. 2. Example of a pro-active response to natural contamination of groundwater by Wisconsin; map depicts the area in which potentially high levels of arsenic are present in groundwater.

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.

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2.4 Clays 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 for 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.

Natural clay deposits and clay-rich tills are widespread throughout all provinces in Canada. Clays and clay-rich tills are also known as aquitards because they present a barrier to groundwater flow and it is hard to obtain groundwater from them. Wells completed in clay or clay till will produce a very limited water supply.

There is an emerging potential for increased reliance on these deposits by the mining and agricultural industries as well as provincial and local governments to limit the migration of contaminants both in natural settings and as clay liners. In response to this interest, there has been an increased focus in research on the physical, chemical, and biological processes that control migration of contaminants in these media. For example, the importance of intensive and specific research into the characteristics of clay-rich deposits was evidenced by an international workshop on the subject held by the National Academy of Science (U.S.A.) in 2001.

Issues

Clay can be an effective barrier to the movement of contaminants from surface into groundwater. Clay barriers are increasingly used by industry and government to limit migration in natural settings and as clay liners in water disposal/storage areas. 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.

Natural clays

The composition of natural clay deposits is quite variable. Natural clay consists of two zones: an oxidized fractured upper zone extending up to 5 m below surface, and an unoxidized zone below. The unoxidized zone is generally non-fractured, but fractures may extend from the oxidized zone over 10-20 m into the unoxidized zone.

Research has also demonstrated that biological and chemical reactions can slow the migration of inorganic and organic contaminants through clay. Biological reactions are controlled by microbial activity such as denitrification. Chemical reactions are controlled by non-biological activity such as sorption, exchange, and precipitation.

Characteristics of nonfractured clays

Nonfractured clays have common characteristics. These include:

1. presence of geochemically unoxidized material;
2. very low hydraulic conductivity, generally $<5x10^{-10}$ m/s (hydraulic conductivity of a medium-grained sand deposit is $\sim 1x10^{-4}$ m/s);
3. downward groundwater flow at average linear velocities of less than one metre per 1000 years;
4. a variety of isotopic tracers that indicate that the water can be tens of thousands of years old; and
5. field and laboratory studies that show the dominant solute transport mechanism in unweathered clay deposits is diffusion.

Characteristics of fractured clays

Fractured clay-rich deposits have common characteristics. These include:

1. presence of geochemically oxidized zones;
2. hydraulic conductivities that are typically two to three orders of magnitude greater than the unweathered clay;
3. higher groundwater velocities in fractures than in unfractured clay;
4. dynamic lateral groundwater flow;
5. contain isotopic tracers that indicate the water is recent in age; and
6. studies that show the dominant contaminant transport mechanism in weathered clays is advection through fractures (with diffusion into the matrix).

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 know that clays commonly act as barriers to contaminant migration if the clay is between a contaminant source and an aquifer. 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 on 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 more complete understanding of the potential for use 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) describing the impact of facilitated transport of contaminants (e.g., metals) by dissolved organic carbon; (4) quantifying the interactions between dissolved contaminants and the clay-rich matrix material and the resulting impact on the migration of potential contaminants; and (5) 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. For example, much higher atmospheric levels of deuterium occurred during the 1950s than during the decades before and after, and these elevated deuterium concentrations can be seen diffusing downward through clay deposits.

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.

At present, adequate funding does not appear to be a limitation to support critical research programs. 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.

The existence of natural clay deposits at surface may not always indicate that a barrier to contaminant transport exists. Fractures are common in natural clay deposits and act as a pathway for contaminant transport to aquifers. Fracturing must be addressed during activities that may have an impact on groundwater quality (e.g., location of waste disposal sites, defining groundwater protection zones, etc.)

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. Better management practices are needed to ensure that these waste disposal/storage sites will not cause groundwater contamination.

Therefore, before using clays for 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.

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2.5 Pathogens in Groundwater

Background

In May of 2000, the municipal water supply for the Town of Walkerton, Ontario, was contaminated by bacteria causing over 2,000 reported cases of illness and 6 deaths. The source of the bacteria was traced to an agricultural source upstream from an improperly constructed town well. As a result of this incident, the level of public concern about bacteria in groundwater has dramatically risen. However, bacteria are not the only organism that can contaminate groundwater. These organisms that pose a threat to human health are collectively known as pathogens, and include bacteria, viruses and protozoa.

Table 2: Common Pathogens of Concern.		
Bacteria	Viruses	Protozoa
Escherichia coli	Rotavirus	*Giardia lamblia cysts*
Salmonella	Poliovirus	*Cryptosporidium parvum oocysts*
Shigelia	Adenovirus	
Campylobacter jejuni	Norwalk	
Yersinia enterocolitica	Hepatitus A	
Vibrio cholerae		
Helcobacter		
Enterococci		

Pathogens are the most prevalent contaminant in water causing illness. Typically pathogen problems are associated when surface water (lakes, rivers, reservoirs) is the source of drinking water. 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

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. 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. Because there have been few past cases of municipal water supplies relying on groundwater being contaminated by pathogens, 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, in that the former will survive longer.

Sources of pathogens in groundwater

The primary sources of pathogens in groundwater in agricultural regions are fecal wastes and waste disposal systems, including manure storage piles and lagoons, septic systems, land spreading of manure and biosolids. These wastes contain tremendous numbers of pathogens. For example, 1 litre of community wastewater contains 3 to 20,000 *Cryptosporidium oocysts*, 10,000,000 to 100,000,000 fecal coliform bacteria, and 1,000 to 10,000 Enteric Virus. Other sources include landfills, and dead animals (e.g., mice) in wells.

The pathways by which pathogens may enter groundwater include leaching through the soil to the

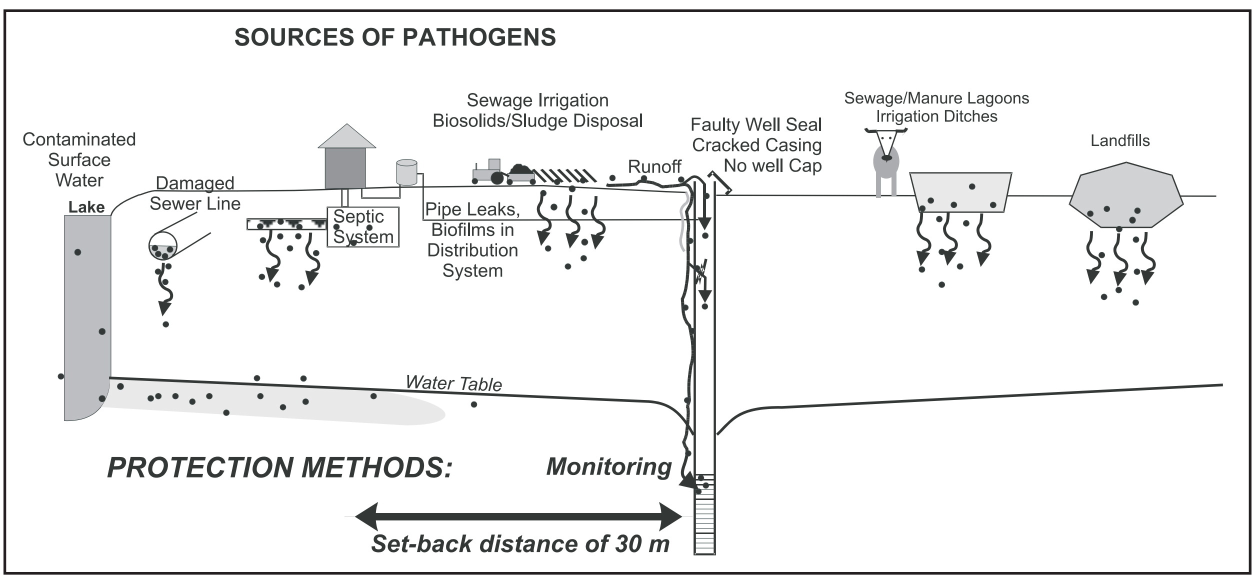

Fig. 3. Potential sources of pathogens to groundwater from rural, agricultural, municipal and natural sources.

water table with infiltration, direct flow through fractures from surface to the water table in bedrock or till, via poorly constructed or maintained wells and unplugged boreholes, or via direct transport from subsurface wastewater disposal sites to wells.

Transport and survivability of pathogens

Understanding the factors responsible for controlling the survivability and transport of pathogens in the subsurface is crucial for protecting public groundwater supplies. Once pathogens enter the subsurface, their survivability and movement towards water supply wells will be controlled by three main factors:

1. properties of the soil or aquifer material (grain size, pore size, connectivity of pores, fracturing, mineralogical composition, metal oxide coatings, amount of organic material);
2. properties of the groundwater (ionic strength, pH, temperature, groundwater velocity); and
3. properties of the pathogen (size, surface composition, mortality rate, reproduction rate, inactivation rate).

Pathogens will be carried by moving groundwater. Hence the higher the groundwater velocity, the faster the pathogen transport. Natural groundwater velocities are typically higher in coarser material, such as gravel (10 - >100 m/d), fractures (1 - >10,000 m/d), sand (0.05 – 1 m/d), than in fine-grained silt and clay (<0.01 – 0.05 m/d). However, groundwater velocity will increase exponentially closer to a pumping well. Also, cooler groundwater temperatures favour the survivability of pathogens.

The size of the aquifer material (and correspondingly the size of the pore spaces) act to filter the pathogens; large pathogens cannot fit through small pore spaces. The pore spaces of fine silt and clay (<0.3 μm) will not permit the movement of bacteria (1 – 5 μm) or protozoa (4 – 14 μm), but will permit the movement of some viruses (0.02 – 0.9 μm). The pore spaces in sand (5 μm) will permit movement of some bacteria. The pore spaces in gravel (>100 μm) and aperture spacing in fractures (>10 μm) could easily permit the movement of pathogens.

The physical and biological properties of pathogens cause them to favour attachment onto the aquifer material rather than freely moving with groundwater flow. This limits their extent and rate of spreading and lowers the concentrations of pathogens in groundwater. Hence, widespread contamination of groundwater by pathogens leaching through fine clayey and silty soil is rare. Groundwater contamination from pathogens is more likely to occur through gravel, coarse sand, or fractures. Once in groundwater, only under very favourable conditions (coarse gravel, fractures, high velocities) will pathogens migrate over large distances, and even then, the reported travel distances have been in the range of 10s to 100s of metres. Bacteria contamination of wells is common; surveys consistently indicate that between 10% and 36% of individual rural wells in Canada are contaminated by bacteria. In many cases, the bacteria originates as contaminated runoff entering the well at ground surface (through improper seals, cracks in the casing, or fractures which directly connect surface to the well intake). Many other contaminated wells are shallow dug wells, improperly located (e.g., gravel or fractures with a direct link to surface runoff, immediately adjacent to a septic system, manure pile, etc.), poorly constructed (borehole not properly sealed, surface runoff flows to well, etc.), or poorly maintained (cap left off the top of the wells, casing has corroded, etc.). However, it is not known how many wells are contaminated by bacteria moving from the aquifer into the well.

What we know

Pathogens (bacteria) are a common contaminant in rural wells in Canada and most likely to be associated with shallow wells. The primary source of pathogens contaminating groundwater is fecal waste and waste systems (manure, biosolids, septic systems). Aquifers vulnerable are shallow (water table near surface, no low permeable layer between surface and water table,) and are composed of high permeability material, such as gravel or fractured rock.

Many pathogens, including coliform bacteria and viruses, may survive for over a year in groundwater. Coarse-grained sand, gravel and fractured rock do not filter most pathogens, allowing them to move from surface to the water table, and 100s of metres with groundwater flow. However, bacteria and viruses prefer to attach themselves to the aquifer materials, which prevents extensive transport and minimize concentrations in groundwater.

What we do not know

We know that many wells are contaminated by bacteria, but we do not know what type of bacteria, (e.g., the pathogenic bacteria at Walkerton, Ontario, *E.coli.* 0157:H7). We also do not know much about viruses and protozoa in wells.

Although there have been many laboratory studies to assess the transport and survivability of pathogens in groundwater systems, 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, especially with respect to viruses and protozoa.

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.

A major concern is that the livestock industry is shifting from small livestock farms or mixed livestock-crop farms to intensive operations (e.g., hogs, cattle, chickens). The impact on groundwater of potentially large loading of contaminants (especially manure) within a small area and the distance these contaminants will travel are not known.

Policy perspective

The threat to rural groundwater supplies will increase in the future as the sources of pathogens in rural areas increase. The agricultural industry continues to move towards more intensive livestock operations. Municipalities are increasing the spreading of biosolids in rural areas. The number of septic systems has been increasing over the past several decades due to an increasing number of residents in semi-rural and lakeshore areas. Therefore, 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 setback distances, (5) source-water monitoring, (6) groundwater quality/well testing, and (7) minimum well construction and maintenance standards.

Current water-quality regulations and guidelines (CDWG, set back regulations for septic systems, etc.) 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. Policy is needed, therefore, for improved regulations for set back distances for wells, and new water quality guidelines and testing procedures for a variety of pathogens other than coliform bacteria.

Water-quality regulations and testing frequency for wells are focused on municipal systems; no regulations for water-quality testing of individual wells exist. Most provinces recommend that an individual well owner test the well water when the well is drilled and annually after that, but these are not regulations. Poor groundwater quality and contaminant levels above CDWG that are not acceptable from municipal systems are 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.

There is also a need for research into understanding the key factors controlling transport and survivability of bacteria, viruses and protozoa in aquifers and wells, as well as developing and enacting regulations. This research may require the development of new tools and techniques for sampling, detecting and characterizing pathogens for which no standard tests are currently conducted. In particular, knowledge on the survivability of viruses and protozoa in groundwater is very limited.

