CHAPTER 15

Intensive use of groundwater in North America

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ABSTRACT: From the permafrost of Canada's High Arctic to the tropical humid forests of Mexico's Yucatán Peninsula, the North American continent contains a remarkable diversity of climatic regimes, landscapes, and ecosystems. The abundant precipitation characterizing Southern Mexico and coastal areas of the USA and Canada contrasts with the arid climates of the Southwestern USA and Northern Mexico. The availability of groundwater and surface water also varies considerably. In Canada, 30% of the population relies on groundwater for all uses combined. The USA used about 471,000 Mm^3 of freshwater in 1995 to meet the needs of its 300 million inhabitants. About 105,000 Mm^3 was obtained from groundwater. In Mexico, groundwater provides 39% of the water supply. Both Mexico and the USA are experiencing problems associated with groundwater pumpage –especially in the large population centers and agricultural regions that are located in arid climates.

Three selected groundwater examples are described in this chapter, one for each country, to show the importance of groundwater in North America: land subsidence in Mexico City; the overexploitation of the Floridan aquifer in the USA; and the issue of transboundary water and water exports in Canada.

1 SUSTAINABILITY OF GROUNDWATER RESOURCES IN NORTH AMERICA

Groundwater is part of the hydrologic cycle and, as such, it is interconnected with other elements of the hydrologic cycle. Thus, groundwater discharge supports the base flow of streams, helps to maintain levels of lakes and wetlands, and prevents seawater from encroaching into aquifers. Under natural conditions, in all but severely arid environments, water from precipitation recharges the groundwater reservoir, circulates through it, and eventually discharges to streams, lakes, wetlands, or coastal waters. The groundwater system is said to be in dynamic equilibrium when, on average over several years, the amount of water recharging the groundwater system is balanced by the amount of water discharging from it. Under such conditions the amount in storage in the system remains relatively constant.

Groundwater withdrawals disturb the dynamic equilibrium. The volume of water obtained by pumpage is balanced by changes in other elements of the hydrologic cycle. In humid environments, pumpage is generally balanced by increased recharge and/or reduced natural discharge. In arid environments, storage is often reduced significantly. The term *safe yield* is commonly used to quantify the amount of water that can be sustainably withdrawn from groundwater reserves. However, its definition –the maximum amount of water that can be withdrawn from a groundwater basin without producing an undesired result– is less useful as a measure of sustainability today then when it was first coined in the early part of the 20th century. The reason for this is that, by defining a single, target volume –a *maximum amount of water*– the perception is fostered that groundwater is to be used solely as a commodity. The fact is the amount of groundwater that can be withdrawn *without producing an undesired result* will vary widely from place to place and over time depending on a number of interrelated factors. These include hydrogeologic setting, climate and climate change, land use and land-use change, groundwater quality and groundwater quality change, and the like. It also will depend on the current and future availability of surface water resources. Very importantly, the amount of groundwater that can be withdrawn for use as a commodity will also depend on the amount that must be allocated to protect the *common good* that is, the environment and ecosystem function. Sophocleous (this volume) correctly states that "many uses and environmental values (of groundwater) depend on the depth of water –not the volumetric amount– (that is) theoretically available".

It is also important to recognize that social and economic factors often will play a controlling role in the decision about the *best use* of a groundwater resource. Abderrahman (this volume) puts forward strong social and economic reasons for the use of Saudi Arabia's non-renewable groundwater resources. Thus, it is only after taking into consideration the importance of groundwater as a *common good* and the social and economic realities facing a small community, nation or broad international region that we can arrive at a true measure of the amount of groundwater that is available for use.

This chapter provides an overview of groundwater resources in Canada, the USA and Mexico, and examples of the issues facing each nation as it strives to meet changing demands for a safe and sufficient supply of freshwater.

2 IMPORTANCE OF GROUNDWATER IN NORTH AMERICA

From the permafrost of Canada's High Arctic to the tropical humid forests of Mexico's Yucatán Peninsula, the North American continent contains a remarkable diversity of climatic regimes, landscapes, and ecosystems. The abundant precipitation that characterizes Southern Mexico and the coastal areas of the USA and Canada contrasts with the arid desert landscapes of the Southwestern USA and Northern Mexico. The availability of groundwater and surface water also varies considerably. Large population centers in areas of water scarcity pose a considerable challenge to water managers across North America. Contamination of groundwater and surface water by point and nonpoint of sources of pollution in hydrogeologically vulnerable areas effectively diminishes the amount of water that is available for use.

2.1 *Groundwater resources of Canada*

Canadians are fortunate to possess an abundant supply of surface water and even greater quantities of high quality groundwater. Many aquifers in Canada are found in deposits of sand and gravel formed by rivers or lakes that were created from melting glaciers during the last ice age. Aquifers of this type provide most of the water supply for the Kitchener-Waterloo region in Ontario and the Fredericton area in New Brunswick (Fig. 1). In Manitoba, the Carberry aquifer (a long-buried delta of the ice-age Lake Agassiz) is a prime source of agricultural irrigation water. A major sand and gravel aquifer located in British Columbia's Fraser Valley is widely used for municipal, domestic and industrial water supply.

Beneath the soil of Prince Edward Island, water found in a thick, fractured formation of sandstone provides the Island with its entire water supply. In the cities of Winnipeg in Manitoba Province, and Montreal in Quebec Province, substantial aquifers formed from fractured rock are used for industrial water supply.

Canada used about 45,000 Mm^3 of freshwater in 1991, 44,000 of which comes from surface waters and only 1,000 from groundwater. These data, however, can be misleading with regard to the overall importance of groundwater resources as currently (2002) 30% of the population (10

