ON THE INVENTORY OF THE GROUNDWATER RESOURCES OF CANADA AND THE CONCEPT OF SUSTAINABLE GROUNDWATER DEVELOPMENT

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ABSTRACT
In Canada, groundwater contributes to about 30 percent of the water supplied by municipal systems, agriculture, and other users. Groundwater use in Canada has seen an important increase since the 1970s; it went from 10% in the late 1960s to 30% in the late 1990s, a 20% increase in less than 30 years. The trends are that groundwater use will continue increasing in Canada. On the other hand, the groundwater resources at the scale of the country remain virtually unknown. The last comprehensive evaluation of the knowledge of the occurrence and hydrodynamic behaviour of groundwater, particularly related to the hydrogeological regions of Canada, was done in 1967 by the Geological Survey of Canada (GSC). Recent federal and provincial initiatives include assessments and an inventory of regional aquifers. The concepts developed to carry out an inventory of the groundwater resources of Canada are introduced with a series of regional-scale assessments of key Canadian aquifers. The sustainable yield concept of regional aquifers is discussed and a working definition is proposed.

RÉSUMÉ
Au Canada, l'eau souterraine représente environ 30 p. 100 de l'eau qui alimente les systèmes municipaux, l'agriculture et d'autres usages. La consommation en eau souterraine au Canada a connu un important accroissement depuis les années soixante-dix; elle est passée de 10 p. 100 à la fin des années soixante à 30 p. 100 à la fin des années quatre-vingt-dix, soit une augmentation de 20 p. 100 en moins de 30 ans. Les tendances actuelles indiquent que la consommation en eau souterraine continuera d'augmenter au Canada. D'autre part, les ressources en eau souterraine à l'échelle du pays demeurent pratiquement inconnues. La dernière évaluation exhaustive des connaissances sur l'occurrence et comportement hydrodynamique de l'eau souterraine, dans les régions hydrogéologiques du Canada, a été réalisée en 1967 par la Commission géologique du Canada (CGC). Des initiatives fédérales et provinciales récentes incluent la caractérisation et l'inventaire des aquifères régionaux. Dans cet article, nous introduisons les concepts qui ont été développés pour effectuer l'inventaire des ressources en eau souterraine du Canada, en nous appuyant sur une série d'études de caractérisation régionale des principaux aquifères canadiens. Le concept du développement durable des aquifères régionaux est discuté et une définition de travail est proposée.

1. INTRODUCTION

In contrast to other developed nations, Canada does not have a national-scale and current inventory of its groundwater resources. As a country, Canada does not have a national strategy to manage water resources, these are managed independently, and sometimes, differently, by the provinces and territories. Thus, there are no specific plans at the national level. However, a general sense is slowly emerging in that groundwater is to be kept as a strategic resource against climate changes, severe droughts, and/or water exports. The mapping of the groundwater resources of Canada is by no means complete. Coverage is variable among jurisdictions, and what has been accomplished has not been done to consistent standards. Such is Canada's groundwater corundum.

Canada's valuable groundwater resources are very significant but because they are hidden below the ground they are less understood and known. Nevertheless, ten million Canadians rely on groundwater for their water supply, and the health of our streams and ecosystems depends upon it. Groundwater also sustains economic activity and provides significant water supplies for industries involved in manufacturing, mining and agriculture. It is a renewable resource that requires improved levels of investigation, information systems and wise management to protect its integrity, security and its sustainable management.

As a country, Canada seems reluctant to manage its water resources wisely and in an integrated fashion. Integrated water-resource management means the inclusion of social, environmental, and economic factors applied to both surface water and groundwater simultaneously. Furthermore, an integrated management does not separate water quantity from water quality, it considers both to be inextricably interconnected. Although acknowledged by most, this is still a rare practice in most countries. Canada has the potential and expertise to apply this approach, but it lacks the will.