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2.6 Agricultural Impacts on Groundwater

Background

The public has generally taken good quality groundwater in rural areas for granted, and it is only since the tragedy at Walkerton, Ontario, that people have become more aware of groundwater contamination in agricultural areas. 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 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 (they are not dependent on a municipal or community water supply). Hence, growers and producers are typically the first to feel the impact of changes to groundwater quality due to contamination.

Groundwater quality in agricultural areas is affected by agricultural activities such as: application of pesticides, fertilizer and manure on fields; storage and disposal of animal wastes; improper disposal and spills of chemicals; and irrigation. The types of groundwater contaminants from these agricultural activities can be divided into three main categories: nitrate, bacteria, and pesticides. Groundwater quality can also be affected by domestic septic systems, improperly constructed or abandoned wells, improper handling, storage and disposal of fuels and chemicals, and through irrigation. In addition, septic systems are an important source of contamination because most farms and rural residences have their septic system and well fairly closely placed (e.g., near the house).

Although agricultural activities have caused groundwater quality to diminish over time, most areas are still within CDWG limits. However, in some areas of Canada (e.g., the Prairies), groundwater quality is naturally poor or borderline with respect to CDWG for human needs, livestock watering and irrigation due to high levels of sulfate or salts. Any degradation of groundwater quality in these areas may severely limit agricultural activities.

Issue

Groundwater contamination due to agricultural activities is widespread throughout 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.

Contaminants in agricultural areas

Economic pressures have forced the concentration of livestock operations, raising the risk of impacts on groundwater quality from manure management. 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%. More manure is produced and spread over a smaller area. Areas most at risk (and have experienced significant impacts) from intensive livestock production are located in southern British Columbia, Alberta, Ontario and Quebec, and parts of PEI, New Brunswick and Nova Scotia. Of particular concern is the spreading of manure in sensitive groundwater recharge areas, near surface waters, and near operational or abandoned wells.

Some activities cause widespread contamination of several km^2, and are known as non-point source contamination (e.g., application of pesticides, fertilizer and manure to fields). Other activities cause very localized groundwater contamination and these are known as point source contamination (e.g., septic systems, fuel spills).

Nitrate

The primary source of nitrate in groundwater in agricultural areas is from fertilizer applied to fields, runoff from animal waste storage sites, manure spreading on fields, and septic systems. Nitrogen is added to soil to sustain crop production. Excess nitrogen is converted to nitrate (soluble form of N) which is then leached to the water table. Nitrate is present as both a non-point source contaminant (due to application of fertilizer and manure spreading) and as a point source contaminant (septic systems, waste storage sites)

Bacteria

The primary sources of bacteria in groundwater in agricultural regions are manure spreading on fields, runoff from waste disposal sites, and septic systems. Manure has a particularly high proportion of bacteria, and many of these bacteria are pathogenic to people. Bacteria are present as both a non-point source contaminant (due to manure spreading on fields) and as a point source contaminant (due to waste disposal sites, septic systems). Bacteria do not move very far through fine soils and sand. However, bacteria can move to the water table through cracks in the soil or fractures in clay and rock. Hence, widespread contamination of groundwater by bacteria leaching from the surface or moving into aquifers from contaminated wells is rare. Although bacteria contamination in wells is common, the vast majority of wells contaminated are shallow dug wells or wells that are improperly located, constructed, or poorly maintained. Contamination of a shallow well is typically not caused by bacterial contaminated groundwater moving from an aquifer into the well, but from surface runoff entering the well at groundwater surface (through improper seals, cracks in the casing, foreign objects, or fractures which directly connect the surface to the well intake.

Pesticides

The sources of pesticides in groundwater in agricultural areas are from herbicides, insecticides, and fungicides applied to fields. Pesticides are present as both a non-point source contaminant (due to application of pesticides to fields) and as a point source contaminant (due to improper disposal of wastes, cleaning equipment, spills, etc.).

What we know

Contamination of groundwater and wells due to agricultural activities is common in all agricultural regions of Canada. Contamination of groundwater and wells is caused by a combination of agricultural activities, soil conditions, groundwater environment, meteorological conditions, well construction, surface topography and, hydrology.

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 therefore detections and concentrations are highly variable from region to region. Most high concentrations of pesticides in groundwater are due to spills.

Given the characteristics of bacteria, it is not likely that widespread bacterial contamination of an aquifer will occur. However, it is much more likely that bacterial contamination of shallow wells to the water table (much less common in deep wells completed in confined aquifers) can occur. Improper well construction or inappropriate well location is a common cause of bacterial contamination of a shallow well. But it is not known how frequently bacteria in a well can originate as contaminated groundwater from an adjacent aquifer. Bacteria in a shallow well typically originate as (1) contaminated surface runoff flowing to the well or (2) a foreign object entering the well. Contaminated runoff enters the well through improper seals around the casing, corroded/leaky well casing, fractures that directly connect the well to ground surface, etc. The proportion of wells contaminated by bacteria vary among agricultural regions across Canada from 9% to 43%, and well surveys show frequency of wells with bacteria contamination 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

We have a lot of knowledge about the types of contamination, their sources and their transport and persistence in groundwater from site or field scale studies. However, 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 is to elevated concentrations of nitrate or pesticide but at concentrations below CDWG. We know that many wells are contaminated by bacteria, but we do not know what type of bacteria, (e.g., the pathogenic bacteria at Walkerton, Ontario, *E.coli.* 0157:H7). 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. We need to determine strategies to prevent their survival. Also, 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. The impact on groundwater of potentially large loads of contaminants (especially manure) within a small area and the distance these contaminants will travel are not known.

Policy perspective

Generally we have sufficient knowledge to define agricultural best management practices relating to soil conservation practices, waste management procedures, and pesticide/fertilzer 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. Most of the past research has focused very narrowly on site or field scale studies. Research is still required on a large regional or watershed scale, and this research needs to integrate relationships among watershed characteristics, surface hydrology, groundwater, meteorology, soil properties, agricultural management practices, etc. Most instances of contamination, especially by bacteria, are due to improper agricultural practices or poor well construction.

As the agricultural industry continues to move towards more intensive livestock operations, more agricultural contaminants that we know about (e.g., nitrate and bacteria) and some we do not know about (e.g., pharmaceuticals, viruses) will be produced, and, hence, the potential for groundwater contamination will increase. All growers and producers (both small operators and intensive livestock operations) should be required to complete and follow an Environmental Farm Plan. Also, all wells should be tested regularly for nitrates, bacteria and pesticides. But the cost to individuals and municipalities is too large to conduct an extensive and regular sampling/analyses program. Ontario has developed a Nutrient Management Act that is designed to protect water sources from manure. This law is aimed at both large livestock operations and small farms. By their sheer numbers and extensive distribution throughout Ontario, small farms generate most manure by total volume. But because of recent provincial legislation that exempts small farms from complying with the deadline, only time will tell if the legislation is successful at reducing nitrate levels in groundwater.

There are regulations governing water-quality standards and frequency of testing for municipal water treatment systems (both surface water and groundwater). However, no similar regulations for individual wells exist. For example, groundwater having poor quality and contaminant levels above CDWG that would not be acceptable for municipal systems is frequently being used as drinking water from individual wells in rural areas. 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.

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2.7 Rural and Municipal Issues

Background

Increasing public concern over groundwater quality in rural areas as a result of the bacteria contamination at Walkerton, Ontario, has put pressure on government agencies to protect these groundwater resources from agricultural activities. But, agricultural growers and producers are not the only people in rural areas competing for groundwater resources. Nor are agricultural activities the only activities that may contribute to groundwater contamination in rural areas. Non-agricultural residents and activities dependent on groundwater include single-owners, small subdivisions, municipalities (from small villages to large cities), and recreational areas (seasonal residences, campgrounds, parks, resorts, etc.). 100% of Prince Edward Island population, both rural and urban, rely on groundwater as the source of their domestic water. Major cities in Canada that rely on groundwater for a large proportion of their domestic needs include Regina, Kitchener-Waterloo, Winnipeg, Fredericton, and Charlottetown.

Issues

An increasing non-agricultural population not only depends on groundwater as a reliable source of good quality water, but also may have an 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. Therefore, land management and groundwater practices that include agricultural – rural - urban activities and needs must be adopted on a regional scale, and such implementation of practices requires input from the public, stakeholders and policy makers.

Municipal Impacts on Groundwater

Urban expansion into traditional rural and agricultural areas presents a threat to groundwater quality for both rural and urban residents. Urban growth, from small villages to large cities, is occurring everywhere in Canada. 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, such as southern Ontario and New Brunswick. As municipalities expand into rural and agricultural areas several problems may occur. Activities associated with urban development that may contribute to groundwater contamination include landfills, existing or 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.

Municipalities dependent on groundwater tend to locate their groundwater supply wells (well field) in rural areas outside of town, 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. Deicing salt is used on rural roads, but not at the volume and intensity found in compact urban road networks. Urbanization is accompanied by the introduction of industrial sites, gasoline stations, spills, etc. which could enter the subsurface near a supply well.

The City of Kitchener-Waterloo is an example of how urban growth has enveloped a well field. The Greenbrook Well Field, formerly in a rural area, is now well within the urban boundaries of the city. Increased use of deicing salt has accompanied an increased density of roads that are now within the well field. This increased use of deicing salt has resulted in a steady increase in chloride concentrations in several supply wells to the point where concentrations exceed the CDWG of 250 mg/L (from 60 mg/L in 1974 to 300 mg/L in 2000). The groundwater is now being dilutedwith water from other wells. It is projected that even if all deicing salt application ceased today, it would take decades for the contaminated groundwater to be flushed from the aquifers, and, in fact, it is projected that chloride concentrations at the supply wells would continue to increase for many years

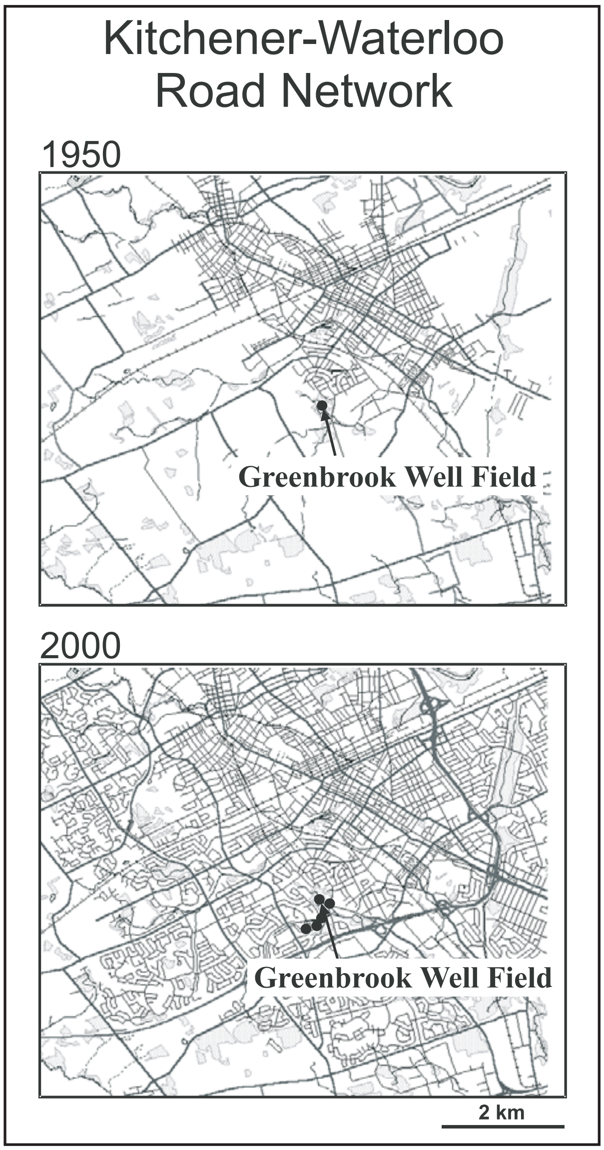

Fig. 4. Example of a municipal well field (Greenbrook Well Field, Kitchener-Waterloo, Ontario) that was originally located in a rural area but has now been surrounded by urban growth (from Bester et al., 2002).

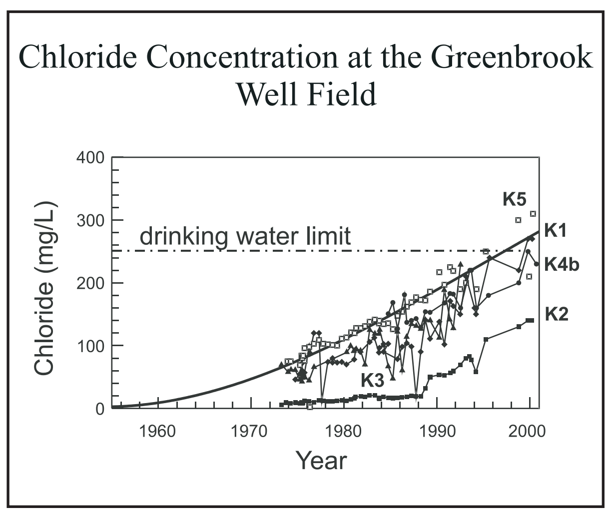

Fig. 5. The impact of long-term contamination from road deicing salt on groundwater quality at a municipal well field (Greenbrook Well Field, Kitchener-Waterloo, Ontario) (from Bester et al., 2002).

The considerable proportion of urban areas that is impermeable (pavement, roofs, etc.) 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), and reductions in replenishment of streams as groundwater baseflow. Accompanying a decreased quantity of groundwater recharge is a decrease in groundwater quality. This problem has occurred in the Oak Ridges Moraine area north of Toronto, and has resulted in restriction on development to protect groundwater and surface water recharge areas.

Expansion of urban areas into rural areas formerly serviced by individual wells may create groundwater contamination problems if these individual wells are not properly abandoned (well must be sealed). Improperly abandoned wells offer a direct pathway for the migration of urban contaminants to aquifers.