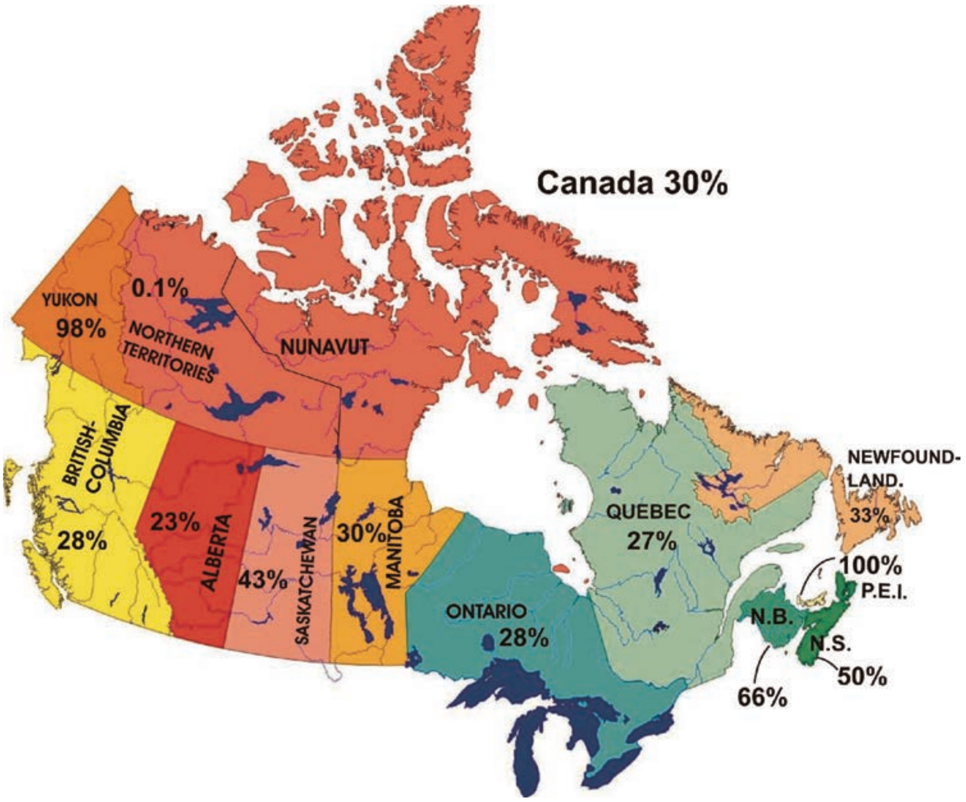


Figure 1. Groundwater use in Canada; 30% refers to overall groundwater use in Canada.

million people) rely on groundwater for their water supply. Small domestic wells located in rural areas account for most of the groundwater withdrawals in Canada. The rate at which groundwater is being withdrawn is constantly increasing.

Households and agriculture practices are the main users of groundwater resources in Canada (Table 1).

Table 1. Percent distribution of fresh surface and groundwater use in Canada in 1991.

	Industry %	Agriculture %	Domestic %	Total (Mm^3)
Surface water	71%	11%	17%	44,100
Groundwater	14%	43%	43%	1,000
Total (by use)	70%	12%	18%	45,100

The geographical distribution of groundwater use in Canada ranges from 0.1% in the northern territories to 100% in the province of Prince Edward Island (Fig. 1).

An *abundant mentality* has developed in Canada regarding surface water. Thus, while ample information is available about its surface waters, there is only scattered information available regarding Canada's groundwater resources. The sustainable natural yield of major regional aquifers systems in Canada is unknown and there is no unified, consistent approach to mapping major aquifers or quantifying the Canadian groundwater resources. Information regarding underground diffusion rates, surface water/groundwater interactions, recharge and discharge rates and storage capacity is needed for the development and the adoption of effective sustainable safe yield extraction practices and protection against contamination.

Public awareness in groundwater dramatically increased since the *E. coli* accident that killed 7 people in Walkerton, Ontario, in 2000. The *TCE* contamination in Shannon, Quebec, has led to a change in mind and strategy regarding groundwater. In many regions of Canada, there is mounting concern about groundwater depletion, and instances of aquifer contamination. Recognition of the provincial and territorial responsibility for groundwater has resulted in more emphasis on groundwater monitoring, management, and regulations within provincial governments.

Several looming issues are likely to further awareness of Canada's groundwater resources:

- Increase in water demands. Groundwater usage went from 10% in 1970 to 30% in 1998.
- Groundwater depletion, and instances of aquifer contamination.
- Recognition of large knowledge gaps in the country's groundwater resources.
- Bulk water exports. Exports of water to the USA under the North American Free Trade Agreement (NAFTA) and to other countries to meet growing demands with Canadian water.
- Climate change impact and adaptations.

Groundwater currently poses administrative problems in Canada because groundwater resources belong to, and are managed by, the provincial governments. Thus, jurisdictional issues prevent Canada from having a unified, consistent knowledge of its overall groundwater resources. The legal and jurisdiction framework for groundwater management is fragmented, inconsistent, and incomplete. Groundwater management practices vary from jurisdiction to jurisdiction, and in some cases, do not exist at all. This problem has been acknowledged for long but only recently a framework of collaboration for groundwater studies at the national scale has been designed (Rivera *et al*., in press). The Geological Survey of Canada (a federal agency) in conjunction with its provincial and other partners is presently (2002) developing plans to map and conduct groundwater research in several major aquifer systems across the country, as a major inventory of Canada's groundwater resources since 1967. The plan will focus on providing basic groundwater data and geological mapping essential to manage Canada's groundwater resources at a national scale. Its culmination is proposed as a *National Groundwater Management Strategy*. In that framework, jurisdictions and researchers agree on a long-term commitment to studying the groundwater resources of Canada with a unified vision. The next 10 years will see the development of the first Canadian inventory and consistent assessment of the groundwater resources of Canada.

The International Joint Commission (IJC) also has recognized groundwater as an issue to be fully addressed within the context of Canada-USA shared waters in the 21st century. In their 2000 report (IJC 2000), the IJC made a call to all governments (federal, provincial and states) to enhance groundwater research in order to better understand the role of groundwater in the Great Lakes Basin both as a drinking water supply and to maintain streamflow to the lakes' tributaries.

2.2 *Groundwater resources of the USA*

Major rock types that constitute aquifers are thick alluvial deposits such as in the Central Valley of California, the high plains area, and the Mississippi River alluvium; glacial drift deposits in the North Central and Northeast USA; unconsolidated sediments of the Atlantic and Gulf Coastal Plains; consolidated limestones and dolomites in the Florida peninsula and adjacent coastal parts, and in Texas, New Mexico, and the central regions; sandstones in the Appalachian Mountains and plateau areas and in the Colorado plateau area; basalt of the Columbia lava plateau; and igneous and metamorphic crystalline rocks of the Western Mountains, the Piedmont –Blue Ridge Region, and the northeast and superior uplands.