Over the last few years, there have been many concerns in Canada about the country's groundwater resources, these involve questions about their future sustainability and quality. The sustainability of groundwater resources is a function of many factors, including depletion of groundwater reserves, reduction in streamflow, loss of wetland and ecosystems, saltwater intrusion, and changes in groundwater quality. Each groundwater system and development situation is unique and requires an analysis adjusted to the nature of the existing water issues.

Groundwater will likely become a more strategic national water resource in Canada. Thus, there is an urgent need for the characterization and delineation of the groundwater resources found within Canada at both regional and national scales. It is therefore recognised that both groundwater quantity and quality have to be accurately inventoried, its vulnerability to contamination understood and any potential for over-exploitation, thoroughly evaluated. These knowledge gaps will need to be reduced to provide better information to assist in management of the resource.

This paper introduces the concepts developed to carry out an inventory of the groundwater resources of Canada, with a series of regional-scale assessments of key Canadian aquifers. The sustainable yield concept of regional aquifers is discussed and a working definition is proposed. A very preliminary synthesis of the groundwater stored in aquifers is presented with results from completed regional studies across Canada, as well as the implications for groundwater use and its role in the hydrologic cycle.

2. REGIONAL GROUNDWATER RESOURCES AND USE

The groundwater use in Canada varies from province to province, from none in the Northwest territories to 100% reliance in the province of Prince Edward Islands in the Atlantic (Table 1).

Table 1. Groundwater use in Canada, (Statistics Canada, reported in 2003, with data from 1996).

	Population reliant on GW (%)	Municipal water system reliant on GW (%)
Newfoundland and Labrador	33.9	23.5
Prince Edward Island 1	100.0	100.0
Nova Scotia	45.8	41.7
New Brunswick	66.5	72.7
Quebec	27.7	36.7
Ontario	28.5	42.7
Manitoba	30.2	50.0
Saskatchewan	42.8	65.7
Alberta	23.1	29.0
British Columbia	28.5	45.3
Yukon Territory	47.9	100
Northwest Territories & Nunavut	0	0
Canada	30.3	41.2

As shown in Table 1, in 1996, 30% of Canadian population (close to 10 million people) relied on groundwater resources for their drinking water. Many of these people lived in small municipalities or in rural areas where the water distribution systems were fed totally or partially by groundwater—it often being the only reliable source of water available.

The groundwater use in Canada has increased from 10% in 1970 to 30% at present. The use of water in the various sectors indicate that agriculture and domestic uses are by far the ones using the most of groundwater (Table 2).

Table 2. Freshwater withdrawals in Canada, by sector, in 1991.

	Industrial	Agriculture	Domestic	Total
Surface water	71%	11%	17%	44.1 km^3
Groundwater	14%	43%	43%	1.0 km^3
Total	70%	12%	18%	45.1 km^3

Groundwater sources generally provide water that is safe to drink. This is especially true if the well field is protected from pollutants. Aquifers that are close to the surface are more prone to contamination by pollution, which partially explains the poor water quality that is characteristic of many shallow wells in Canada. Some studies have pointed out that, groundwater generally lies within 20 meters of the surface in southern Canada. (Cherry, 1987).

In the 60s and 70s in Canada, drainage basins were used as frameworks to studying groundwater flow systems (Brown, 1967), generally at shallow depths. As knowledge increased, it became possible to more closely define groundwater flow systems, particularly at greater depth; studies were directed more towards flow systems not defined by detailed surface topography but general surface elevations, geological knowledge, and the hydrological properties of the rock through which the water flows.

Hydrogeology is now a relatively mature science, where we understand much about the physics and chemistry of groundwater flow; despite that fact, the groundwater resources of Canada are still not well understood. The last attempt at a national assessment of Canada's groundwater resources was in 1967 (Brown, 1967) – over 35 years ago. Recent federal and provincial initiatives indicate a new momentum towards a comprehensive assessment and inventory of regional aquifers. The document *Canadian Framework for Collaboration on Groundwater* (Rivera *et al*., 2003a) produced by a national ad-hoc Committee, is being used as a catalyst to fill in the knowledge gaps of the groundwater resources in Canada.