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. Municipalities are disposing of increased volumes of municipal biosolids by spreading it over the surface of agricultural lands, resulting in deterioration in the quality of groundwater and surface water. Also, municipalities are expanding into areas occupied by current and former disposal sites and these are affecting supply wells.

Even growth of small villages without municipal water treatment systems or municipal wastewater treatment systems may affect groundwater quality. Individual homes in these small villages have their own groundwater supply well and septic system. Hence, as the village grows, the number of supply wells and septic system increases. Thus, more groundwater is pumped from an area under the influence of increasing septic system loading.

Source protection

Historic and current land-use practices have affected groundwater quality in urban areas. Essentially all municipalities dependent on groundwater as their source of water 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 that include both wellhead protection and modification to land-use practices have had proven results in protecting groundwater quality. Because source protection requires land-use restrictions, it is a difficult concept for municipalities to adopt because it places restrictions on economic development.

New Brunswick's wellfield protection program

The Province of New Brunswick has implemented an excellent (and an international awarding winning!) wellfield protection program. Protection 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 (groundwater, rivers, air quality, waste water, environmental effects, etc.). Hydrogeologists have been recently hired within various regions to implement the groundwater protection measures.

Wellfield protection programs have been, or will be by 2008, implemented for all 56 municipal wellfields (20% of population) under the "Wellfield Protected Area Designation Order". Various activities within a well field protection area are controlled within three zones surrounding a well or well field, reflecting that different contaminants persist, travel, and pose risks differently.

Zone A or High Risk Zone, which is closest to the well, represents the 250 day capture area for contaminants in bedrock aquifers and 100 day capture areas in sand and gravel aquifers. It has the greatest control on both the varieties of activities (septic systems, sewer lines, manure, petroleum products, chlorinated solvents, pesticides, etc.). Zone B or Medium Risk Zone, which surrounds Zone A, represents a 250 day to 5 year capture area. Although the risk from bacterial transport is greatly reduced, other contaminants, such as petroleum products, chlorinated solvents, etc., still pose a threat to the well. Zone C or Low Risk Zone, which surrounds Zone B, represents a 5 to 25 year capture area. Controls still exist for chemicals and activities, such as chlorinated solvents and petroleum products, but are less stringent. For example petroleum storage of up to 2000 L is permitted.

There are some exemptions. For example, small petroleum storage facilities for homes are exempt.

Existing sources are exempt but they will be phased out. For example, existing petroleum sites in Zone A within 10 years, and in Zone B within 25 years; existing dry cleaning sites will be phased out within 3, 5 and 7 years, respectively in Zones A, B and C.

Individual wells (40% of population) are also being protected by both Potable Water and Water Well Regulations. All new wells are sampled for quality. All wells are being entered into a data management system.

What we know

Surveys indicate that the occurrence of groundwater contamination in Canada is equivalent to that seen in other countries (Europe, U.S., many developing countries). Urban development throughout Canada is expanding rapidly into areas that have been traditionally rural or agricultural. 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 (e.g., Kitchener-Waterloo is proposing a >80 kilometre pipeline from Lake Erie), or move the well field further into rural areas which may be susceptible to agricultural contaminants.

Urban areas produce wastes that are typically disposed in rural areas (municipal/industrial landfills and hazardous waste disposal sites). These waste disposal sites threaten rural wells, and threaten municipalities themselves as the urban areas grow and their well field expands. Increased disposal of municipal biosolids may have an impact on groundwater quality. If improperly abandoned wells exist in the area of land surface spreading, these wells offer a direct pathway for the migration of contaminants from surface to an aquifer.

Agricultural activities may impact on municipal water supplies. Manure or pesticide spreading on the land surface is especially a problem if undertaken close to an improperly constructed or inappropriately located municipal well or well field. Increased disposal of manure from intensive livestock operations have had a documented and significant impact on groundwater quality, including municipal supplies.

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.

There have been numerous documented cases of improperly constructed and maintained wells that have presented pathways for contaminants to enter a well. Also, it is suspected that improperly abandoned wells present a potential threat to groundwater quality as they offer a pathway for contaminated surface water and runoff to move into an aquifer. There are probably 100,000s of abandoned wells in Ontario alone, and most were never properly sealed.

What we do not know

Sufficient knowledge does not yet exist to assess adequately the magnitude of the diverse groundwater quality impacts occurring in both rural and urban environments. 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 we know that improperly constructed wells are pathways for contaminants to enter wells, we do now know the extent of the problem. Although it is widely suspected that improperly abandoned wells offer a pathway for contaminants to enter aquifers, there is very little scientific evidence to either 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. Typically in Canada, wells are registered when drilled, but are not registered when abandoned. Abandoned shallow dug wells, which are typically unregistered, are a potential problem. We will probably never know about them until a groundwater contamination or health problem emerges.

Policy perspective

As urban areas expand into traditionally rural areas, the threat to groundwater quality from urban sources of contamination will threaten both rural residents and municipalities relying on groundwater supply wells. Land-use 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. In addition, long-term groundwater management requires consideration of evolving land use practices and water requirements in both rural and urban settings. Implementing these land-use practices may require a major philosophical change within municipalities and local governments with respect to how they view development: there is a need to 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.

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2.8 Mining and Metals

Background

Metal mining has traditionally been a major resource industry in Canada. Mining occurs in all provinces and territories (except PEI) in Canada as both open pit and underground mines. Currently there are over 90 active metal mines. 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 produces tremendous volumes of waste, mainly in the form of waste rock during the mining operation and tailings during the ore processing stage. Lesser volumes of waste are produced during the smelting and metal finishing processes. It is estimated that mining activities in Canada have produced about 350 million tonnes of waste rock, 510 million tonnes of sulfide tailings, and 55 million tonnes of other waste. Typically groundwater contaminants from mine site wastes include metals, sulfates and acid generation. Metals include iron (e.g., Nickel Rim Mine, Ontario), nickel (Lynn Lake Mine Manitoba), copper and zinc (e.g., Sherridan Mine, Manitoba), and arsenic (e.g., Giant Mine, Northwest Territories).

Issue

There are probably over 10,000 abandoned mines across Canada. In Ontario alone, it is estimated that there are more than 6,000 abandoned mines. 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, these sites represent a source of serious contamination to groundwater and aquatic systems for potentially hundreds to thousands of years.

Contamination from metal mining

Mining produces a tremendous amount of waste rock that is disposed in piles that can cover hundreds of hectares. Waste rock has a large grain size, and hence a high hydraulic conductivity. This permits the rapid transport of water (as infiltrating precipitation) and oxygen through the waste rock. Waste rock from metal mines typically contains sulfide minerals, although the levels are often low (less than 0.1% sulfur by weight). The movement of water and oxygen through the waste rock drives the oxidation of sulfide minerals (e.g., pyrite) producing high concentrations of dissolved sulfate and iron in groundwater, as well as acidic water. As precipitation moves downward through the waste rock to the water table, it will carry the dissolved sulfate and metals and increased acidity to the groundwater regime where it will move away from the site by groundwater flow. The contaminated groundwater often discharges to lakes, rivers, streams and wetlands causing severe acid drainage problems. Field, laboratory and modelling studies undertaken by researchers indicate that the oxidation process can continue for hundreds of years. This can lead to continued groundwater and surface water contamination long after a mine has closed and the site abandoned. Concentrations of iron and sulfate in water can be very high. For example, at the Iron Mountain site in USA, concentrations of iron and sulfate have been measured at 86,000 mg/L and 760,000 mg/L respectively (for comparison, the CDWG for iron and sulfate are 0.3 mg/L and 500 mg/L, respectively). The water can become extremely acidic; a pH less than -2 has been measured at the Iron Mountain Site.

The tailings are deposited hydraulically in a natural depression or within a man-made impoundment area facilitated by an embankment or a dam. The amount of tailings produced can be huge, with some tailings impoundments covering hundreds of hectares. Generally tailings are fine grained, with a low to moderate hydraulic conductivity, and a moderate to high sulfide content. For example, the Nickel Rim mine tailings at Sudbury, Ontario, has a sulfur content of 5% by weight. Oxidation reactions in tailings occur in two stages. In the unsaturated zone above the water table, precipitation and oxygen infiltrating downward through the tailings will oxidize metal sulfide minerals (e.g., pyrite) to produce dissolved sulfate and metals, and increase the acidity of the water. The dissolved metal (e.g., ferrous iron) will also undergo oxidation and it will precipitate as a metal hydroxide, thus removing dissolved metal from the water. However, this reaction will further increase the acidity of the water. The acidic water will dissolve carbonate, hydroxide and aluminosilicate minerals, and in the process the acidity of the water will decrease and some of the metals will precipitate.

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. Contaminants can travel via groundwater flow hundreds of metres from a mine waste site. The 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 that release metals and generate acidity in groundwater. 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 high levels of metals and very 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 the flow of water 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.

In general we know very little about existing and potential groundwater quality problems at abandoned mine sites across Canada. Site evaluation is required, but the extent to which this has occurred varies from province to province. Although 50% of Ontario's 6,015 abandoned sites have been inspected, less than 1% have been tested for physical and/or chemical stability, and remedial work is currently underway at fewer than 5%. Quebec has inspected all of its 1,000 abandoned sites, with stability tests completed at most sites, and remedial measures underway at 95 sites. British Columbia, which has few abandoned mines (most mines are active), is currently developing a database of its active and abandoned mines.

Policy perspective

There is a recent federal regulation aimed at controlling the release of contaminated effluent from active mines to surface waters. Some 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 to ensure that groundwater quality is protected. 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 abandoned mines, and especially to assist in the selection of appropriate remedial technologies where groundwater has become contaminated.

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 throughout Canada 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. Currently commitments vary with company and jurisdiction. The closure costs for the Falconbridge Mine in Ontario are estimated to be $175 million, and currently the company has set aside $100 million. However, when the Giant Mine in the Northwest Territories closed in 1999 only a $500,000 bond was set aside to cover site closure costs.

There are international programs focused at developing unified prediction approaches for mine tailings and waste rock. These programs are supported by the International Network on Acid Rock Drainage Prevention (INAP), an industry sponsored research forum. Programs such as these capture the knowledge of both industry and researchers. These programs should be supported by (and joined by) government agencies that can use this knowledge when modifying and issuing standards. The current guidelines should be revisited to assess the rationale for the approaches recommended.

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2.9 Spills: LNAPLs and DNAPLs

Background

Chemical leaks or spills frequently involve organic substances that do not readily dissolve in water. This class of liquids is known as Non-Aqueous-Phase-Liquids (NAPLs). Groundwater contamination by this class of chemicals has been a major concern throughout the world because of their widespread use and production, and and because they pose a significant risk to human health at very low concentrations (in the range of parts per billion). NAPLs are associated with gasoline (benzene, toluene, xylene), electrical transformers (PCBs), wood preservatives (creosote), industrial degreasing agents (tetrachloroethylene (PCE), carbon tetrachloride), dry cleaning fluids (trichloroethene (TCE)), the manufacturing of dyes (chlorobezene), and intermediate chemicals used in the production of other chemicals (polyvinyl chloride (PVC)).

There are numerous sites throughout Canada where NAPL spills have contaminated groundwater. Most contaminated sites are very small, such as a gasoline station or a dry cleaning store. Other sites are larger, such as petroleum refineries, chemical plants, wood-preserving plants, waste disposal facilities and industrial sites. Because some of these contaminated sites, such as False Creek site in Vancouver, the waste disposal site at Ville Mercier in Quebec, the former

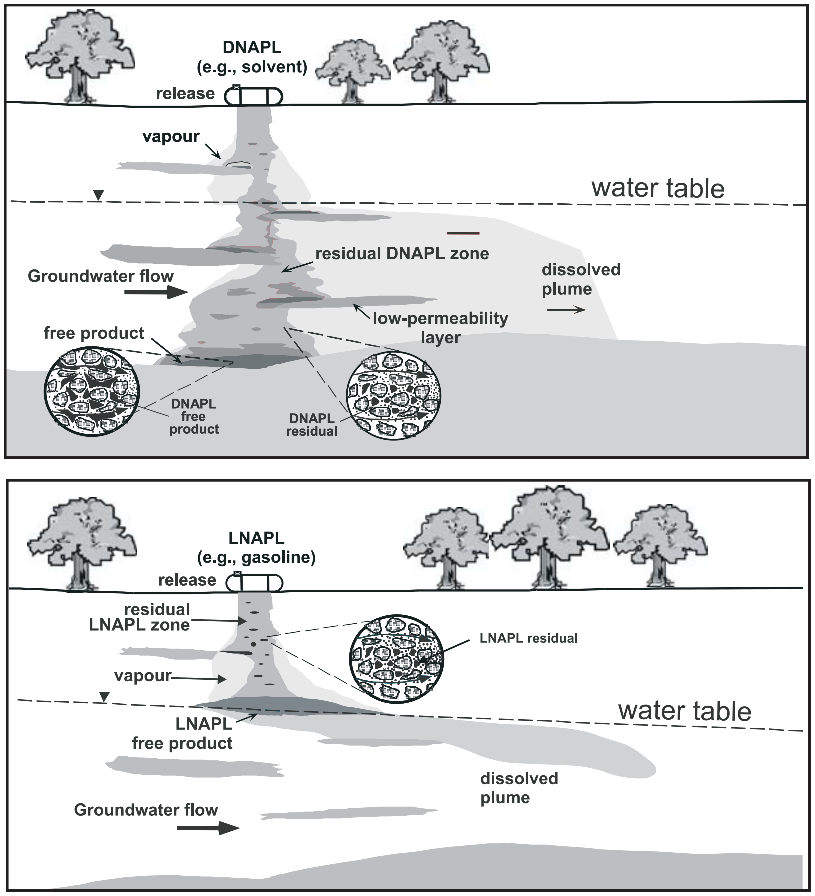

Fig. 6. Schematic representation of LNAPL and DNAPL migration through the unsaturated and saturated zones, and its partitioning into a vapour phase, a dissolved contaminant plume, and residual droplet in the pore spaces.