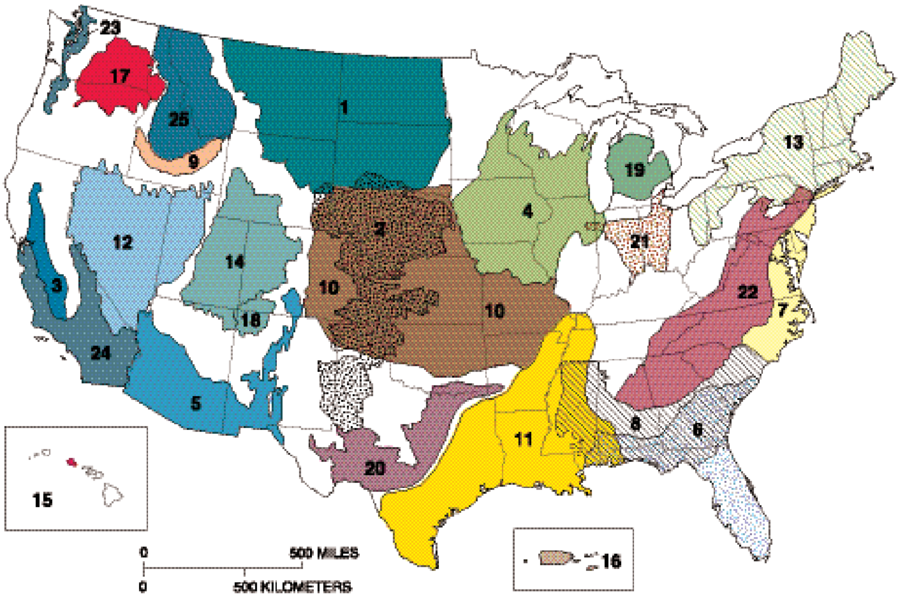
The major regional aquifer systems (Fig. 2) have been studied extensively by the U.S. Geological Survey (USGS) under its *Regional Aquifer System Analysis Program*. Digital simulation based on compilation of mostly preexisting data was used extensively to further the understanding of recharge and discharge relations and the response of the aquifer systems to pumpage. Results of this program have been published by the USGS in a number of professional Papers, Water Resources Investigations Reports, Open-File Reports, and journal articles (Sun *et al.* 1997).

Maps showing the aerial extent of the major aquifers have been compiled by the USGS into a groundwater atlas of the USA (USGS 2001). The atlas also describes in summary fashion the hydrogeology of the major aquifers. Heath (1984) classified 15 groundwater regions based on components of and arrangement of the groundwater system, nature of water bearing openings, mineral composition of the rock matrix, water storage and transmission properties, and nature and location of recharge and discharge areas. Eleven of the groundwater regions are based on physiography.

In 1995, a total of 471,000 Mm^3 of freshwater was withdrawn for use from surface water and groundwater sources (Solley *et al.* 1998). Of this total, 105,000 Mm^3 was obtained from groundwater. The fresh groundwater withdrawals were used mainly for irrigation and livestock (67.3%); and for public supply (19.7%). Table 2 shows how freshwater was used for various purposes in 1995 in the USA.

Table 2. Fresh surface water and groundwater use in the USA in 1995.

	Irrigation and livestock %	Public supply %	Industrial-mining %	Domestic-commercial %	Thermo-electric %	Total (km^3)
Surface water	33.2	9.5	6.9	0.8	49.6	366
Ground-water	67.3	19.7	6.7	5.6	0.7	105
Total by use	40.9	11.8	6.8	1.8	38.8	471



Modified from Sun, R.J., and Johnston, R.H., 1994, Regional Aquifer-System Analysis program of the U.S. Geological Survey, 1978–1992: U.S. Geological Survey Circular 1099, 126 p.

EXPLANATION

Regional aquifer system study areas

1 Northern Great Plains
2 High Plains
3 Central Valley, California
4 Northern Midwest
5 Southwest alluvial basins
6 Floridan
7 Northern Atlantic Coastal Plain
8 Southeastern Coastal Plain
9 Snake River Plain
10 Central Midwest
11 Gulf Costal Plain
12 Great Basin
13 Northeast glacial aquifers
14 Upper Colorado River Basin
15 Oahu, Hawaii
16 Caribbean Islands
17 Columbia Plateau
18 San Juan Basin
19 Michigan Basin
20 Edwards–Trinity
21 Midwestern basins and arches
22 Appalachian valleys and Piedmont
23 Puget–Willamette Lowland
24 Southern California alluvial basins
25 Northern Rocky Mountain Intermontane Basins

Figure 2. Regional aquifer systems in the USA.

Groundwater withdrawals have increased from a rate of 47,000 Mm^3/yr in 1950 to a rate of 105,000 Mm^3/yr in 1995. Peak rates of withdrawals occurred in 1975 and 1980, at 113,000 and 114,000 Mm^3/yr. They have declined somewhat since. The decline is attributed to reduced demands for irrigation water, new technologies in the industrial sector, recycling, and improved plant efficiencies. Conservation programs in many states have also contributed to reduced water demands.

Regionally, the rates of groundwater withdrawals in 1995 were greatest in California: 20,000 Mm^3; Missouri basin: 13,000 Mm^3; lower Mississippi: 13,000 Mm^3; Arkansas-White-Red River basins: 10,000 Mm^3; South Atlantic-Gulf: 10,000 Mm^3; Texas-Gulf: 8,000 Mm^3; and the Pacific Northwest: 8,000 Mm^3.

The quality of groundwater in the USA varies widely from place to place. The quality is influenced by the quantity and quality of precipitation, land use activities overlying aquifer recharge areas, the mineral composition of the aquifers, and the length of time groundwater resides in the aquifer. Surficial quartz sand aquifers in undeveloped lands of the humid East may contain water very low in dissolved solids, soft and somewhat acidic. In contrast, groundwater from deeply lying sand stone, shale, and lime stone sequences in the mid-continent area may be very hard, high in dissolved solids, and alkaline. Perhaps the most pervasive and chronic anthropogenic influence on groundwater quality has been the enrichment of nitrate concentrations. The major sources of nitrate are agricultural fertilizers and domestic waste waters. Such nonpoint source problems have affected shallow aquifers throughout most of the USA. Point sources of contamination, on the other hand, have resulted in numerous, relatively small but acutely contaminated groundwaters.

Competition for water in the USA will increase in the 21st century as communities strive to meet the demands resulting from continued population and economic growth, and from efforts to protect and enhance aquatic ecosystems. The fact that virtually all surface waters in the USA are fully allocated strongly suggests that groundwater will become an increasingly important component of water supplies in the future. Although the USA is blessed with relatively large volumes of groundwater, local and regional overdrafts of groundwater reserves already have resulted in many ill effects. These include lowering of water tables, salt-water intrusion, land subsidence, and lowered base flow of streams. Contamination of groundwater from planned and inadvertent actions also has affected large volumes of groundwater and caused water managers either to seek alternate sources of supply or add expensive water-treatment facilities. Thus, it is imperative to quantify how much can be withdrawn to meet near-term needs without either impairing the resource or undermining its availability to meet future needs, including ecosystem sustainability.