It can be argued that "we know a lot about groundwater", but few would disagree that there are significant information gaps. These gaps include the need to map aquifers, better understand the amount of groundwater being stored and used, and improve knowledge about renewable rates. Furthermore, there is a need to improve our understanding of the place of groundwater, and the interactions with other components, in the complex water cycle.

How much groundwater do we really have? Which are the major regional aquifers in Canada? What is the volume of groundwater stored? What are the recharge rates of regional aquifers? What are the groundwater fluxes of regional aquifers? What is the average residence time of groundwater in regional aquifers as estimated from the fluxes and volumes? What is the groundwater use in Canada? What is our understanding of the interactions between groundwater, surface water and aquatic ecosystems? How sustainable are the groundwater resources?

These and other questions need to be answered and discussed. This is a first essay and an attempt to address these issues through a partial inventory of the groundwater resources of Canada with the available information and knowledge gathered by regional-aquifer assessments performed by the GSC.

2.1 Concept of regional aquifer

We use the concept of "regional aquifer" as defined by Tòth (2002), and modified and adopted by Rivera et al. (2003b) for the GSC. A regional aquifer is a hydrostratigraphic unit limiting the cross-formational rate and/or volume of fluid flow through its matrix material to values that are insignificant as compared to the rates and or volumes involved in the problem considered (the areal extent commonly exceeds hundreds of square kilometers).

Regional aquifer may be further defined in terms of both spatial and temporal scales and also in relation to surface water bodies. We will distinguish three spatial scales: regional, local and site. The regional scale typically extends to greater than 1000 km^2 and is in general in steady-state conditions (at least as observed in Canada). The local scale is typically hundreds of square kilometers and it may be both in steady-state and transient conditions. The site scale is generally less than 100 km^2 and is typically in transient conditions (i.e., effects of pumping).

Finally, a regional aquifer may be defined, either in addition to, or independent from the above, when its hydraulic connection with a surface water body (river, lake) is important. That is, when an important amount of volume of the surface water body is maintained by the aquifer, or when the aquifer receives an important amount of water form a surface water body on a yearly basis and at the basin scale (e.g., the surface water basin).

Many aquifers in Canada are in unconsolidated deposits of sand & gravel formed by rivers or lakes created from melting glaciers during the last ice age; regional examples of these are: Kitchener-Waterloo ON; Fredericton area, NB; Carberry aquifer, MB; and Fraser Valley aquifer, BC. Many other regional aquifers are in fractured-rock formations; regional examples of these are: Entire P.E.I. (sandstone); Winnipeg region (carbonate, shale), MB; Montreal region (carbonate, dolostone, dolomite), QC; and Moncton area (carboniferous), NB.

3. RATIONAL FOR AN INVENTORY OF THE GROUNDWATER RESOURCES OF CANADA

A national inventory of groundwater resources was first suggested at the 1st National Workshop on Groundwater in 2000, and confirmed at the 2nd National Workshop on Groundwater in 2001. It became a National Co-operative Program within the Canadian Framework for Collaboration on Groundwater (Rivera et al, 2003a).

Various initiatives are in the planning process or being developed in Canada on a province-by-province basis (Alberta's 'Water for Life' and 'La Politique de l'Eau' of Quebec), and in some cases, these are even different within the same province (Ontario's 38 Water Conservation Authorities). However, as a country, Canada lacks a coherent, comprehensive, long-term water vision or strategy; most of the water investments are done to develop surface water resources, very little is being done to assess and develop groundwater.

The development and management of groundwater resources requires the <u>assessment</u> of GW resources at all scales: locally, regionally, provincially, nationally, and internationally. A national assessment of GW resources requires an inventory (for provincial management), and a parallel scientific effort allowing the assessment to be rigorous and scientifically-based.