CWML site at Smithville in Ontario, and the Sydney Coke Oven and Tar Ponds at Sydney in Nova Scotia, have severely contaminated groundwater and have affected the water supply for numerous people, they have attained widespread media and public attention through Canada.

Issue

NAPLs pose a threat to groundwater for several reasons. First, once they have entered the subsurface, they are very difficult to remove because, in the case of DNAPLs, which have a density greater than water, the NAPL has migrated to a considerable depth below ground surface. Another issue is that of solubility. NAPLs, when mixed with water, will remain as a separate phase from water; however, NAPLs are sufficiently soluble to contaminate groundwater to orders of magnitude above CDWG. As a result, a dissolved plume will migrate along with the flow of groundwater. The rate of dissolution from the NAPL to the dissolved phase is generally very slow and consequently, NAPLs can persist in the subsurface for long periods. Groundwater that contains the dissolved phase of these NAPLs can be contaminated well beyond CDWG.

NAPLs

NAPLs can be divided into two categories: (1) LNAPLs (lighter-than-water NAPLs such as gasoline), and (2) DNAPLs (heavier-than-water, such as chlorinated solvents). The behaviour of these two types of NAPLs is quite variable in the subsurface. When an LNAPL is introduced at the ground surface via a spill or leak, it will migrate down into the subsurface and, because it is lighter than water, it will stop at the water table and form a pool. This pool will slowly dissolve to create a contaminated groundwater plume that tends to be shallow. DNAPLs, in comparison, sink deeper into the aquifer and are stopped only by low-permeability barriers, such as clay or bedrock. Contaminated groundwater plumes can result from the dissolution of (1) DNAPL pools, which form on these low-permeability layers, or (2) residual DNAPL, which is left behind in pores or fractures as the DNAPL migrates downward through the aquifer. Hence the depth of the dissolved plume will vary corresponding to the depth of the DNAPL source.

Remediation of NAPLs

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. There are several steps involved in the full remediation of a NAPL leak or spill. First, realistic clean-up criteria and objectives must be set (e.g., not "we will do our best" or "we will remove all contamination") that are based on adequate risk reduction; this will serve as the basis for the technological application. Secondly, if an aquifer is contaminated with NAPLs, remediation requires that the NAPL be located. Once this is done, the source zone (e.g., leaking barrel, contaminated soil, etc.) must be removed or contained, otherwise, the NAPL will continue to slowly dissolve into the groundwater and this dissolved plume will continue to grow for many years. Next, this dissolved plume must also be remediated to some specified level of clean up. Finally, continuous and long-term monitoring must be carried out to ensure that the aquifer has been cleaned.

However, the remediation of groundwater contaminated with NAPLs (and especially DNAPLs) is very difficult. There are technical challenges with each of the above steps that prevent or limit our ability to remediate sites contaminated with NAPLs. Also, even if we are able to remediate a site, the costs commonly involve $1,000,000s and in some case may exceed $100,000,000s.

The technologies for controlling the dissolved plume are at various stages of development. These technologies available for this task include:

1. *Pump and treat:* Contaminated groundwater is removed from an aquifer through pumping wells, and sent to a treatment facility to remove the contaminants from the water;
2. *In-situ permeable reactive barriers:* Material designed to enhance the chemical or biological breakdown of the dissolved NAPL contaminants is placed in trenches to intercept the contaminated plume as it flows through the barrier; and
3. *Natural attenuation:* Some contaminants will be removed from groundwater within a short time and within a short travel distance through natural degradation, attenuation and dissolution processes.

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. Also, the current state of technologies to do this is well developed. 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.

What we know

Based on the history of chemical use, we can anticipate the presence of NAPLs. For example, trichlorethene (TCE) is typically found in groundwater near drycleaning facilities, and benzene is common at gas stations. However, in most cases the exact location of the NAPL source may be difficult to find. In this case, 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. We have some technologies that are quite effective in remediating some NAPLs in some groundwater environments (e.g., pump and treat to remove gasoline from a sandy aquifer).

We know concentrations of dissolved NAPLs are generally very low, However, because Canadian Drinking Water Guidelines (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 heterogenieties 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^3. 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. Questions that both researchers and regulatory/policy personnel may ask include: How much DNAPL must be found and remediated; is 100% removal required, or is 90% sufficient? 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 (e.g., If at a given contaminated site, all contaminants can be removed will anyone ever drink this groundwater?)?

A potentially useful approach to transfer scientific awareness of the issues and state of the technologies to policy people would be the demonstration of remedial technologies, outcomes, costs and public policy implications at a few controlled field sites such as currently being undertaken at CFB Borden and Smithville in Ontario. Policy personnel should be involved in the validation and demonstration of emerging technologies for NAPL remediation.

In the 1980s, the petroleum industry successfully brought regulators, policy people and industry into partnership with researchers to evaluate and demonstrate groundwater contamination processes and remediation technologies. The research/ demonstration was field-based and provided a focused, realistic environment for meaningful exchange of knowledge. A key recommendation is to rekindle this partnership for LNAPLs and undertake such a partnership for DNAPLs.

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 $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 the site will never be completely remediated even if millions of dollars are spent. Also, groundwater scientists can often locate potential areas for spills; however, a limitation in policy in many cases is remediation costs are not the responsibility of the party who made the spill. 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.

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2.10 Petroleum Industry Issues

Background

Petroleum was first discovered near Petrolia in southwestern Ontario, but it was the discovery of oil at the Leduc field in Alberta in the late 1940s that greatly expanded Canada’s petroleum industry. Canadian conventional production of oil and gas is primarily focused in Alberta, southern Saskatchewan, and northeastern British Columbia. Smaller production occurs in Manitoba, Ontario, and the Northwest Territories.

There are several activities during the petroleum process from exploration to petro-chemical production that could affect groundwater quality. Oil and gas exploratory boreholes and production wells are drilled through aquifers often used as a source of water for rural residents, municipalities, irrigation, and livestock watering. Drilling and petroleum processing produce liquid wastes. Pipelines that transport oil and gas from production wells to storage facilities to refineries and petro-chemical plants are buried above rural groundwater sources. Contaminants produced in the petroleum industry that pose a threat to groundwater quality fall into four categories:

1. *Hydrocarbon* releases from drilling, spills, pipe breaks, leaking storage tanks, flare-pits, and blow-outs;
2. *Saline formation-water* releases from sump-pits, spills, and leaking pipelines;
3. *Metal* releases through formation water and flare-pits; and
4. *Naturally occurring* radioactive materials which are present in petroleum at low concentrations but can become concentrated in pipe scale.

Although the petroleum industry is becoming more conscientious about groundwater contamination and better technologies and procedures are used to prevent it, contamination will continue to occur but generally at a very localized and small scale.

Issue

The greatest threat to groundwater quality from the petroleum industry stems from the legacy of a century of (1) exploration, development, and refining (improperly abandoned exploration 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). All can act as local sources of groundwater contamination today.

Past petroleum activities

Abandoned oil and gas wells and exploration boreholes may act as a pathway for contaminant (oil, gas, saline water) migration from depth to aquifers near surface. Although boreholes wells are, as a contaminant source, individually very small, 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. When abandoned, these wells are sealed with a concrete plug near the base of the casing to prevent upward migration of contaminant fluids. In addition, the wells are constructed of steel casing that prevents formation fluids from moving into the well. If the concrete seal and the steel casing remains intact, there will be little possibility of contamination of shallow aquifers. However, although these wells were properly abandoned under existing regulations and with the current technical expertise, there is concern about the long-term viability of concrete seals within casing and integrity of steel casing to corrosion, especially because many abandoned wells are over 50 years old.

Oil and gas production typically produces brine that must be disposed through disposal wells. These brines may be as much as several times more saline that sea water. Typically the produced brine from wells and refineries is disposed back into the production formation or deeper formations. Also, the refinery and petrochemical industry produces liquid hazardous wastes that are often disposed by injection into 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 the disposal depth is too shallow and is hydraulically connected to shallow aquifers. Disposal wells in Alberta are very deep (> 650 m) and there are no reported instances of a disposed fluid coming up a well. In Ontario, the wells were much shallower (< 300 m). The shallow disposal depth in Lambton County in Ontario, 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 more common source of shallow groundwater contamination is through accidental spills. The most common source of brine contamination is through leaking pipelines. Accidental hydrocarbon releases can occur from spills during transportation, pipe breaks, leaking storage tanks, flare-pits, and blow-outs. These spills are generally very localized and at surface. Hence, they are amenable to remediation by current techniques. Because of the number and age of these localized types of impacts, industry and government have adopted various risk-based methodologies to prioritize sites for active versus passive groundwater remediation. An example of a successful policy response is the "Alberta Orphan Fund" in

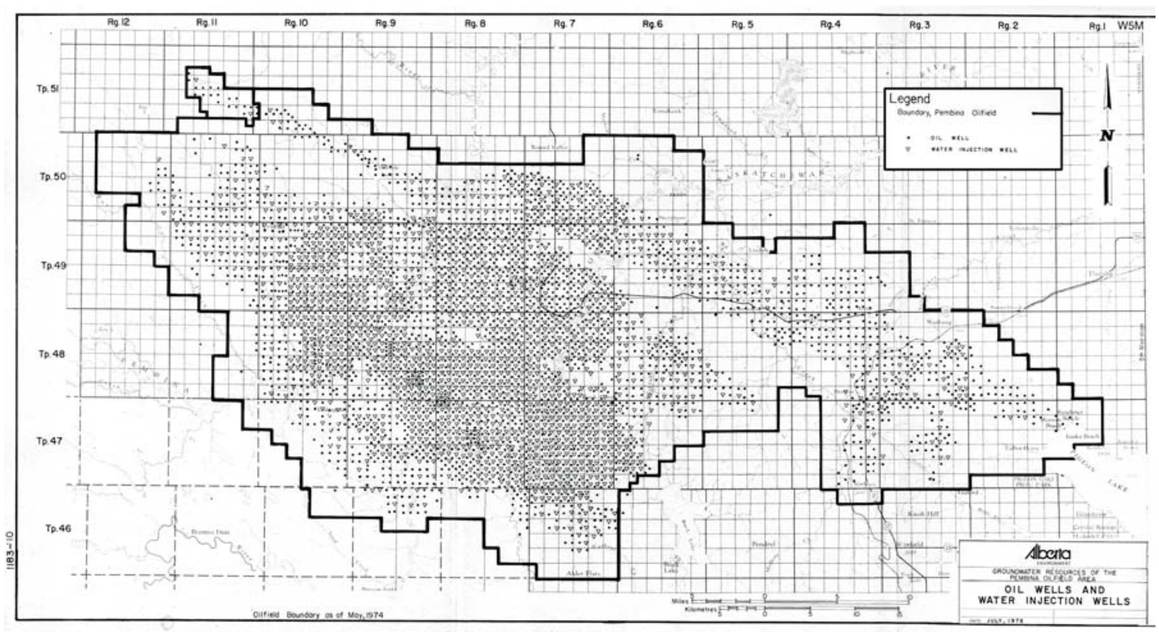

Fig. 7. Map showing the number and density of oil wells and water injection wells, as of 1976, in the Pembina Oil Field, Alberta.

which $8,000,000 has been paid into a trust fund by industry to remediate orphan sites.

Future petroleum activities

The decline of conventional oil reserves and the wholesale embrace of natural gas by American electrical generators as a clean fuel has driven Canada's petroleum industry to diversify in five substantial new directions: (1) offshore drilling on the East Coast and possibly the West Coast; (2) foothills gas; (3) Arctic gas; (4) oil sands; and (5) coal-bed methane.

Current offshore drilling activities are located in the oceans off Canada's east (Hibernia, Sable Island) and west coast. Offshore exploration and development have no impact on groundwater in these areas, except in the transmission system that moves product to refineries. Offshore drilling and production for natural gas occurs within the Canadian portion of Lake Erie. Since 1913, about 2,500 gas wells have been drilled, but only about 500 are still in production and about 20 new wells are drilled annually. Produced gas is transmitted to five collection facilities along the north shore of Lake Erie through a 2,500 km pipeline network located on the bottom of Lake Erie. Drilling for oil through offshore wells is banned, but oil fields under Lake Erie are developed through directional drilling from shore. The U.S. has never allowed offshore drilling for oil and gas, but allows production through directionally drilled wells from shore. Although there are no significant cases of groundwater contamination, the US EPA has banned future drilling and production from the US fields beneath Lakes Erie and Michigan. There is no plan for a similar ban in the Canadian portion of Lake Erie.

Exploration activities and pipelines associated with foothills gas and Arctic gas bring new challenges in applying groundwater protection and remediation practices to alpine, boreal forest, and tundra environments. Little is know about groundwater flow and contaminant transport in permafrost, except that it does not behave like porous or fractured media. More research is needed in applying known techniques and technologies in these types of environments. As well, a good baseline understanding of groundwater flow and geochemistry is lacking for much of Canada's onshore petroleum exploration areas.

Oil sands developments in northeast Alberta are growing rapidly. Currently 25% of Canada's oil is obtained from oil sands and by 2005 this proportion will grow to 50%. Bitumen-mining operations create large pits and tailings ponds that have an impact on local and regional groundwater quality. In-situ thermal-recovery operations might mobilize naturally-occurring groundwater contaminants, like arsenic. A good baseline investigation of natural groundwater geochemical quality and variability is essential. The in-situ operations also produce brine waste. Disposal options are limited because the oil-sands area is generally within a salt-intolerant, boreal forest environment. Industry and regulators are examining and approving deep-well injection schemes for these operations. Site-specific research on rock-water interactions in deep-well disposal zones is needed. A number of disposal zones interact with surface water through groundwater discharge to streams. An assessment of the dispersive capacity of these disposal zones and their interactions with surface water is urgently needed. The same can be said for sequestration of greenhouse gas in deep aquifers. Research is also needed on the cumulative environmental impact of these mega-projects on all parts of the ecosystem, including groundwater.