Groundwater law in the USA is handled by the states and its development has been sporadic and uneven (Bouwer 1978). Four doctrines govern withdrawal and use of groundwater: the English Rule, the American Rule, the Correlative-Rights Rule, and the prior appropriations doctrine. The English Rule allows landowners to withdraw as much groundwater from below their land as they wish, since they have absolute ownership of the groundwater. Most Eastern states follow the English Rule. The American Rule is similar to the English Rule but restricts use of groundwater to a reasonable-type use on the owner's land. Landowners can pump as much as they wish within those restrictions. Many of the Eastern states have applied reasonable use restrictions to the English Rule.

Some Western states have adopted the Correlative Rights Doctrine or the prior appropriations doctrine to manage groundwater withdrawals. The Correlative Rights Doctrine, a modification of the American Rule, provides for an equitable distribution of withdrawal rights where groundwater is in limited supply. Land owners are restricted to withdrawing groundwater amounts in proportion to the land area that they own over the groundwater supply. The doctrine originated in California.

In states such as Nevada and New Mexico, groundwater belongs to the public and is appropriated chronologically. Historical use determines the quantity to which an appropriator is entitled. Water can be transferred to any site for beneficial use. Appropriators with the most seniority have protection over junior appropriators according to a chronological hierarchy.

Many states use a system of permitting for drilling a well and of licensing drilling to control pumping of groundwater. In addition, some states regulate withdrawals by permitting diversion amounts, especially in areas declared *critical*. A more detailed analysis of water laws in the USA can be found in Smith (this volume).

2.3 *Groundwater resources of Mexico*

The National Water Commission (*Comisión Nacional del Agua*, CNA) has identified 653 aquifers throughout Mexico. Escolero & Marín (2000) describe 11 hydrogeologic provinces. A new classification based on new studies carried out by the CNA as well as academic institutions proposed 33 hydrogeologic provinces (Escolero *et al.*, in press). Two hydrogeologic provinces merit special attention. The first is the Mexican Transvolcanic Belt, which consists of high mountains with intermontane valleys with thick lacustrine deposits. The Mexico City Valley typifies this type of province. The second is the Peninsula of Yucatan located in Southeastern Mexico. This province has one of the largest carbonate platforms of the world in which a mature karstic system is present. The Peninsula has a thin freshwater lens floating over denser saline water (Marín 1990).

More than 72,200 Mm^3 of water was used by the 100 million inhabitants of Mexico in 1998 (Table 3, Fig. 3). Of this, 28,500 Mm^3 came from groundwater. Groundwater withdrawals are carried out through more than 275,000 groundwater extraction wells. Groundwater supplies 34% of the agricultural water use, for irrigation; 69% of the domestic water supply; and 59% of the water used by industry. Table 3 shows the breakdown of water use by groundwater and surface water and by activity. The first and second lines show the percentages of surface water versus groundwater, respectively, used by each activity, and the third line shows the percentage of total water used by each activity.

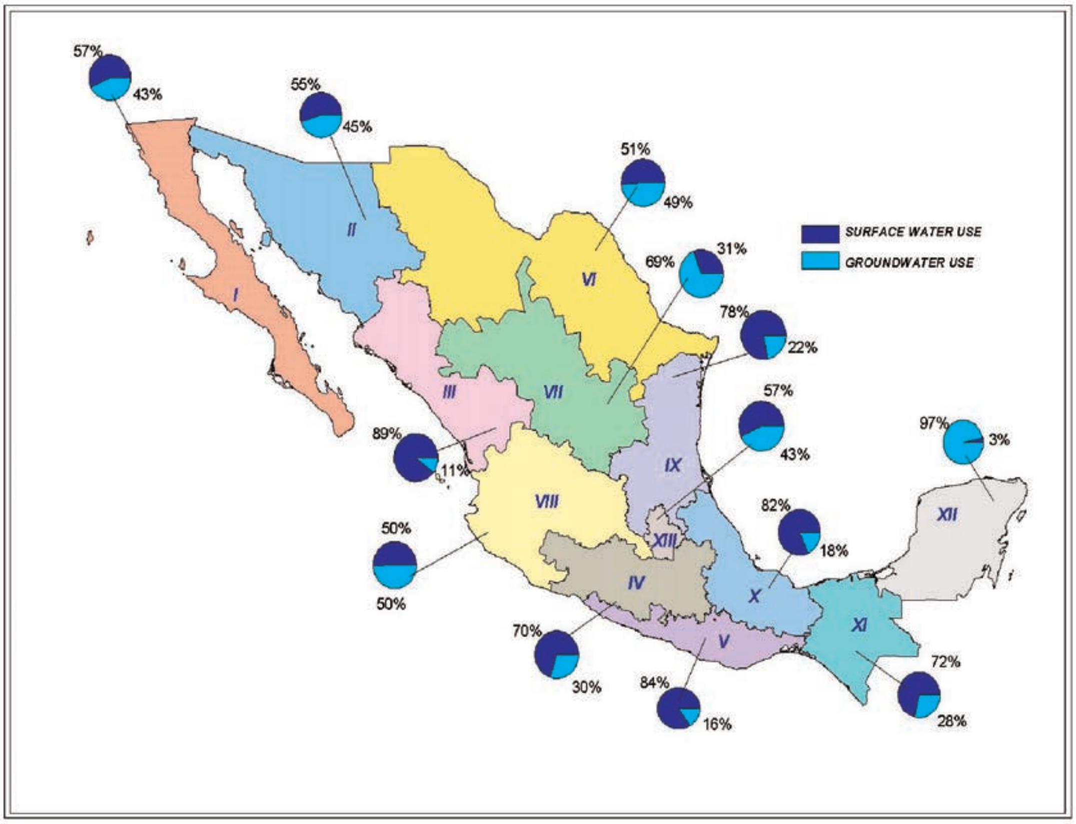


Figure 3. Mexico's National Water Commission's administrative regions.

Table 3. Fresh surface water and groundwater use in Mexico in 1998.

	Industry	Agric.	Domestic	Other	Total (Mm^3)
Surface water	41%	66%	31%	33%	43,700
Groundwater	59%	34%	69%	66%	28,500
Total (by use)	8%	78%	11%	3%	72,200

Mexico faces a number of common groundwater problems:

- Sea-water intrusion of coastal aquifers such as the Riviera Maya in areas where land development is occurring.
- Land subsidence in Mexico City (with rates that vary of less than 1 cm/yr to more than 40 cm/yr)
- Fractures due to the overexploitation of the groundwater in Querétaro, Toluca, Celaya, Aguascalientes.
- Urban contamination in Mérida, Yucatán from the leachates of landfills and spills, and diffuse contamination from agricultural and livestock activities (Steinich *et al.* 1998, Marín *et al.* 2001, Pacheco *et al.* 2001, Pacheco *et al.*, in press).