A series of quantitative regional assessments that are gradually integrated into a national inventory will be developed. The assessment of aquifer dynamics will include: recharge, discharge, estimation of sustainable yield, and quantification of aquifer vulnerability at the regional scales.

A full inventory of the groundwater resources of Canada will provide basic knowledge, which will :

- Assist all levels of government in making informed decisions (e.g., protection, management, and sustainability)
- Benefit Canadians who use groundwater
- Be applicable to all regions of Canada
- Be integrated with the applicable municipal, provincial, territorial, and federal groundwater mandates

The National Groundwater Inventory (NGI) is not a stand-alone project, it will be built progressively by provincial and national agencies adopting a standardize workflow. The NGI will start in the priority areas of each jurisdiction in Canada and thereafter builds out to the peripheries. The GSC will play an important role in coordinating infrastructure and housing the national inventory.

The rational, selection and assessment of key regional aquifers in Canada, as defined in the Groundwater Program of the Geological Survey of Canada, are discussed below.

4. SAFE YIELD AND SUSTAINABLE DEVELOPMENT CONCEPTS

Historically, the management of groundwater resources was based on measures of the "safe yield" of a pumping well, and later of an entire aquifer, frequently taken to equal the long-term average recharge in the case of a whole aquifer or a percentage of the maximum drawdown of a well based on a long-term pumping tests (Theis, 1940; Todd, 1959). This approach had as its primary goal the fulfilment of economically and socially imposed demands for water which was assumed should be satisfied. Under the approach of sustainable development of groundwater resources, there has been a shift of emphasis to recognise the needs of the aquatic environment such as groundwater-fed springs, wetlands, riparian zones, rivers and lakes. This is even more relevant in Canada where most of the shallow aquifers have hydraulic connections to surface water bodies.

A relatively new approach to sustainable development includes socio-economic and environmental issues. It is currently argued among water scientists, that sustainability is a socio-economic term, not a scientific one. The reasoning is that, historically, sustainability was linked simply to water available for human uses over a long period of time. Now, however, sustainability also is linked to aquatic ecosystems that are dependent upon groundwater inflows. Nearly all groundwater withdrawals have an impact on the amount of groundwater that discharges to streams. Therefore sustainability becomes whatever society accepts with respect to trade offs between environmental impacts and economic impacts.

Another current school of thought acknowledges that "water resources sustainability is not a purely scientific concept, but rather should be viewed as a perspective that can frame scientific analysis" (Alley and Leake, 2004).

In Canada water has always been taken for granted. Thus, there has been no consistent approach to develop groundwater resources in a sustainable manner. The province of Alberta was among the first to regulate the use of the safe yield obtained from wells in the 1960s. The safe yield from a well, Q_n, (n= 20 years), is estimated based on the available drawdown, H, in the well and the transmissivity of the aquifer. The estimate is made using a modified form of Jacob's equation for a well with a 20-yr lifespan.

There is, however, no existing definition of sustainable development for groundwater resources in Canada as compared, for example, with countries in the European Union. The methodologies currently emerging in the EU for sustainable development re to water, are based around the concept of integrated river basin management. Under this perspective, the achievement of sustainable groundwater development is done through the balance of recharge inputs to aquifer storage (the groundwater resource) against discharge outputs for economic, environmental and human (social) benefits (Hiscock et al, 2002).

4.1 Proposed working definition

Keeping the regional-scale scope for the assessment of aquifers, we propose that the volume of groundwater that can be extracted from a groundwater system (one or more aquifers hydraulically interconnected) be such that it does not cause adverse effects to humans and the environment. These effects may be:

- groundwater overexploitation (withdrawals exceeds recharge)
- long-term harm to ecosystems (decrease in, or obliteration of, groundwater-fed streams, ponds, or lakes)
- saltwater intrusion
- changes in groundwater quality
- Land subsidence due to compaction of aquitards
- Decrease of water table with increasing pumping costs
- Changes in land drainage patterns

Some or all of these may be used as indicators for groundwater availability and for managing the resource. It is acknowledged, however, that the sustainable development of groundwater resources is an evolving issue and should be performed by phases.