Coal-bed methane produces gas from fractured coal de-pressured by de-watering. Large volumes of water (up to >900 m^3/day per km^2) of marginal chemical quality (500 – 5,000 mg/L TDS) needs disposal. The impact of disposing of these volumes of water at surface or in the near subsurface in Canadian environments is totally unknown. Coal-bed methane production is becoming an increasingly important source of gas in the United States, and the first commercial production in Canada occurred in Alberta during 2002.

More scientific research on low-cost, in-situ (underground) and ex-situ (above ground) bioremediation techniques would be welcome. As well, much more research is needed on the risks and benefits of natural attenuation in Canadian-specific environments. Much research has been borrowed from American sites with much different climate, soil-types, etc. Their applicability to the Canadian context is often less than ideal.

What we know

We know that aging field, production and refining facilities, flare-pits, drilling sumps, improperly abandoned boreholes, past spills, and aging subsurface infrastructure all can act as local sources of groundwater contamination today. Exploration activities and pipelines associated with foothills gas and Arctic gas will bring new challenges in applying groundwater protection and remediation practices to alpine, boreal forest, and tundra environments. Oil-sand mining operations create large pits and tailings ponds that have an impact on local and regional groundwater quality. *In situ* oil-sand operations may have an impact on regional groundwater chemical quality. *In situ* oil-sand operations and conventional oil and gas production produce brine wastes that need disposal. Coal-bed methane production requires disposal of large volumes of marginal-quality to brackish groundwater.

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. Current remedial technologies were developed for soil and climatic conditions found in temperate regions of Canada. It is not known how these remediation technologies work in alpine or tundra environments (e.g., long and cold climates, permafrost). We need baseline hydrogeological investigations in coal-bed methane and exploration frontier areas to be able to recognize and track groundwater contaminants. We need to investigate the effectiveness of natural attenuation processes in all Canadian environments. Further research and baseline hydrogeological information are required to determine the long-term and cumulative environmental impacts of the oil-sands mega-projects, both the impact of mining and the impact of the tailings ponds. We need to determine if thermal projects, such as the steam injection for enhanced recovery of heavy oil, are mobilizing natural contaminants in groundwater 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. For example, will the streams of northeast Alberta become affected by deep-well disposal of oil-sand wastewater? We need to determine if the brackish water from coal-bed methane production should be disposed to surface water (if salinity is sufficiently low it could be a resource), or should it be injected into the subsurface.

Policy perspective

The threat to groundwater quality from all aspects of past activities (from exploration, through field production, storage, transportation, and refining/ petrochemical production) represents a major challenge to governments and industry. For example, 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. The associated costs of ensuring abandoned wells are secure or remediating contaminated aquifers are immense. There is a need for ongoing government-supported surveys of baseline conditions, and ongoing supported monitoring of groundwater chemical quality. Reliance on natural attenuation or current technologies for remediating contaminated sites may not be effective in all Canadian environments. Therefore, research or industrial development funds should be targeted to assessing groundwater remediation concepts and technologies in field conditions relevant to Canadian needs. Approval of non-conventional energy developments and development in frontier areas without adequate baseline groundwater knowledge may have unintended future consequences, affecting groundwater quality on a regional scale.

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2.11 Risk Assessment

Background

Computer models are widely used by the hydrogeological and regulatory community to simulate groundwater flow and contaminant transport. These computer models (also known as numerical models) are generally applied to two tasks: (1) to provide insight into factors controlling groundwater flow and contaminant transport or explore the implications of making an assumption about the nature of hydrogeological systems, and (2) to predict the future response of the groundwater system. The main advantage of these computer models is that a large number of scenarios can be simulated in a short period of time, considerably faster than the time-scale of natural systems.

Computer models are best suited for the first task because once the model is set up, it is relatively simple to change the input parameters in order to examine the effect of such changes on the groundwater system. Also, with the advance of processing speed on personal computers, a suite of simulations can be undertaken and analyzed in a short period of time. However, computer models are commonly used for, and expected to, provide accurate information about future events. For example, computer models are used to predict consequences to the hydrogeological environment of a spill of a hazardous material on the ground surface. Specifically, the model attempts to answer such questions as: Will the contaminant reach the water table? Will the contaminant reach a local water-supply well? What will be the concentrations of the contaminant at the well? How long will it take for the contaminant to reach the well at a specific concentration?

The procedure for building a computer model is well understood and well defined. One crucial step in building the model is estimation of the values of the parameters and boundary conditions required by the model (e.g., values of hydraulic conductivity or recharge, surface water levels). Once reasonable estimates for these parameters have been made, the model can be used to make predictions.

A major challenge in constructing accurate models to simulate groundwater flow and contaminant transport is that the real world is too complex for us to simulate every aspect or every detail. At a microscopic scale, groundwater and contaminants move through an array of pores and fractures whose spatial distribution cannot be measured in the field nor reproduced in a model. At a macroscopic or watershed scale, the presence of sedimentary sequences, variations in meteorological and hydrological conditions, as well as surface conditions, are again too complex to incorporate fully into a model. These microscopic to macroscopic conditions all have an impact on groundwater flow and associated contaminant transport. In addition, typical groundwater and contamination studies have far fewer measurements in both space and time than one would expect given the complexity of hydrogeological environments. 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 invaluable tools that can be used to aid in assessment of groundwater quality. Unfortunately, there is typically considerable uncertainty in the predictions from a computer model 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.

Uncertainty analyses

Groundwater systems exhibit considerable natural variability. For example, the process by which aquifer sediments are deposited can result in a layered system. A seemingly homogeneous sand aquifer can exhibit variations in hydraulic conductivity of 1 to 2 orders of magnitude. Because hydraulic conductivity is fundamental in the flow of groundwater and the subsequent transport of contaminants, such variability can significantly affect the flow of groundwater. Another example is that the exact nature of a contaminant source (in both space and time) may be poorly known. Regardless of how much time and effort are spent on field work, a site will never be characterized with 100% certainty.

This uncertainty in natural systems is transferred to the numerical models when we define a conceptual model for a hydrogeological site and assign values for the model parameters. Specifically, when setting up the computer model, there will be uncertainty in the input parameters required by the model. Because of the uncertainty of these input parameters, there will be considerable uncertainty associated with any results from the computer model.

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.

In dealing with this uncertainty from a computer modelling perspective, there are several methods available. The first technique, commonly undertaken in the past, 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 weigh these two simulations when making decisions.

The fourth method for dealing with this uncertainty is to perform an uncertainty analysis. Rather than using a single input value for a required parameter, this technique makes use of the known range of values for the parameter. From field measurements, we can determine the probability distribution of a parameter (e.g., hydraulic conductivity) and hence determine the mean, variance, and degree of spatial correlation between neighbouring measurements. High-speed computers are used to perform thousands of simulations using a range of values, and then are used to evaluate the numerous outputs from all these simulations, producing a probabilistic distribution of the results. For example, this could be the probability of a contaminant reaching a water-supply well within a specified time period, given the uncertainty in the input parameters.

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. 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 hydraulic conductivity 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 (e.g., few, if any, push-button software packages are available).

Policy perspectives

Computer models can be valuable tools to study groundwater quality issues. However, predictions from these models 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.

Further refinement of uncertainty analysis with respect to parameter characterization and model error should be encouraged. In practice, building ever more complex models to represent hydrogeological processes seems to be given greater emphasis than the quantitative determination of prediction uncertainty. Regulators can encourage project proponents and their consultants 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 is likely to involve trade-offs with model complexity. Where it is feasible, computer modelling should move beyond deterministic calculations adopting a conservative bias, sensitivity studies, or practical worst-case evaluation.

Emerging research themes involve development of more powerful techniques for mapping spatial variability in hydrogeological parameters. Research is needed in the quantification of prediction uncertainty that can be attributed to errors in data (when will the collection of additional data no longer reduce uncertainty?) and model structure (what is the impact of an incorrect numerical model or the misrepresentation of the conceptual model?).

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2.12 An Overview of Rural Well-Water Quality in Canada

Background

Approximately 25% of Canadians rely on groundwater as their source of drinking water. This figure includes homes, recreational facilities and residences (lakeshore cottages, resorts, campgrounds, etc.), and municipalities. Most provinces have conducted surveys of groundwater quality in rural wells. Groundwater analyses from these well water surveys have focused on three contaminants most prevalent in rural/agricultural areas: nitrates, bacteria and pesticides.

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, it must be realized that results from well surveys reflect contamination in wells and not necessarily contamination in aquifers. Contaminants found in well water may reflect a problem with well construction or surface contamination, rather than contaminated groundwater flowing into the well. However, a nation-wide perspective on groundwater quality from rural wells can be obtained from a compilation of these regional or specialized surveys.

Issue

Numerous surveys of well water quality throughout Canada consistently show that pathogens represent by far the most common well water contaminant. 10 to 40% of all rural wells have coliform bacteria occurrences in excess of drinking water guidelines. Nitrate concentrations exceed guidelines in about 15% of rural wells. By contrast, pesticides exceed acceptable concentrations 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 recommended in drinking water guidelines.

Summary of provincial surveys

Bacteria are the most common contaminant detected in rural wells. Well water quality surveys in Ontario (1,208 wells), New Brunswick (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 British Columbia, 6% of 813 wells in Alberta, 17% of 1,484 wells in Saskatchewan, 2-19% of 29-119 wells in Manitoba, 13-14% of 1,212 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 1,300 wells, Quebec was 4.3% of 70 wells (in an area of intense agriculture), British Columbia 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 be 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.

What we know

The main contaminants detected in rural wells are bacteria and nitrates. Very few wells contain pesticide concentrations above CDWG. TCE and PCE are occasionally detected in municipal wells. 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). Studies by the U.S. EPA, extrapolated to Canada, suggest that pathogens in groundwater supplies cause many cases of gastrointestinal illness each year in Canada.

Investigations into the contamination of well water suggest that well water contamination is often related to poor well location (too close to manure disposal sites or septic systems), poor well construction (no seal on the outside of the casing, leaking casing), poor maintenance (leaving cap off 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

Very little is known as yet about how pathogens move and persist in groundwater. In fact, most studies have focused on coliform bacteria, and little research (or few surveys) has been conducted on other pathogens in groundwater such as viruses. 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.

Groundwater seepage into rivers, lakes and estuaries is slow and its impacts on surface water quality are usually small compared to those of surface water runoff and erosion. In Canada, there are few documented cases where discharge of contaminated groundwater has had a significant impact on surface water and aquatic ecology. A nation-wide review of such impacts should be carried out 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. However, given the results of numerous regional and provincial surveys, and extrapolating the results of the proportion of wells with contaminants above CDWG, we can estimate the population relying on contaminated wells as a source of drinking water.

Table 3: Summary of contaminated wells in Canada (from van der Kamp, 2003).

contaminant	CDWG (MAC or IMAC)	well	% wells exceeding CDWG	estimated population relying on contaminated wells
Arsenic	25 μg/L	all	3 - 8	300,000
TCE and PCE	30 to 50 μg/L	municipal	0.2 - 0.6	70,000?
Pesticides	2 to 200 μg/L	rural	0.0 - 0.5	10,000
Nitrate	45 mg/L	rural	5 - 17	400,000
Bacteria	0 E coli/100 mL<5 or 10 coliform/100 mL	rural	10 - 36	1,000,000

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 Canada in high risk areas

Numerous well water surveys have been carried out in all parts of Canada. What is needed now is a critical review of these surveys, followed up by studies of: (a) source, movement and fate of pathogens in the subsurface, (b) public health studies related to well water contamination, (c) source area protection measures, and (d) well placement, construction and abandonment practices.

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Chapter 3.

Groundwater-related Initiatives and Perspectives

In the course of organizing this workshop, it became evident that there were other initiatives underway or proposed that directly relate to groundwater quality in Canada. Consequently, short reviews were provided for three initiatives - the Canadian Framework for Collaboration on Groundwater, CCME's Water Quality Monitoring Action Plan, and the Canadian Water Network. This session also seemed a logical place to provide various perspectives - one municipal and one American - on the topic of linking groundwater science to policy. This session on Groundwater-related Initiatives and Perspectives also helped explore possible avenues for sustaining the dialogue between the science and policy groups.

Canadian Framework for Collaboration on Groundwater

A National Ad-hoc Committee on Groundwater representing government, industry and academia has developed a Canadian Framework for Collaboration on Groundwater that puts forward a shared vision on how to manage, protect, and sustain Canada's groundwater resources. The Framework's goals are focused on four main areas:

1. acquiring a high standard of groundwater information and knowledge;
2. improving communications and collaboration among all groundwater stakeholders;
3. establishing effective linkages of groundwater information systems; and
4. providing a resource base accessible to all levels of government and stakeholders.

Recently it has become clear that due to financial restrictions, the requirement for multi-disciplinary expertise, and the inter-jurisdictional nature of groundwater, no single agency is able to address all related issues adequately. Canada's groundwater resources must be managed through close multi-governmental and stakeholder co-operation.

The Framework document identifies a series of national co-operative programs recommended at the recent national groundwater workshops held in Quebec City in 2000, and in Calgary 2001. It is a working document for discussion purposes and does not necessarily represent the views of any given government or non-government agency. The Framework structure will provide immediate access to current science and technology in support of policy design and regulations, while respecting the jurisdictional responsibilities of each level of government in all provinces and territories of Canada, and recognizing the contribution of universities, industry and other stakeholders.