In some areas of Mexico, the disturbance of the natural hydrogeologic setting has resulted in environmental issues for residents of selected hydrogeologic basins. For example, high concentrations of arsenic have been detected in Torreón, Coahuila. High concentrations of fluorine have been detected in Aguascalientes.

According to Article 27 of the Mexican Constitution, all goods found in the subsurface, including minerals and water, belong to Mexico. Under this article, a new law dealing with the water as a whole was issued in 1992. Groundwater withdrawals are regulated through the LAN (*Ley de Aguas Nacionales*, or: Law of National Waters) and RLAN (*Reglamento de la Ley de Aguas Nacionales*, or: Regulation). This law primarily deals with the granting of permits to withdraw groundwater and it provides a general background for protecting the aquifers from contamination.

The CNA is the federal institution responsible for administering water issues in Mexico. Until 1989, all decisions regarding groundwater management were taken at the CNA headquarters. Currently, however, the decisions for groundwater management are being reverted to the regional and states offices of the CNA. The country has been divided into 13 administrative regions. The Peninsula of Yucatán, lies within Region XII. The administrative structure of the CNA is as follows: 1) the national headquarters are located in Mexico City; 2) there are 13 regional administrative offices; and 3) the 20 states offices corresponding to each one of the states without a regional office.

Different aspects related to water are regulated at all three levels: federal, state, and municipal level. And at all three levels different government agencies have their say. For example, hazardous waste sites are regulated by the *Instituto Nacional de Ecología* (National Institute of Ecology, INE) with the coordination of the CNA. In addition to federal laws passed by Congress, there are Presidential Decrees which must be complied with, throughout the country.

The LAN and RLAN consider three legal figures, that by public concern can be issued through presidential decree and are of application at the federal level, the first designated *Zone of restrictions (Zona de Veda)*, where CNA regulates the groundwater extractions closely. The second designated legal figure is the *Regulation of the aquifer*, within these zones, CNA establishes rules and regulations that only pertain to this aquifer in particular, including restrictions for new groundwater extractions. The third legal figure is named *Reserve zone*, where CNA may limit the use of groundwater from these zones, since they are entitled by decree to assign specified volumes for uses such as drinking water (primarily).

The CNA has instituted three types of committees to help manage water resources in the different hydrologic regions. These are known as *Consejos de Cuenca*, *Comisiones de Cuenca* and *Comités Técnicos* (Basin Councils, Basin Commissions, and Technical Committees, respectively). The basin type primarily involves representatives from all three branches of government (federal, state, and municipal) as well as representatives from the industrial, agricultural, and drinking water supply sector; the Basin Council is established for wide basins and the Basin Commissions are setup to address specific problems. The third type, the Technical Committee (*Comité Técnico*), is composed primarily by registered groundwater users. Currently, there are 25 *Consejos de Cuenca*, 6 *Comisiones de Cuenca* and 33 *Comités Técnicos* operating throughout Mexico.

Recently, a program called *Agua Limpia* (clean water) was started by the Federal Government through the *Comisión Nacional del Agua*. This program in essence concentrated in trying to chlorinate all public drinking water supplies. As a result of this program, which is still in effect through December 1, 2001, the deaths related to pathogens transported by water have diminished considerably.

Currently there are only thirteen PhD's in hydrogeology in Mexico. In Mexico, there are several groundwater programs but only three award a PhD in hydrogeology. If one considers related disciplines such as mathematics, geophysics, geochemistry, and geology, the number of scientists working in groundwater related areas increases to over 30 persons. Clearly, this number is still insufficient to address all of the groundwater issues that face a country such as Mexico.

3 GROUNDWATER ISSUES IN NORTH AMERICA

3.1 *Mexico City: An example of the effects of groundwater pumpage on water quality and subsidence*

Mexico City lies within the Valley of Mexico, which is located between 98º40' W to 99º25' W longitude and from 19º05' N to 19º37' N latitude. It lies within the Mexican Transvolcanic Belt (MTV). The MTV consists of an area of approximately 105,000 km^2. The Valley of Mexico is located in an endoreic basin. The elevation of the valley floor ranges between 2,240 and 2,390 m.a.s.l., with an extension of 9,600 km^2. Mexico City is located in the lower part of the basin with a mean elevation of 2,240 m.a.s.l.

Mazari-Hiriart *et al.* (2000) have described the regional hydrogeology of the Mexico City Valley which consists of: a) a lacustrine zone, created by clay deposits from the old lake system; b) the piedmont or transition zone; and c) the surrounding mountain area. Marín *et al.* (in press), have suggested that the main recharge zone for the Mexico City Valley is located at the piedmont.

Throughout the valley floor, there is a regional aquifer. Lesser *et al.* (1990) have subdivided the regional aquifer that underlies the Valley of Mexico into three sub-aquifers. These are: 1) the granular aquifer found underneath the city; 2) the one found in the southern portion of the valley, comprising the southern areas of the Mexico City Valley; and 3) the area to the northeast of the valley. The regional aquifer is composed of fractured volcanic rocks, which are covered by lacustrine and alluvial deposits of lower hydraulic conductivity values. For this reason, the aquifer within the Valley of Mexico is confined in some areas, and semi-confined in others.

Recharge to the aquifer comes from the highest parts of the basin and the hillsides of the three mountain ranges located to the east, west, and south (with the latter area providing the highest recharge to the aquifer). Historically, the whole valley floor has been the discharge zone for the Mexico City Valley. Dewatering of the Mexico City has been a troublesome engineering challenge since the time of the Aztecs (Marín *et al.*, in press). Currently, the untreated wastewaters are disposed of on the surface and in an underground drainage system. These waters are used for irrigation north of Mexico City in the Valle del Mezquital.

3.1.1 *Water quality*

Although one might think that the thick uppermost lacustrine deposits may protect the aquifer, this is not the case for Mexico City. Mazari-Hiriart *et al.* (2000) showed in a bacteriological study of 40 wells, that the wells found in the lacustrine deposits are more contaminated. Their results suggest that the urbanized area in the western side of the city and the *ad hoc* settlements are having a negative impact on the water infiltrating and recharging the aquifer, especially in the lacustrine area, which showed the highest percentage of contaminated wells. Two possible explanations are: 1) although the population in that area has drainage facilities, the well casing may be fractured due to differential sinking in the city, leading to possible contamination; or 2) part of the low-income families who have settled on the river banks, in the transition zone, have no drainage and dispose domestic wastewater directly into watercourses.