In a first phase, any program which includes long-term, sustainable development of groundwater resources, must begin with a thorough scientific assessment of the aquifer(s) involved. An important understanding in these assessments is the hydrodynamic equilibrium, whereby a balance should be quantified between the groundwater that is available and all the components involved in the complex overall water cycle. Furthermore, the actual use of groundwater (pumping) should be known as close as possible, and used in the assessment of the hydrodynamic equilibrium.

Given the complexity of these process and the number of variables involved, the best way to perform the analysis is with the use of numerical models. The numerical models should be carefully built and calibrated and should be revisited at least every 5 years as post-audits. That is, the accuracy of the model's predictions should be examined *a posteriori* by correcting uncertainties and errors in the original model. In that way, the models can be kept constantly calibrated and could be used as decision-making tools to evaluate the sustainable yield and long-term development of the aquifer(s).

Other phases may include social, economical and other environmental issues, such as costs of pumping, urbanization, industry development; or linkages to climate changes when these are suspected to have impacts to water resources (Rivera et al., 2004).

We could cite as a possible example the recent drought situation in the Prairies. In those unexpected cases, having a clear understanding of the long-sustainable yield for regional aquifers, may help alleviate drought by using water in an integrated manner, or in a conjunctive use with surface water. For instance, extracting more water from wells in dry periods (from storage) and less on wet periods (replenishment).

The bottom line is that we need to:

- Have a detailed quantitative assessment;
- Design and operate a groundwater monitoring system; and
- Build, calibrate and periodically revise numerical models.

We proposed that optimal groundwater development conditions be based around the concept of sustainable safe yield (Ssy) of an aquifer system, both as function of space and time:

$$Ssy = f\left[\frac{\partial Ss}{\partial x_i};\frac{\partial Ss}{\partial t}\right] \quad (1)$$

where Ss represents the aquifer storage (calculated from the aquifer specific storage). The sustainable safe yield (Ssy) can then be calculated with a balance equation, such that :

$$Ssy(x_i,t) = (R+\Delta R)-(D+\Delta D)-Q+\frac{dV}{dt} \quad (2)$$

where: R and D are natural recharge and discharge rates; ΔR and ΔD are change in recharge and discharge; Q is pumping; V is the volume of water stored in the system; and ΔV/Δt is the rate of change in storage (Ss). When dynamic equilibrium is reached in eq. (2), there is no further withdrawals from storage (Ss), so that ΔV/Δt=0 and the system is in steady-state.

When ΔV/Δt=0, then Q=(ΔR-ΔD) which is the pumping, or capture, of the system, and this is considered to be sustainable.

When assessing a regional aquifer with a sustainable development goal, Ssy [f(X_i,t)] should be assessed considering all of the following:Water budgets (natural and disturbed);

- Quantification of natural recharge (from precipitation or induced surface water bodies);
- Quantification of natural discharge (e.g., surface water bodies);
- Quantification of withdrawal (pumping f(t));
- Hydraulic diffusivity per area (T/S or K/Ss);
- Inventory of surface-water bodies; and
- Assessment of natural boundary conditions.

The evolving concept of sustainability presents a challenge to hydrogeologists to translate complex socio-economic and political questions into technical questions that can be quantified systematically. Hydrogeologists can contribute to sustainable water resources management by presenting the longer-term implications of groundwater development as an integral part of their aquifer assessments. Finally, we recommend that sustainable development of groundwater resources be accompanied, or be an integral part of, water management practices at the municipal and/or provincial level.

5. SYNTHESIS OF CURRENT KNOWLEDGE

This is an analysis supported by a number of regional-scale studies and based on current hypothesis and expert opinion. Some indications are drawn from completed regional projects, as well as from basic knowledge of the geology and hydrogeology of Canada.