Ref: http://www.cgq-qgc.ca/cgsi

CCME Water Quality Monitoring Action Plan

At present, there is no established Canada-wide network for water quality monitoring. Responsibility for monitoring is scattered among multiple agencies and jurisdictions and there are few points of coordination. As a result, water quality monitoring efforts are often fragmented, monitoring of some key issues and stressors is lacking, and the existing distributed programs and their data/information are not synthesized to form integrated regional or national pictures. With adverse health outcomes resulting from poor water quality in Walkerton, North Battleford and other Canadian communities, calls for timely and reliable information on water quality are growing. Without an integrated base of information, timely reporting to Canadians is often difficult at a regional or national level, and the effectiveness of decision-makers is hindered.

In May 2001, CCME Ministers committed to link existing water quality monitoring networks to ensure Canadians have access to comprehensive information. The CCME Action Plan on Water is designed to achieve this commitment by building a common vision towards a *network of networks* approach for water quality monitoring in Canada. This network will be an association of distributed water quality monitoring networks and programs, run by multiple jurisdictions and partners, that contribute to a national water quality information base. It recognizes and operationally reflects the CCME Statement of Principles to Guide Cooperative Arrangements on Environmental Monitoring and Reporting.

A national CCME-funded water quality monitoring experts workshop was held in October 2002 for water quality monitoring experts, managers and practitioners to present, discuss and explore current capacities, efforts, new challenges, opportunities, lessons learned, strategies and options towards strengthening linkages among distributed networks in Canada.

Canadian Water Network

The Canadian Water Network (CWN) is a federally funded Network of Centres of Excellence. The CWN's mission is to ensure Canada's leadership role in management and sustainablity of water resources, in protection of human and aquatic ecosystem health, and in sustaining economic growth in the water technology and services sector. The principal role of the CWN is to foster an integrated, coherent and national vision for water management and provide the sound research foundation needed to contribute effectively and objectively to national policy deliberations and development of regulations.

The Network was formed in November 2001 and includes 175 researchers from 38 universities, 29 companies, and 40 government agencies. Its administrative centre is located at the University of Waterloo.

Encouraging the diffusion of knowledge and technologies through multidisciplinary, multi-jurisdictional research is the main thrust of the Network. Research themes include wastewater management, safe drinking water, infrastructure and groundwater, among others.

The CWN seeks to develop a network of highly qualified experts to help combat the declining expenditures on preventing, monitoring and remediating water problems at many government levels across Canada. It notes that a national water strategy in Canada is still lacking. The challenges of the Network will be to establish itself as a catalyst for action, facilitate the networking culture, bring focus to a very diverse research program, and better connect academia, government and industry.

Ref: http://www.nce.gc.ca/nces-rces/cwn_e.htm

A Municipal Perspective

The Federation of Canadian Municipalities (FCM) created a national policy - water options team to influence federal regulations, budgets (including groundwater) and drinking water quality. Its key focus has been on watershed management. The FCM supports delineation of watershed boundaries, as well as better identification of land use activities that could affect surface and groundwater quality, to improve risk management strategies.

Municipalities are not always capable of doing all that is required to deliver safe drinking water. Participation by all levels of government is needed to ensure that infrastructure is adequately funded, national standards for water quality are provided, and operator training is improved. The FCM advocates use of full cost pricing for infrastructure services, the importance of water demand management in general, and the need to improve land-use planning to reduce the negative impact on water quality. It was noted that the U.S. Safe Drinking Water Act requires the assessment of public drinking water supplies, and that $26 billion has been allocated annually since 1998 from state revolving loan funds to do this. This was noted as a potential model for Canada.

A U.S. Perspective

The stronger federal presence in water resources issues in the U.S. was noted using the U.S. Geological Survey's National Water Quality Assessment (NAWQA) and the Regional Aquifer System Analysis (RASA) Programs as examples. The long-term goals of the NAWQA Program are to assess the status and trends in the quality of the nation's surface and groundwater resources, and to provide a sound, scientific understanding of the primary factors affecting the quality of these resources.

To foster the science-policy linkage in the U.S., the Water Science and Technology Board (of the U.S. National Research Council) has been a focal point for studies related to water resources. Their objective is to improve the scientific and technological basis for resolving important questions and issues associated with the efficient management and use of water resources. The Board frequently uses Blue Ribbon Panels to help bring together top scientists to address timely issues.

In addition, the U.S. has many well-funded environmental groups (i.e., Natural Resources Defense Council) to promote a "green agenda" and ensure that important issues get public attention. This differs from Canada in that major U.S. funding agencies (e.g., National Science Foundation) take a proactive approach to research, and their priorities focus on research that impact human problems.

The main messages included: sound policy development needs high quality science; blue ribbon panels are helpful in solving problems; the "carrot and stick" approach to funding guides research towards solving priority problems; the large scale of difficult water-related problems necessitates a multi-disciplinary approach; and the paradigm shift towards green technologies provides significant industrial opportunity for Canada.

Ref: http://www7.nationalacademies.org/wstb/WSTB_Mission_Statement.html

Chapter 4.

Groundwater Quality Issues in Canada: Problem Status and Some Implications by Dr. John A. Cherry, Professor and NSERC Chair in Contaminant Hydrogeology

The following is a summary of Dr. John Cherry's after-dinner presentation during the workshop. It incorporates issues raised during the question-and-answer period following his presentation and follow-up discussions with colleagues at the workshop.

Problem status:

Our groundwater resources provide drinking water for 8 million Canadians. These resources have suffered from long-term neglect in nearly all parts of Canada. This neglect stems from a weak government framework and regulations for groundwater monitoring, management and protection in Canada. However, out of the recent tragedies has come an exceptional circumstance. There is now real interest at the political level in taking action to improve the role of government in groundwater management. This provides exceptional opportunity for the policy and research communities to cause long-term improvements in the Canadian groundwater situation. Several recommendations for action that could be taken at minimal cost are presented.

Canada in the environmental context

Canada is faring poorly in comparison with other developed countries with regard to the environment. A recent assessment, done by the Environmental Law and Policy Group at the University of Victoria and based on data assembled by the Organization for Economic Cooperation and Development (OECD), ranks Canada's environmental record to those of other industrialized nations in the OECD. "The results prove that Canada has one of the poorest environmental records of the industrialized countries. The primary finding is that for the twenty-five environmental indicators examined, Canada's overall ranking among OECD nations is a dismal 28th out of 29."

Canada in the groundwater quality context

It is clear that in terms of groundwater quality protection Canada ranks far behind the United States and some northern European Countries. Some indicators of this lag are:

1. People are becoming more concerned about the public water supply; bottled water has become a way-of-life for an increasing number of Canadians.
2. There is no anticipation or prediction of problems by assessing the record of contamination events in other countries.
3. Causing groundwater contamination beneath private property is not strictly illegal and therefore there are no strong incentives to avoid such events. This is a problem because nearly all on-property groundwater contamination eventually causes off-property contamination after years or decades pass.
4. Laws and regulations for groundwater protection are often weak and/or unenforced in most areas of Canada. Lack of enforcement is often related to inadequate numbers of government staff or lack of political will.
5. There is avoidance of minimum national standards or regulations for groundwater quality; each province does its own thing, with large gaps in performance between the worst and the best.
6. Huge gaps exist between the actual scientific knowledge used in policy and decision making and the knowledge available from the research community.
7. Much of our limited government funds for groundwater issues are spent on problems of immediate political sensitivity rather than problems of importance based on rational and organized assessment of risk to human health or the environment or cost benefit.

There are many examples of groundwater crises in Canada, where political risk is the main, if not the only criterion for action. Examples of political-risk decision making include groundwater contamination incidents at Regina, SA, Smithville, ON, Elmira, ON, Ville Mercier, PQ, and Walkerton, ON. The performance of government is nearly always the same. Governments are caught off guard and respond with unscientific decisions, causing huge waste of tax dollars and loss of public confidence. By the time relevant information available from the research community somehow gets into the hands of policy/decision makers, the critical decisions for large expenditure commitments (and public promises) have been made. For this to change, senior levels of government administration will have to become aware of how the existing approach wastes money, and then mechanisms need to be put in place for the relevant scientific knowledge to be located or developed in a timely manner so that it can be used when crises arise.

Some unique aspects of groundwater contamination

There are some unique aspects of groundwater contamination that require a different management approach than is needed for surface water management:

- Most important contaminants in groundwater are not noticeable by taste, colour or odour; hence homeowners generally have no awareness that they may be drinking contaminated water because the water is clear, cool, and generally tastes okay.
- Much contamination found in wells today is usually caused by long-ago events, with the result that cause-and-effect are rarely obvious.
- Contaminant plumes in aquifers are often difficult to locate.
- The number of aquifers that supply Canada's drinking water greatly exceeds the number of rivers and lakes providing drinking water.
- Most rural residents who rely on well water for their households live in the country or small towns and use their own private wells as their source of groundwater.

It is more difficult to protect groundwater users through monitoring than it is to use monitoring to protect the users of rivers and lakes (i.e., it is almost impossible to locate wells properly, adequately sample groundwater, and analyze every potential contaminant in order to ensure groundwater contamination is detected before it reaches public wells. Inadequate monitoring likely results in more Canadians suffering adverse health effects due to contaminated groundwater than due to contaminated surface water.

Why is Canada so far behind the United States, Germany, Denmark and others in groundwater monitoring, management and protection?

It is because of our political system:

- Backbenchers and opposition MPs/MLAs rarely initiate legislation; therefore, any backbenchers who feel strongly about environmental issues or local contamination problems are irrelevant.
- Our constitution puts groundwater in the provincial jurisdiction making federal intervention (i.e., consistency in regulations and involvement in groundwater crises) difficult.
- The political system cannot be changed, so change will have to come through pressure and perseverance within the existing system.

How can we overcome this disadvantage caused by our political system?

- The civil service at all levels of government must strive to make advances whenever and wherever possible, particularly when the political climate is favourable.
- Up-to-date science rather than other perceptions of reality needs to be used in our problem solving.
- The environmental NGOs, such as Pollution Probe, Sierra Club and Greenpeace, are essential elements to create public awareness and political incentive.
- Members of the research community must be more proactive; we must strive to bring scientific advances to the attention of decision makers and the large professional community.
- Government agencies must seek out what the research community has to offer, both in terms of science per se and the knowledge that the research community has of groundwater policies and activities in other countries.

Some recommendations of things that we could do without allocation of large new funding

1. Set up a federally funded arms-length organization equivalent to the U.S. National Academy of Sciences
   - To use members of the research community in Canada and elsewhere to access leading knowledge from the research community focused on problems of national/provincial relevance; this organization would address problems put forth from various parts of Canadian society.
2. Establish an environmental crisis assistance office to respond quickly with credible scientific advice in response to new crises (e.g., the former Environmental Secretariat of National Research Council – cancelled in 1982).
3. Strengthen the environmental audit arm of the Auditor General's office to achieve reliable and independent reporting on the state of the Canadian environment, including groundwater environment.
4. Establish permanent "hydrogeological survey" organizations in each province to conduct subsurface data acquisition /compilation (applied research).

5. Rationalize the groundwater research mandates for each of the federal departments so that they make sense in terms of the overall Canadian needs and research capacity and capability in Canada.
6. Develop an improved framework for identifying and funding research at Canadian universities so that those Canadian problems suitable for academic research are not ignored.
7. Establish a federal office to track what goes on in other countries with regards to strategies/practices of groundwater monitoring, management and protection, so Canada can more readily take advantage of advances being made in other countries. This office should develop minimum Canadian guidelines/expectations so that the provinces can compare their situations to a reasonable minimum.
8. Bring clarity of groundwater issues and economics to the attention of our politicians, so that they can see the need for particular legislation/regulations.

Reasons for some optimism

Although I have focused on Canada's poor record in the groundwater domain relative to comparable countries, there are some signs of recent progress that may yield long-term benefits, for example:

- The creation and operation of the Groundwater Protection Act of New Brunswick.
- The creation of a professional staff of groundwater specialists in several regional (municipal) governments and local "conservation authorities" in Ontario such as Waterloo Region.
- The recent creation of four positions for groundwater professionals in Nova Scotia (brings the provincial groundwater professional staff to six, up from 2 in 2000, but still down from the staff of 8 in 1980).

The main question now

Will the Walkerton effect on our Ministries of the Environment and our federal government result in permanent steps forward, or will the influence only be temporary, as generally has been the result from past groundwater pollution crises in Canada?

Chapter 5

Linking Water Science and Policy

In addition to the policy perspectives highlighted in each of the science updates, 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

There was wide-spread consensus that in Canada the bulk of the research effort and expertise in the groundwater quality area now rests in academia. The technical expertise in provincial agencies has been especially reduced. Consequently, academics often feel insulated from the government decision-making process, and conversely, policy and program managers are not getting the required research intelligence they need to help them make better decisions. In fact, this was the main motivation for holding the current workshop. Suggestions included getting government policy and program managers explicitly involved with some of their research projects, to build in policy considerations up front in these research projects and research funding, and for government to encourage managers to participate in learning sabbaticals at universities. Participants concluded that to strengthen the link between science and policy, the onus rested not only with researchers, but also with practitioners by more aggressively seeking out the science that would strengthen their agency's management response. Additional suggestions are highlighted below and in the final section of this workshop report.

2. Policy should keep pace with evolving science

There was general agreement that the water-related regulatory and policy response needs to keep pace with the evolving science. Delegates argued that there is currently sufficient groundwater knowledge to have avoided the tragic events of Walkerton, Ontario. However, the reality is that the current science is only one of many factors considered in the development of public policy. Some experts argued that Canada has lagged behind most developed countries in proactively managing its groundwater resources, largely because of the perceived limitless supply of water. In any case, workshop participants argued there is currently sufficient scientific knowledge and technology expertise to make significant improvements to groundwater management in this country.