Marín *et al.* (in press) report two different sources of water found in the subsurface of the Valley of Mexico based on stable isotope and major ion geochemistry. They were able to identify water of meteoric origin, with a short residence time in the springs located along the mountain flanks that surround the basin and water that had changed in chemical composition as it traveled through the rocks. Cortés *et al.* (1997) estimated that the average residence time for the Valley of Mexico is on the order of 50 years. Natural water quality is acceptable for human use (which typically has less than 500 mg/L TDS) except for the water found in the vicinity of Texcoco Lake, where typical waters have a TDS of 30,000 mg/L and concentrations as high as 130,000 mg/L TDS have been reported (Herrera 1995). Texcoco Lake has one of the lowest elevations of the valley, and thus, it is likely that groundwater discharge gravitates to this area. Evaporation of this water, with its high TDS load, leads to salt accumulation. Since the time of the Aztecs, this area has been mined for salt (Durazo & Farvolden 1989).

3.1.2 *Land subsidence*

Due to the thick clay layers that are present throughout the Valley of Mexico, land subsidence became a major problem once groundwater extraction began on a regular basis in the middle of the 19th century. This problem (which continues today) became more acute in the 1940s when major groundwater withdrawals from the regional aquifer started; these rates reached a maximum of 46 cm/yr in 1950–1951 (Herrera 1995). In 1959, for example, the subsidence rate in the center of the valley was on the order of 40 cm/yr (Durazo & Farvolden 1989). Birkle *et al.* (1998) reported land subsidence greater than 9 m in the Valley of Mexico as a result of groundwater withdrawals. Current land subsidence values for the Basin of Mexico range from zero (no subsidence) to more than 35 cm/yr in the Xochimilco area.

Mexico City, with a population of 8.5 million inhabitants (within the city, and approximately 20 million including the surrounding areas) obtains approximately 55% of its drinking water from groundwater (on the order of 19 m^3/s). As the population of Mexico City has continued to increase, so has the demand for groundwater. For example, as of 1988 Lesser *et al.* (1990) estimated that more than 33 Mm^3 of groundwater were being withdrawn from storage annually, and that this volume is in excess of the recharge to the aquifer system. Arreguín-Mañón & Terán (1994), and Arreguín-Mañón (1998), discuss the recent hydrogeologic history of the basin.

Until the end of the last century, the supply of drinking water for Mexico City was provided by springs located to the west and south of the city. Between 1900 and approximately 1930, when the city's population increased but still remained below one million, water-supply sources shifted progressively from springs to artesian wells. With time, these wells, and other new wells, were drilled deeper and deeper and were equipped with pumps, thereby rapidly modifying the regional groundwater head.

In order to provide the larger amounts of water needed for economic growth (Fig. 4), city authorities created a very ambitious program of groundwater exploitation.

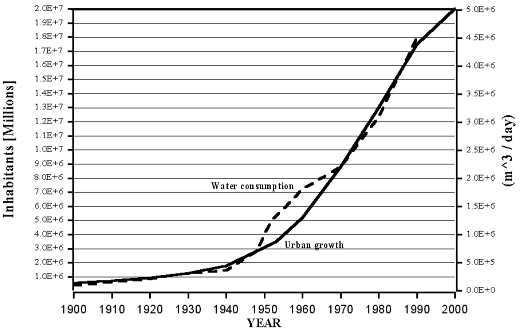


Figure 4. Urban growth and water consumption in Mexico City (Rivera *et al.* 1991).

Starting in 1934, deep wells (> 50 m) were drilled in the downtown area and to the north and west of the city. Later, in the early 1950s, additional wells were drilled south of the city. Local groundwater remained the only source for the city's water supply until the beginning of the 1960s, when the city authorities started to import both surface and groundwater from other basins in neighbouring states. In 1980, total pumping rate exceeded 21 m^3/s from more than 600 wells in Mexico City alone. Figure 5 is a histogram of the pumping data in Mexico City for the period of 1934–1986.

During the same period, more than 6 m of land subsidence was observed at some locations (Fig. 6), constituting one of the most remarkable cases of subsidence in the world because of its magnitude and its extent. Since the 1940s, this phenomenon, observed at a regional scale, has been ascribed principally to groundwater exploitation.

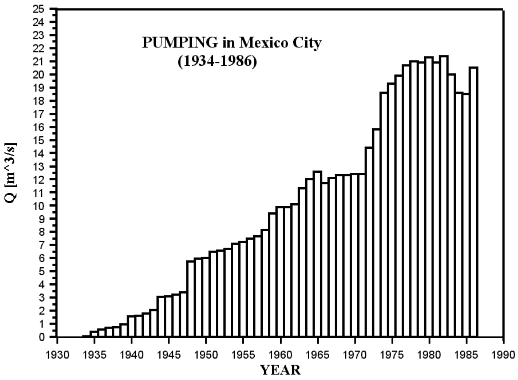


Figure 5. Groundwater pumping in Mexico City for the period of 1934 to 1986.

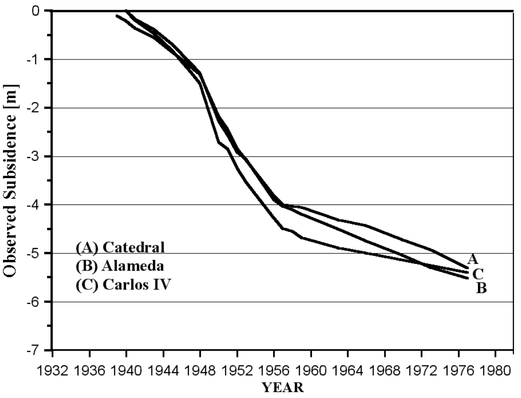


Figure 6. Subsidence observed in Mexico City for the period of 1934 to 1977.

A hydrogeologic explanation of the subsidence in Mexico City was given by Rivera (1990). Consolidation alters the physical properties of the aquitards (interbedded in the exploited aquifers) and causes significant changes in hydraulic conductivity (*K*) and specific storage coefficient (S_s); in turn, these changes result in sediment compaction, reflected at the surface as subsidence. Another effect of the reduction of these parameter values during consolidation is a decrease in aquitard leakage. As a result, a longer time is required to reach steady state, and there is less subsidence than would be predicted by a standard linear analysis. Rivera (1990) performed an extended quantitative analysis of this coupled hydraulic-mechanic phenomenon.

A coupled three-dimensional numerical model was built by Rivera *et al.* (1991). The water budget in the city fully assessed and the observed subsidence was reproduced very closely with the non-linear model. The model could be used for groundwater management practices.