Most of the regional aquifers so far inventoried by the GSC were found to be exploited at shallow depths, to a maximum of 200 m, but most between 20 to 100 m depths. Possible reasons for this are: abundance of freshwater at shallow depths; it is cheaper to build and maintain; quicker to develop and use; generally of good quality; fears that deeper groundwater might be of lower quality; and indications of decreasing permeability with increasing depth.

While there is no complete and clear knowledge of trends from coast to coast, some trends can be drawn from regional projects completed so far by the GSC, and from basic knowledge of geological, hydrogeological, climatological and groundwater use conditions across Canada.

Certain local conditions dictate otherwise; however, in general there is not a steady drop and depletion of the groundwater level in Canada, nor is there evidence of decreasing volumes (e.g., groundwater storage in aquifers) or declining supplies. Most of the regional aquifers in Canada are in pre-development conditions. That is to say that they are in hydrodynamic equilibrium (recharge equals discharge).

In general, Canadian regional aquifers cannot be compared to regional aquifers in the U.S.A., many of which are either fully developed or overdeveloped (i.e., discharge is greater than recharge). They include aquifers such as the Ogallala in the High Plains or the San Joaquin Valley in California.

Only one aquifer has been documented having an important decline of the groundwater level. The Estevan aquifer in southern Saskatchewan (Maathuis and Van der Kamp, 2003), where the water table was locally lowered by more than 45 m - and by nearly 20 m as much as 20 km away - by a field of pumps extracting water for electricity generation. However, this drop is a local decline. Pumping was halted in 1994. While the pumping was originally thought to be well within the sustainable yield of the aquifer, further studies now show that recharge is occurring at a rate of only 1 mm to 3 mm per year, suggesting the local water table will take thousands of years to fully recover.

On the water quality side, there are instances of groundwater contamination in Canada, however, most are at the local level (i.e., from point sources such as livestock effluents, mining, other Industry, waste disposal sites). A few are at the regional level, from diffused contamination (i.e., non-point sources such as agriculture). Groundwater is a renewable and finite natural resource that is vulnerable to natural and human impacts. Modern urban development, agricultural practices and land use are the main causes of groundwater quality problems in Canada.

5.1 Key Canadian Regional Aquifers

A first evaluation of regional aquifers was done following previous hydrogeoolgical regions proposed by Brown (1967). A new hydrogeological regions map was produced using the digital Geological Map of Canada, the National Atlas Climate Regions and permafrost zones.

The physiographical groundwater regions from the GSC (Figure 1; Rivera et al., 2003b), are:

- Cordillera
- Western Canada Sedimentary Basin
- Canadian Shield
- Hudson Bay lowlands
- Southern Ontario lowlands
- St-Lawrence platform
- Magdalena basin
- Appalachian mountains
- Permafrost

Most of the aquifers that can be found in the first three regions are bedrock aquifers and intermontane valley or overlying sediment aquifers. The Southern Ontario lowlands and St-Lawrence platform regions, contain sediment aquifers with buried bedrock aquifers. The Magdalena basin on eastern Canada is one of the most productive aquifers composed of carboniferous rock forming bedrock with highly fractured aquifers.

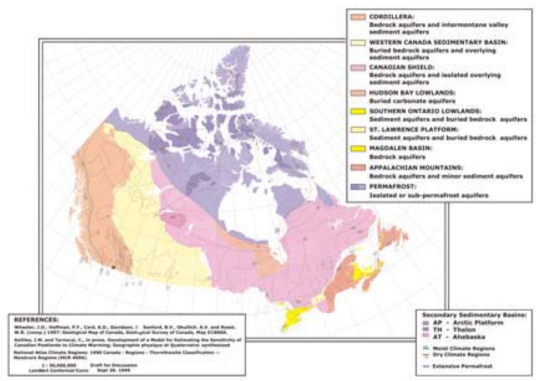

Figure 1. Hydrogeological regions of Canada (modified from Brown, 1967).