3. Getting the science out

For various reasons, the results of some 20 years of groundwater quality research in Canada, for the most part, are not making their way to decision-makers. Some argue the technical (research) community has the responsibility to convince government authorities that protection of groundwater quality is a priority. In fact, scientists have little incentive to ensure their study results are communicated to "lay", decision-making audiences. Further, scientists rarely have the inclination to be politically active. Others may argue that it is up to government authorities to seek the advice of scientific and technical experts for their policy and regulatory initiatives. This is warranted because most of the research funding comes from government. There are numerous creative ways to improve on this, such as electronic networks, regular science-policy meetings, improved incentive structures for government funded research, and the use of expert panels to help bring the required research to support government priorities. This workshop is the first step towards this need to "get the science out," and the final chapter of this report offers additional details.

4. Repositories for scientific information and expert directory

To help "get the science out," there is a need for repositories of organized scientific information on groundwater quality. This should be updated regularly so that it is readily available for decision-making. In addition, an expert online directory could be developed where willing scientists with expertise in groundwater quality could serve as expert contacts to policy-makers on various issues.

5. Expert panels for quick decision-making

Typically, researchers and policy developers are on different time tracks. The development of policies, regulations and programs often happens at a rapid pace and the need for quickly attainable, up-to-date information, including science, is paramount. In Canada, there appears to be no existing mechanism to initiate priority groundwater quality research for policy making. In the U.S., as an example, the Water Science and Technology Board of the National

Research Council, frequently uses Blue Ribbon Panels to help fund research towards priority policy development areas. Such expert panels can also provide immediate guidance for groundwater contamination problems. Workshop participants were strongly supportive of the expert panel approach in Canada.

6. 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. At a minimum, there was keen interest in what various jurisdictions were doing with respect to policy initiatives. There is a need for a concise, regularly updated compilation of groundwater quality policy and program initiatives across Canada for quick reference, for the purpose of sharing and learning from previous experience. Also, the content of future groundwater quality science-policy workshops should be developed based on the research needs of policy and program managers.

7. 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.
- regional/watershed assessments.

Chapter 6

Maintaining the Dialogue

Workshop delegates were extremely supportive of the need for continued information exchange and dialogue between the science community and policy/program managers in the area of groundwater quality. As this report is being produced, the CCME is considering options for maintaining and, indeed, expanding on the dialogue initiated during the workshop. In addition to presenting the recent science, workshop participants were also insistent that future initiatives at maintaining the dialogue also include recent policy initiatives and programs, across the country, directed at improving or maintaining groundwater quality.

Follow-up Workshops - The potential for periodic follow-up workshops (both general "State of Groundwater Quality in Canada" and specific groundwater quality issues), or perhaps dedicated sessions at selected conferences, for both the science and policy communities was viewed as desirable. Additional opportunities included future joint workshop sessions with two significant contributors to the current workshop - Canadian Water Network and CRESTech - both of which have considerable institutional and public policy mandates in their respective initiatives. The science topics to be presented at any follow-up meeting should, in part, be responsive to the current policy needs and pressures at that given time. Finally, developing periodic state of the science or science assessment reports on groundwater quality is another option.

Electronic Networking - Various electronic media, such as dedicated or re-vamped web sites, electronic bulletin boards, moderated chat rooms, and subject-specific, subscription-based email lists will be considered as a means of ensuring that the flow of information continues. An additional possibility is development of an expert directory where scientific experts could be quickly consulted for urgent groundwater issues. Although these kinds of electronic networks require sustained effort and resources, and have met with varying levels of success in the past, they may prove effective at maintaining interest in the period between workshops.

Ultimately, the logic for bringing researchers and policy managers together is to ensure better public policy decisions, and herein lies CCME's interest. Bringing the latest scientific knowledge to decision makers is critical in helping to target programs, and in developing and implementing more refined policies to remediate and protect groundwater quality. The dialogue at this workshop, reflected in these proceedings, serves as a starting point for this improved resource decision making.

Appendix 1: Workshop Program

March 21-22, 2002

Alpine Ballroom - Sheraton Gateway Hotel - Toronto Airport

Day 1 - Thursday March 21

11:00 - 11:30 ***Welcome and Introductions***
Ken Dominie, Co-chair, Water Coordination Committee, CCME; and Assistant Deputy Minister, Ministry of Environment, Newfoundland
Al Kohut, Water Protection Section, BC Ministry of Water, Land, and Air Protection

11:30 - 12:00 ***Overview of groundwater flow and contaminant transport processes***
Dr. Robert Gillham, NSERC/Motorola/EnviroMetal Technologies Inc. Industrial Research Chair in Groundwater Remediation, Dept. of Earth Science, University of Waterloo

12:00 - 1:00 lunch

13:00 - 13:30 ***Fractured rock environments***
Dr. Kent Novakowski, Queens University, Dept. of Civil Engineering

13:30 - 14:00 ***Natural groundwater contamination***
Dr. Carol Ptacek, Research Scientist, National Water Research Institute, Environment Canada

14:00 - 14:30 ***Role of aquitards in contaminant containment***
Dr. Jim Hendry, NSERC-Cameco Research Professor, Dept. of Earth Sciences, University of Saskatchewan

14:30 - 15:00 ***panel discussion #1: Linking science to policy:***
facilitated by **Dr. Dan McGillivray**, CRESTech

15:00 - 15:30 coffee

15:30 - 16:00 ***Pathogens***
Dr. William Woessner, Dept. of Geology, University of Montana

16:00 - 16:30 ***Agricultural activities***
Dr. Dick Coote, Agricultural Watershed Associates, Ottawa

16:30 - 17:00 ***Rural and municipal activities***
Dr. David Rudolph, Dept. of Earth Sciences, University of Waterloo

17:00 - 17:30 ***panel discussion #2: Linking science to policy:***
facilitated by **Dave Briggins**, N.S. Environment and Labour

18:30 - 20:30 dinner
with presentation by Dr. John Cherry, NSERC Industrial Chair in Contaminant Hydrogeology, Dept. of Earth Science, University of Waterloo

Day 2: Friday March 22

7:30 - 8:30	breakfast (introductions for the day)
8:30 - 9:00	***Mining and Metals*** **Dr. David Blowes,** Canada Research Chair in Groundwater Remediation, Dept. of Earth Sciences, University of Waterloo
9:00 - 9:30	***Spills (DNAPL's & LNAPL's)*** **Dr. Jim Barker**, Dept. of Earth Sciences, University of Waterloo
9:30 - 10:00	***Impact of the petroleum industry*** **Dr. Kevin Parks**, Senior Hydrogeologist, Alberta Geological Survey, Edmonton
10:00 - 10:30	***panel discussion #3: Linking science to policy:*** facilitated by **Dr. Susan Till**, NRCan
10:30 - 11:00	coffee
11:00 - 11:30	***Risk assessment and uncertainties*** **Dr. Leslie Smith**, Cominco Chair in Minerals and the Environment, Dept. of Earth and Ocean Sciences, University of British Columbia
11:30 - 12:00	***Watershed management, groundwater protection zones, and monitoring*** **Darryl Pupek**, Director, New Brunswick Ministry of Environment and Local Government
12:00 - 12:30	***panel discussion #4: Linking science to policy:*** facilitated by **Dr. Alex Bielak**, NWRI
12:30 - 14:00	lunch
14:00 - 14:20	***Well water quality in Canada*** **Dr. Garth van der Kamp**, National Water Research Institute, Environment Canada
14:20 - 15:20	***Groundwater Initiatives and perspectives:*** Canadian Groundwater Association; **Jamie McDonald**, Director and Past President of the CGWA Federation of Canadian Municipalities; **Russell Powers**, Co-Chair of FCM's National Water Options Policy Team Framework for Collaboration on Groundwater; **Dr. Alfonso Rivera**, Chief Hydrogeologist, Geological Survey of Canada, NRCan CCME Water Quality Monitoring Action Plan; **Rob Kent**, Manager, Science Liason & Integration Branch, Environment Canada Canadian Water Network; **Don Lewis**, Executive Director, Canadian Water Network U.S. perspective; **Dr. Frank Schwartz**, Ohio Eminent Scholar, Ohio State University
15:20 - 16:25	***Synthesis and Recommendations:*** facilitated by **Dr. Graham Daborn**, Director of the Policy and Governance Theme for CWN and Director of the Acadia Centre for Estuarine Research ***overview of the workshops by:*** university: **Dr. Frank Schwartz**, Ohio Eminent Scholar, Ohio State University provincial government: **Jim Gehrels**, Groundwater Studies Coordinator, Ont. MOE federal government: **John Cooper**, Director, Water Issues, Environment Canada non-government organization: **Rick Findlay**, Director, Pollution Probe
16:25 - 16:30	***Concluding Comments from CCME*** **Ken Dominie**, Co-chair, Water Coordination Committee, CCME

Appendix 2: Speakers' Biographies

Dr. James. F. Barker

Dr. Barker is a professor in the Department of Earth Sciences, University of Waterloo, Waterloo, Ontario. He holds a Ph.D. from the University of Waterloo, where he has been a faculty member since 1980. He is currently Chair of the Earth Sciences Department. Jim's research has concentrated on the migration, fate, and remediation of organic contaminants in groundwater. Petroleum hydrocarbons (MTBE and alcohols), coal tar creosote organics, and other industrial chemicals have been emphasized. His research uses field studies, with supporting lab and modeling studies, at contaminated sites and at the experimental aquifer site at Canadian Forces Base Borden. Current research emphasises the use of monitored natural attenuation for groundwater remediation. Also being developed are more active, *in situ*, remedial technologies, emphasizing enhanced biodegradation.

Dr. David Blowes

Dr. Blowes is a professor in the Department of Earth Sciences, University of Waterloo, Waterloo, Ontario. He received B.Sc., M.Sc. and Ph.D. degrees from the University of Waterloo in Earth Sciences and Contaminant Hydrogeology. He is currently a Professor in the Department of Earth Sciences, University of Waterloo, where he holds a Canada Research Chair in Groundwater Remediation. Dr. Blowes has conducted research on the fate and remediation of metals at mine sites and industrial sites, including field investigations, laboratory bench tests and numerical model development. Dr. Blowes holds five international patents on treatment systems to remove contaminants from groundwater, wastewater and agriculture run-off. These technologies have been licensed in Europe, the U.S. and Canada. Dr. Blowes is a recipient of the Ontario Premiers Research Excellence Award and the NSERC Synergy Award for his contributions in groundwater remediation research. He has served as a Review Panel Member for NSERC, and has participated in program reviews for the Australian Nuclear Science and Technology Organization Managing Mine Wastes Programs, and the U.S. Geological Substances Toxic Substances program.

Dr. D. Richard Coote

Dick Coote (Ph.D., P.Ag., P.Eng.) obtained a Ph.D. in the field of Agronomy from Cornell University in 1973, after working for 2 years in Jamaica. From 1973 to 1978 he was the technical coordinator of the Agricultural Watershed Studies of the International Joint Commission's program to determine the effect of land use activities on the Great Lakes. In 1978 he joined the Research Branch of Agriculture Canada as a scientist working on soil and water quality issues. He developed expertise in evaluating soil degradation under different agricultural practices across Canada, as well as studying the effects of acid rain on Canadian soils. He became manager of the Canada Soil Survey in 1991, responsible for federal soil mapping and analysis in all provinces and the Yukon Territory. Since 1996 Dick Coote has operated Agricultural Watersheds Associates, undertaking soil and water research and interpretations for various federal government departments, as well as numerous private companies. He has particularly focussed on groundwater, including modelling of nitrate flow through soils, and mapping vulnerable aquifers. He was the Technical Editor for an extensive report on agriculture and water quality in Canada, published by Agriculture and Agri-Food Canada in 2000 (*The Health of our Water - toward sustainable agriculture in Canada*). His recent experience has included providing technical assistance to the legal team monitoring the Walkerton Inquiry into contaminated water. Since 1987 he has operated a 180 acre farm southwest of Ottawa, where he grows soybeans and various grains, and raises beef cattle.

Dr. Allan S. Crowe

Allan Crowe received his B.Sc. in Earth Sciences from the University of Waterloo, and his M.Sc. and Ph.D. in Hydrogeology from the Department of Geology at the University of Alberta. He has over 25 years of experience in hydrogeology, undertaking projects across Canada. He is currently employed as a Research Hydrogeologist Environment Canada's National Water Research Institute. His principle research interests include understanding the role of groundwater in the hydrological balance of wetlands and lakes and assessing the fate of pesticides in the subsurface, including the development and application groundwater flow and solute transport models. In addition to his research activities at NWRI, he provides technical assistance to several government agencies and committees. He is also an adjunct professor at the University of Western Ontario and at McMaster University. He is Past-Chair of the

Canadian Chapter of the Society of Wetland Scientists, past associate editor of Hydrogeology Journal, member of the Water Resources Theme of CRESTech, and on the National Ad-hoc Committee for the development of "A Framework For Collaboration In Groundwater Across Canada".

Ken Dominie

Ken was born in the small outport community of Francois on the South Coast of Newfoundland. He received his early education in Poet Aux Basques where he graduated from high school in 1965. Ken holds a degree in civil engineering from Nova Scotia Technical College (Halifax) and a Bachelor of Science and a Master in Business Administration from Memorial University of Newfoundland. He began his career with the Newfoundland government in 1974 as a water systems engineer with the Department of Municipal and Provincial Affairs. In 1976, he transferred to the Department of Environment where he has held a number of positions. In May of 1998, he was appointed Assistant Deputy Minister of Environment, a position he currently holds.