Marín *et al.* (in press) have suggested that a hydrogeologic zone be established for the Mexico City Valley aquifer because even if the growth rate for Mexico City continues to decrease, the city will continue to grow, and so will the demand for water. One of the major problems that the city faces is that the predominant zones where recharge to the aquifer occurs is systematically being urbanized. The recharge zone is being paved over to build residential and commercial developments. Marín *et al.* (in press) suggested that a hydrogeologic reserve zone be established immediately along the piedmont. If the hydrogeologic zone is protected, and trees are planted, this would also help to control soil erosion, and as more soil is retained, this would also increase the recharge to the regional aquifer. Legislation already exists considering the establishment of groundwater reserve zones within the National Water Laws and Regulations (Ley Nacional de Aguas 1992, Ley Nacional de Aguas y su Reglamento 1994).

3.2 *Florida, USA: an example of intensive and conflicting uses of the Floridan aquifer system.*

3.2.1 *Geographic extent and use of the Floridan aquifer system*

The Floridan aquifer system is one of the most intensively developed major sources of groundwater in the USA, and perhaps the world. The aquifer system underlies all of Florida, Southern Georgia, and parts of adjoining Alabama and South Carolina for a total area of about 260,000 km^2. In 1995, about 12 Mm^3/d of water was withdrawn from the aquifer for all uses, 77% of which was withdrawn in Florida (Table 4)

Heaviest concentrations of pumpage occur in Central Florida, and along the coastal strip of Southeast Georgia-Northeast Florida. The aquifer system was studied recently under the USGS *Regional Aquifer System Analysis Program* and much of the material here is taken from Johnston & Bush (1988).

In addition to its importance as a water-supply source, the Floridan aquifer system is also used for subsurface storage of wastewaters, treated sewage, and to a lesser extent, industrial wastewaters are injected into the saline parts of

Table 4. Water withdrawals from the Floridan aquifer system in 1995 (in Mm^3/d). [U.S. Geological Survey, WRD, National Water Use Program (unpublished data files), Reston, Va. 1997].

State	Withdrawn	PS	DSS	C-I-M-P	I-L-FF
Alabama	0.03	0.01	0.01	0	0.02
Florida	9.32	3.48	0.58	1.36	3.96
Georgia	2.64	0.52	0.2	0.84	1.09
South Carolina	0.13	0.11	0	0.01	0.02
Total	12.12	4.12	0.79	2.21	5.09

PS: Public Supply.
DSS: Domestic self-supplied.
C-I-M-P: Commercial, Industrial, Mining, and Power Generation.
I-L-FF: Irrigation, Livestock, and Fish Farming.

the aquifer. Most of the treated sewage injection occurs in coastal parts of Southeast Florida and West-Central Florida. Industrial wastewater is injected in extreme Western Florida and in a few places in Central and Southern Florida. Brines from desalination plants is also injected in Southern Florida. In addition, storm runoff is disposed of by gravity drainage wells that tap the Floridan aquifer system in Central and Northern interior Florida, especially in the Orlando area. In recent years, the slightly to moderately saline parts of the aquifer have been used for *Aquifer Storage and Recovery* (ASR) by injecting surplus fresh surface waters and shallow groundwater into the subsurface for temporary storage and withdrawing the stored water for use during times of shortage. Very recently, ASR has been considered as well for storage of water reclaimed from sewage.

3.2.2 *Hydrogeology of the Floridan aquifer system*

The Floridan aquifer system consists of a sequence of hydraulically connected limestones and some dolomite that range in age from Late Paleocene to Early Miocene. Thickness of the sequence varies from a featheredge at outcrop to more than 1,067 m where they are deeply buried. The aquifer's permeability is derived from both primary and secondary porosity varying from openings in fossil hashes, through networks of solution-widened joints, to cavernous openings in karst areas. The aquifer system generally consists of an upper and a lower aquifer separated by rocks of generally lesser but highly variable permeability. Transmissivity of the Upper Floridan aquifer ranges from less than 122×10^6 m^2/d in the Florida panhandle and in Southern Florida to over $2{,}440 \times 10^6$ m^2/d in the unconfined karst areas of Central and Northern Florida. Little is known about the hydraulic properties of the Lower Floridan aquifer, but it, too, has areas of very high transmissivity.

Where the rocks of the Floridan aquifer system are at or near land surface, groundwater in them is unconfined to semiconfined. This condition occurs throughout most of Central and Northern peninsular Florida and much of the extent of the aquifer in the other states. In Southern Florida, along the Atlantic coast of Northeast Florida and Georgia, and in extreme Western Florida, the aquifer is deeply buried and groundwater in it is confined. Extensive karstification of the rocks of the Floridan occurs where they are at land surface or buried at shallow depths. Recharge of the aquifer occurs throughout the unconfined parts and in much of the semi-confined parts where the potentiometric surface of the aquifer is below the water table. Here the flow system is vigorous and marked by many springs, 27 of which discharge more than 2.83 m^3/s. Rainfall averages 135 cm/yr over the region of the Floridan aquifer system (Bush & Johnston 1988) whereas evapotranspiration is 94 cm/yr and overland runoff plus groundwater runoff averages 41 cm/yr.

3.2.3 *Water quality*

Water in the Floridan aquifer system contains low dissolved solids concentration (less than 500 mg/L) throughout most of the aquifer's extent except near the coasts and in Southern Florida. In these latter areas, dissolved solids concentrations are over 1,000 mg/L and reach seawater salinity in some parts. Where the water is fresh, hardness and in some places excessive sulfate concentrations are the only undesirable qualities. However, because the aquifer is at or near land surface over much of its extent, it is highly vulnerable to contamination from anthropogenic activities overlying it. Nitrate enrichment of groundwater has occurred over extensive areas of Georgia and Northern and Central Florida, mostly due to agricultural activities.

3.2.4 *Water management*

When Florida became a state in 1845, its freshwater resources initially were perceived as greatly abundant with 80,000 km^2 of land either permanently or frequently flooded and thousands of springs discharging from seemingly limitless aquifers. But in the last century and a half, land drainage, flood protection, a desirable climate, fertile soils, and sufficient water supplies have encouraged rapid agricultural, industrial, and municipal development that presently supports a resident population of 16 million people and about 40 million visitors each year, and freshwater is no longer abundant and clean. In many parts of the State, water demands and contamination are adversely affecting water supplies as well as many of the natural features, wildlife, and habitats that have attracted people to Florida. Many springs are no longer flowing or are overrun by exotic plants, groundwater levels in some places are continually declining and inducing seawater intrusion, and the Everglades and other unique ecosystems are threatened due to lack of sufficient quality and quantity of freshwater.