A second step included the analysis and selection of key regional aquifers to be assessed by the GSC groundwater program over the next 10 years in collaboration with the provincial governments. Table 3 lists the 30 regional aquifers selected within the GSC groundwater program. In this list, a "key" regional aquifer is an aquifer that responds to GSC priorities (Rivera et al., 2003b).

Six of these aquifers had already been mapped and fully assessed prior to the GSC groundwater program during the period of 1997 to 2003. Other six aquifers from the list will be assessed from 2003 to 2006. After that phase of the program, it is expected to continue the program with another phase whereby at least 10 more aquifers will be mapped by 2010. The results from all of the regional aquifers in the list, will gradually build-up the national inventory of groundwater resources.

Though it is still early to frame a Canadian portrait of the groundwater resources of the country, some indicators of the status and trends in stored groundwater volumes, groundwater flow rates, and uses of groundwater, can already be depicted nationwide.

Groundwater variables are reported primarily by major ("key") regional aquifer systems.

5.1.1 Recharge rates

Table 4 presents recharge rates for some of the regional aquifers whose assessment has been completed by the GSC. As seen in the partial list of table 4, recharge rates range from 70 to 500 mm of recharge per year, accounting to 9% to 30% of the precipitation in the corresponding region.

5.1.2 Groundwater fluxes

Water fluxes constantly happen between the atmospheric, surface an subsurface components of the hydrologic system. Fluxes among these three reservoirs should be understood and quantified. At the regional scale, we generally neglect the storage of water in the under-saturated zone and consider only the water stored in the saturated zone. The fluxes to and from the groundwater reservoir (saturated zone) are called recharge and discharge, respectively. Groundwater fluxes to and from surface water bodies have not been systematically measured in the regional assessments.

Some of the regional projects of the GSC have considered surface water and groundwater connections through the use of boundary conditions in the numerical models built. Two of these are the Mirabel aquifer in St-Lawrence Lowlands, Quebec, and the Oak Ridges Moraine, southern Ontario.

In the Oak Ridges Moraine aquifer system, the groundwater fluxes to streams and lakes are approximately 14 m^3/s and 1.5 m^3/s, respectively, accounting for about a third of the yearly natural recharge to the aquifer system. Thus, following our reasoning from section 4.1 above, in order to maintain those fluxes to surface water bodies, a sustainable yield in that area should account for those fluxes, in addition to the withdrawal for human supply.

Similarly, estimates with a numerical model in the Mirabel aquifer system north of Montreal, showed that groundwater fluxes from the aquifer system to streams (discharge) accounts for 76% (Nastev et al., in review).

Table 3. The GSC Key Regional Aquifers.

Physiographical Region	**Regional aquifer and/or GW region**
CORDILLERA	Fractured aquifers-Gulf Islands
	Nanimo Lowland
	Fraser Lowlands
	Okanagan Valley
	Shushwap Highlands
PLAINS	Paskapoo formation
	Buried valley aquifers
	Upper Cretaceous sands
	Milk River
	Judith River
	Eastend-Ravenscrag
	Inter-till aquifers
	Carbonate rock
	basal clastic unit (Winnipeg)
	Odanah shale
	Sandilands
	Assiniboine delta
Southern Ontario	Oak Ridges Moraine
	Grand River Basin
	Credit River
	Waterloo Moraine
	Upper Thames
St. Lawrence Lowlands	Mirabel
	Châteauguay
	Richelieu
	Chaudière
	Mauricie
	Portneuf
MARITIMES	Annapolis-Cornwallis valleys
	Carboniferous basin

Table 4. Recharge rates of some of the regional aquifers completed.