Dr. Robert W. Gillham

Dr. Gillham is a professor in the Department of Earth Sciences of the University of Waterloo, Waterloo, Ontario. He currently holds the Natural Science and Engineering Research Council/ Motorola/EnviroMetal Technologies Industrial Research Chair in Groundwater Remediation. Concurrent with his academic positions, he has been Director of the Waterloo Centre for Groundwater Research, President of EnviroMetal Technologies, and is currently the Scientific Director of the Canadian Water Network under the Canadian Networks of Centres of Excellence Program. He is a member of the American Geophysical Union, and the Association of Ground Water Scientists and Engineers. He has been the recipient of numerous awards including a Doctor of Science, Honoris Causa from the University of Guelph, was awarded the Miroslaw Romanowski Medal of the Royal Society of Canada and is a Fellow of the Royal Society of Canada. He has been Heiland Lecturer at the Colorado School of Mines, and Nabor Carrillo Lecturer for the biannual meeting of the Mexican Society of Soil Mechanics. He was editor of the Journal of Contaminant Hydrology and has served on numerous regional, national, and international committees on groundwater quality. He has authored or coauthored over 140 publications on various aspects of groundwater, ranging from the behavior of individual groundwater constituents to modeling of groundwater transport, under laboratory and field conditions. Robert Gillham was named to the Order of Canada in 2002. Robert Gillham received a B.S.A. degree in General Science from the University of Toronto; and M.Sc. in Soil Science from the University of Guelph; and a Ph.D. in Agronomy from the University of Illinois.

Dr. M. Jim Hendry

Dr. M. Jim Hendry is a professor in the Department of Geological Sciences, University of Saskatchewan, Canada. He holds the endowed Cameco Research Chair in Aqueous and Environmental Geochemistry and a Natural Sciences and Engineering Research Council of Canada - Industrial Research Chair. Dr. Hendry obtained his Ph.D. in Earth Sciences from the University of Waterloo in 1984. For the past 20 years, his research interests have included the fate and transport of solutes in low permeability geologic materials and biotic and abiotic reactions in unsaturated zones. Dr. Hendry was the Distinguished Darcy Lecturer for 2000. He is also a Member of the College of Reviewers for the Canada Research Chairs Program and is an associate editor for the Canadian Geotechnical Journal. Dr. Hendry is also a past associate editor for the Journal of Ground Water and Contaminant Hydrology and served two terms on the Association of Ground Water Scientists and Engineers board of directors.

Rob Kent

Rob Kent has a B.Sc in Biology/Environmental Resource Science from Trent University and a M.Sc. in Aquatic Toxicology from the University of Ottawa. He has worked in the area of water quality and environmental pollution assessment and management for the provincial and federal governments and consulting sector for 17 years. As Chief of the Guidelines and Standards Division in Environment Canada, he led the development of national water quality guidelines and assessments under the auspices of the CCME for 8 years. He has authored/co-authored over 35 peer-reviewed publications in the areas of water quality, toxicology, guidelines and risk assessments. During the past 2 years, Rob's new team in the Environmental Quality Branch of Environment Canada has been spearheading a campaign to re-vitalize water quality monitoring networks in Canada and he currently directs the national coordination office for the department's water quality monitoring program.

Al Kohut

Al is currently a Senior Groundwater Specialist with the Water Protection Section of the Ministry of Water, Land and Air Protection in Victoria, British Columbia. He started working with the provincial government 27 years ago as a groundwater engineer and has been involved in various groundwater supply and quality investigations. In recent years he has been involved in examining regulatory and non-regulatory options for groundwater management and developing provincial guidelines and standards for well drilling and testing. He holds a Master of Science degree from the University of Manitoba and prior to coming to British Columbia worked as an engineering geologist with the federal government in Western Canada and as a hydrogeologist in Africa for a Canadian consulting firm.

Don Lewis

Don has worked in the private sector for 20 years, for industry and in consulting. His work focussed on environmental assessment of receiving water bodies, wastewater management and disinfection technologies. He has completed collaborative research with industry, government and university researchers in Canada and the U.S. He was hired as the first Executive Director of the Canadian Water Network in November of 2001.

Dr. Kent Novakowski

Dr. Novakowski received M.Sc. and Ph.D. degrees in hydrogeology from the Dept. of Earth Sciences, University of Waterloo in 1982 and 1992, respectively. During the period 1989 to 1998, he led the Groundwater Remediation Project at Environment Canada's National Water Research Institute. In September of 1998, Dr. Novakowski joined the faculty of the Dept. of Earth Sciences, Brock University and is now an Associate Professor in the Dept. of Civil Engineering at Queen's University. Since 1993 he has taught undergraduate and graduate courses in introductory groundwater, groundwater modeling, surface hydrology, and flow and transport in fractured rock. Dr. Novakowski has also contributed to or led numerous short courses on the hydrogeology of fractured rock held in Canada, the U.S., South Africa, and Australia. In addition to teaching, Dr. Novakowski and his graduate students conduct both experimental and theoretical research on the hydrogeology of fractured rock. This includes the development of innovative site characterization techniques, the development of detailed conceptual and numerical models for groundwater flow and contaminant transport in fractured rock, and the study of regional groundwater flow in fractured rock environments. Dr. Novakowski has disseminated his research results through frequent publication in refereed journals, invited seminars and papers in North America and abroad. Dr. Novakowski is presently on the editorial board of the Journal of Contaminant Hydrology, and a recent past Associate Editor of Water Resources Research and the Journal of Groundwater. Dr. Novakowski has consulted on several contaminated sites across North America and is presently acting as the senior advisor to the U.S. Environmental Protection Agency on a pilot project to remediate a TCE-contaminated bedrock site using steam injection.

Dr. Kevin Parks

Dr. Parks is a registered professional geologist in the Province of Alberta and is presently Senior Hydrogeologist, Alberta Geological Survey of the Alberta Energy and Utilities Board, in Edmonton, Alberta. Dr. Parks obtained his Honours Degree in Geology and Master's Degree in Geology, specializing in Petroleum Hydrogeology from the University of Alberta, and his Doctorate in Geology, specializing in Hydrogeology, from the University of Calgary. Dr. Parks has worked both as a professional petroleum geologist and as a hydrogeologist throughout Western Canada, but primarily within the Alberta Sedimentary Basin. As a petroleum geologist, Dr. Parks has worked in conventional oil and gas exploration and development, oil sands, and reservoir characterization with companies such as Dome Petroleum, Chevron Canada Resources, and Petro-Canada Oil and Gas. As a hydrogeologist, Dr. Parks has worked on water-supply and contaminant investigations, mostly in the upstream oil and gas sector, for Alberta Environment and CH2M HILL in Calgary. He is presently leading a team of Edmonton-based geoscientists at the Alberta Geological Survey engaged in hydrogeological mapping and characterization studies of Devonian, Cretaceous, and Quaternary aquifers in support of regulation and development of Canada's burgeoning oil-sands industry in Northern Alberta. He also works in ongoing regulatory reviews of proposed oil-sand developments at the EUB and supports the EUB in hearings and adjudication procedures as a technical advisor.

Russell Powers

Russ is a Councillor and Deputy Mayor of the New City of Hamilton, Ontario. He is a member of the National Board of Directors of the Federation of Canadian Municipalities (FCM) and also the Chairman of FCM's National Water Options Policy Team.

Dr. Carol Ptacek

Dr. Carol Ptacek received her B.A. from the University of Wisconsin-Madison in Geology, and her M.Sc. and Ph.D. from the University of Waterloo in Contaminant Hydrogeology. She is currently a Research Scientist with the National Water Research Institute of Environment Canada and a Research Associate Professor in the Department of Earth Sciences, University of Waterloo. She has conducted research on the fate of organic solvents and petroleum products in groundwater, the fate of metals at mine and industrial sites, and the fate of septic-system derived nutrients and pathogens from on-site wastewater disposal systems. Dr. Ptacek holds five international patents for passive treatment systems to remove metals, arsenic, selenium, radionuclides, pathogens and nutrients from contaminated groundwater, wastewaster, and agricultural run-off. These technologies are licensed in Europe, the U.S. and Canada. Dr. Ptacek is a co-recipient of the NSERC Synergy Award for her contributions in mine remediation research. She has served as Expert Panel Member for the U.S. EPA, and Review Panel Member for NSERC.

Dr. Alfonso Rivera

Alfonso Rivera studied engineering, hydraulics, surface hydrology and quantitative hydrogeology in Mexico, USA and France. He was responsible for the water supply systems of the Laguna Verde Nuclear power station in Mexico and investigated several coastal aquifers along the coast of the Gulf of Mexico. He built the only existing three-dimensional numerical model of the great Mexico City by coupling hydrogeology and mechanics to simulate groundwater overexploitation and land subsidence simultaneously. For 14 years, he worked in European countries as expert hydrogeologist. He was involved in national programs for the underground disposal of radioactive wastes in Switzerland, Germany and France. During his stay in Europe, he was involved in various research institutions and universities in France and Spain. In 1999, Dr. Rivera was appointed chief hydrogeologist of the Geological Survey of Canada. He is responsible for the hydrogeological projects within NRCan and is leading the national program on groundwater within the Canadian Groundwater Advisory Council.

Dr. David L. Rudolph

Dr. Rudolph is an Associate Professor in the Department of Earth Sciences at the University of Waterloo. He teaches in the areas of Applied Hydrology and Physical Hydrogeology. His main research areas include regional groundwater development and management, groundwater movement in fractured low permeability sediments and unsaturated porous media. He has worked extensively on the management of municipal groundwater supplies including the aquifer systems used by the Regional Municipality of Waterloo and other areas within southern Ontario. In addition to collaborative research work throughout North America, he has worked on groundwater management projects in Mexico, Costa Rica, Brazil, Chile and India. Dr. Rudolph is extensively involved with the agricultural industry within the Province of Ontario in the area of environmental impacts and alternative management practices. He is a member of the Water Quality Working Group of the Ontario Environmental Farm Coalition and is currently working on several collaborative research projects in partnership with different agricultural sectors. Dr. Rudolph is a registered professional engineer and member of the Board of Directors of the Association of Scientists and Engineers of the National Groundwater Association.

Karl Schaefer

Karl is a senior science-policy advisor at the National Water Research Institute in Burlington, Ontario. He has a Masters Degree from the University of Waterloo, in the areas of water resources management and environmental economics. His appointment at NWRI serves to strengthen the water science-policy link. He was previously an Environmental Economist and Bi-national Programs Coordinator with the Great Lakes Corporate Affairs Office of Environment Canada in Ontario Region, where he worked on Great Lakes issues. He is a past member of the International Joint Commission's Council of Great Lakes Research Managers.

Dr. Frank W. Schwartz

Dr. Frank Schwartz joined The Ohio State University in 1988 as the Ohio Eminent Scholar in Hydrogeology. He was formerly a Professor of Geology at the University of Alberta. Frank is the author of more than 140 publications and is known internationally for his work on field and theoretical aspects of mass transport, contaminant hydrogeology, and groundwater geochemistry. In recognition of his contributions to hydrogeology, he was named as a co-recipient of the prestigious O.E. Meinzer Award in 1984, a co-recipient of the Excellence in Science and Engineering Award in 1991, and the King Hubbert Science Award in 1997. He was elected as a Fellow of the American Geophysical Union in 1992. In addition to teaching and research, Frank acts as a consultant to government and industry, and in various advisory capacities. He has served on a variety of expert panels of the U.S. National Research Council and chaired the committee reviewing the applicability of contaminant transport models to contemporary problems in hydrogeology

Dr. Leslie Smith

Dr. Smith is a Professor in the Department of Earth and Ocean Sciences at the University of British Columbia. He holds the Cominco Chair in Minerals and the Environment at UBC. His research program has included investigations of transport processes for nonreactive and reactive solutes in fractured rock masses, stochastic analyses of fluid flow and solute transport in heterogeneous porous media, hydrogeological decision analysis and risk assessment, hydrologic processes in waste rock piles at mine sites, parameter estimation and inverse modeling, and radionuclide transport in watersheds near the Chernobyl Nuclear Power Plant. He has served as a consultant for numerous government and private agencies in Canada and the United States. Dr. Smith is a member of the Research Management Committee of the Canadian Water Network. He presently serves as President-Elect of the Hydrology Section of the American Geophysical Union. Dr. Smith is a Fellow of the Royal Society of Canada and the American Geophysical Union. He is a recipient of the Geological Society of America Meinzer Award, the American Geophysical Union Macelwane Medal, and an NSERC Steacie Fellowship. He has served as the Geological Society of America Birdsall Lecturer, and the Canadian Geotechnical Society's Cross Canada Lecturer.

Dr. Garth van der Kamp

Garth van der Kamp obtained his Ph.D. in Hydrogeology in 1973 from the Free University of Amsterdam. At present, he works for Environment Canada at the Saskatoon branch of the National Water Research Institute. His previous experience includes groundwater studies in many parts of Canada and a large CIDA-sponsored rural well project in West Africa. His present research deals mainly with interactions between groundwater and surface water, focusing on the role of groundwater in the hydrologic cycle, and the impacts of landuse on groundwater quality. As Adjunct professor he supervises graduate students from several Canadian universities, and he is a vice-president of the International Association of Hydrogeologists - Canadian National Chapter.

Dr. William W. Woessner

Bill Woessner has been teaching classes in applied hydrogeology at the University of Montana since 1981 including classes in hydrogeology, advanced hydrogeology, groundwater modeling, applied groundwater modeling, surface water–groundwater interaction and groundwater remediation. He received his B.A. in Geology from the College of Wooster, a M.S. in Geology from The University of Florida, a M.S. in Water Resources Management and a Ph.D. in Geology (Hydrogeology with a minor in Civil and Environmental Engineering) from The University of Wisconsin-Madison. Dr. Woessner's research specializes in regional hydrogeology, water supply, surface water-groundwater interactions and groundwater modeling. Recent research has also examined virus transport in groundwater. He is the co-author with Mary P. Anderson of Applied Groundwater Modeling. Professor Woessner has served on committees of the National Research Council, taught short courses on groundwater modeling and acted as a consultant for private companies, the states of Montana and Arizona, and numerous federal agencies. He presented the 2000 Farvolden Distinguished Lecture at the University of Waterloo.

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