	Mm^3/y	mm	% of P
Carboniferous basin	140	130	10
Mirabel	85	70	9
Portneuf	130	250	21
Oak Ridges Moraine	1500	150-200	16-20
Gulf Islands	251	100-500	

5.1.3 Groundwater storage

The volume of groundwater stored in regional aquifers is virtually unknown. However, rough estimates carried out within the assessments indicate a range between 0.8 km^3 (Portneuf), to 50 km^3 (Carboniferous basin), to 150 km^3 (Oak Ridges Moraine). These numbers, however, represent only a fraction of the regional aquifer investigated, at most the upper 100 –200 meters. On the other hand, not all groundwater stored can be exploited, only the annual renewable groundwater and an additional amount which the resource managers would wish to withdraw without casing undesirable effects to the system; that is, using the sustainable development concept as discussed above.

Groundwater removed from aquifer storage is a well known phenomenon in some countries. One of the most striking examples is the very large High Plains aquifer in the USA, located along 8 states from South Dakota to Texas. It has been estimated (McGuire and Sharpe, 1997) that a total of 270 km^3 of water has been removed from the aquifer through 1999, causing undesirable effects such that the water-level declines reduced the saturated thickness of the aquifer to a level which is no longer economical to use.

5.1.4 Groundwater over-exploitation

No instances of over-exploitation have been observed in the regional aquifer assessments so far carried out by the GSC. Over-exploitation of groundwater is understood here as the changes of groundwater storage due to withdrawals, mine dewatering, saltwater intrusion, and land drainage, that exceeds the natural recharge of the aquifer system and for a long period of time.

Based on results from regional-aquifer assessments, and current hypothesis and expert knowledge, it can be said that pre-development conditions prevail most everywhere in Canada.

5.1.5 Sustainability of regional aquifers

Only one regional-aquifer study included an evaluation of its sustainable yield. The Mirabel aquifer system estimated that the current pumping (about 18 Mm^3/y, or 19% of recharge) was sustainable, and that even doubling that amount would not have adverse effects on the system.

5.1.6 Groundwater Monitoring

Groundwater-level measurements from wells and piezometers remain the principal source of information on the effects of natural and anthropogenic stresses put onto groundwater systems. In Canada, while most of the water investments are done to develop surface water resources, very little is being done to assess and develop groundwater. There are a series of national networks to monitor surface water with the participation of all jurisdictions, but there is no national network to monitor groundwater quantity and quality.

Most of the regional aquifers assessed by the GSC have, however modest, a groundwater monitoring network installed as a legacy of the study. Furthermore, current talks with the provinces and other federal departments explore possibilities of establishing a national groundwater network of networks, perhaps within the Canadian hydrometric (surface water) network led by Environment Canada. A preliminary compilation of existing groundwater monitoring wells and data across Canada has been done by the national ad-hoc committee on groundwater (Maathuis, et al., 2003).

6. CONCLUSIONS

With the current inventory of the groundwater resources of Canada, through scientifically-based regional-aquifer assessments, the knowledge gaps of our most precious water resource are slowly decreasing. However, it is still too early to frame a Canadian portrait of the groundwater resources at the national scale. Some trends indicate that there is no overexploitation of regional aquifers and that most of the systems investigated are in steady-state conditions and hydrodynamic equilibrium.

On the other hand, the importance that groundwater reservoirs have on surface water bodies has been demonstrated in some of the regional aquifers investigated so far. Thus, inclusion of surface water-groundwater linkages through quantitative estimates is essential for groundwater management plans on a long-term sustainable development (use) of groundwater resources at regional scales.

Following the experience of the GSC, it became obvious that cooperation among provincial and federal agencies is the key to completing regional-aquifer assessments.

However, we still have to identify together the critical technical factors and underlying scientific, social, and environmental issues that must be taken into consideration in order to quantify the amount of groundwater that is available for use in a sustainable manner. Scientifically-based information will be the backbone for any serious water-management scenario at any scale.

7. ACKNOWLEDGEMENTS

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