Water resources management in Florida has undergone a complete metamorphosis during this same period. Water is now perceived as the most valuable of natural resources. In 1972, the legislature created a two-tiered water management structure headed at the state level by the Department of Environmental Protection (DEP) and at the regional level by five water management districts. Districts are largely defined by watershed boundaries and each is governed by a 9- or 11-member board of interested citizens appointed to 4-year terms by the Governor and confirmed by the Senate.

Over the last quarter century, the DEP and water management districts have been legislatively assigned a wide range of responsibilities and authority to assure full beneficial use and sustainability of Florida's water resources; manage the state's water and related land resources; provide water storage for beneficial purposes; prevent damage from floods, soil erosion, and excessive drainage; preserve natural resources, fish, and wildlife; minimize degradation caused by stormwater discharge; promote recreational development; and more. To accomplish these tasks, the water management districts employ many thousands of professional, technical, and support personnel. This system of water management has been widely acclaimed even though deterioration of Florida's natural environment has not been arrested.

By Governor Chiles executive order in 1996 and legislative amendments in 1997, the water management districts were directed to establish stream flows, lake levels, and groundwater levels for priority water bodies below which there would be significant harm to water resources or natural systems. For areas found to be below these *minimum flows and levels*, water management districts must plan and implement recovery strategies.

In 1998, the legislature set State policy to meet current and future water needs of areas having relative water abundance by encouraging use of water sources nearest the area of use or application. These sources include all those that occur naturally as well as alternative sources such as desalination, conservation, reuse of non-potable water, and aquifer storage and recovery. This policy is known as *local sources first* and effectively limits inter-basin water transfers in Florida. In the more developed parts of the State where water demands exceed easily developable natural surface- and ground-water sources, this policy fosters intensive development of alternative sources.

3.2.5 *Concerns over wastewater storage*

The subsurface storage of wastewaters in the Floridan aquifer system has been problematic in that the rocks counted on to constrain upward migration of the wastewaters are carbonates and have questionable confining properties in many places. Indications of upward migration of the injected wastewaters into overlying freshwater aquifers has been observed in monitoring wells in West-Central Florida and along the southeast coast. To date, however, contamination of drinking water supplies by this wastewater disposal practice has not resulted. Environmental groups continue to fight this practice permitted by Federal and State regulatory agencies. Similarly, the storm water gravity drainage wells in Central Florida inject contaminants directly into the aquifer (Bradner 1991) and although existing wells are allowed to continue, new ones are no longer allowed.

The current plan to restore the Everglades ecosystem in South Florida involves the construction and operation of some 330 ASR wells which would inject an average of 6.4 Mm^3/d of storm water into slightly saline parts of the Upper Floridan aquifer for temporary storage. The stored water would be recovered during dry periods. Considerable controversy has been generated over whether the surface water should be treated prior to injection to meet drinking water standards. The Florida Legislature early in 2001 attempted to pass legislation to allow for injection of colliform-containing surface water without pretreatment, but the resulting outcry from environmental groups and the press forced them to abandon enactment of the legislation. Moreover, the Georgia legislature voted to ban the use of ASR altogether in coastal Georgia.

Very recently, ASR has been proposed using water reclaimed from sewage. The lateral and vertical proximity of the target injection zones relative to drinking water aquifers has continued to fuel the debate over the safety of this practice. The potential for contamination of fresh groundwater or even slightly saline groundwater usable for desalination plant feedwater is of grave concern to many. Florida's water needs are too great to render any supply sources unfit.

3.2.6 *Impacts on the surface environment from intensive pumpage*

An example from the Tampa Bay area on the west-central coast of the Florida peninsula illustrates the impacts that intensive groundwater pumping can have on the surface environment. In this case, the impacts are environmentally unacceptable and the groundwater reservoir cannot be used to its full water supply potential.

The area includes either all or parts of the two counties that border Tampa Bay to the west and north as well as large parts of the two counties further north. The approximately 4,700 km^2 area is bounded by Tampa Bay on the south, the Gulf of Mexico on the west, and extends about 55 km north of the Bay and a maximum of about 70 km landward of the Gulf. Exponential agricultural, residential, and commercial growth has occurred in the area since the 1950s that has resulted in a present water demand of about 1.5 Mm^3/d (Southwest Florida Water Management District 2001). This demand is primarily for public supply and is largely met by pumpage from the highly productive Upper Floridan aquifer that is separated from a thin, sandy surficial aquifer by a leaky, discontinuous confining unit on the karstic limestone surface.

The combination of intensive pumpage, distributed in several regional well fields, and a leaky confining unit induces vertically downward migration of water from both the surficial aquifer as well as associated surface-water features that are in hydraulic connection with the surficial aquifer. Lowered groundwater heads in the Floridan aquifer of over 6 m have caused several former shallow lakes and wetlands to go dry and other larger lakes to recede dramatically. Flows of springs and base flows of streams and rivers in the area have also been reduced. Although seawater intrusion at the Gulf and Tampa Bay coasts is a potential concern, it has only been observed in a few localized areas.

The induced changes in surficial water levels and hydroperiods have, in turn, caused a wide range of environmental impacts in many locations, such as:

- Wetland species changes.
- Intrusion of upland species.
- Ground subsidence.
- Rapid and severe desiccation and oxidation of soils.
- Loss of overstory tree canopy.
- Severe fire damage.
- Wildlife loss.
- Complete loss of habitat.

These impacts are societally unacceptable and a court order now mandates that alternative water sources be developed to allow significant reduction of groundwater pumpage in the area by 2008 with expected restoration of improved environmental conditions over time. Plans to meet the court order include water conservation, surface-water development, reclaimed water, and desalination (Tampa Bay Water 2001).

Accordingly, sustainable groundwater development can only be defined in terms on tolerable changes to the other parts on the hydrologic system. Estimation of sustainable groundwater pumpage involves value judgments as well as technical and economical factors. Specifications of the tolerable amounts of reduction to spring flow, stream flow, levels of lakes, acres of wetlands, or freshwater and groundwater storage, as appropriate, must be done before the level of sustainable groundwater development can be ascertained. Florida is in the process of designating minimum flows of streams and minimum levels in aquifers that must be maintained.

Sustainability of groundwater pumpage can be enhanced by spreading the points of extraction over wide areas. This practice tends to minimize the impact of groundwater pumpage on the natural environment. Artificial recharge of the groundwater system can also enhance sustainability. Aquifer storage and recovery, a means of artificial recharge is being utilized increasingly for the temporal balancing of availability of supply with needs. Expectations are that the Florida aquifer system will need to be tightly managed in order to optimize its use as a water-supply source to help meet Florida's growing population's needs.

3.3 *Canadian: an example of transboundary water and water exports*

Contrary to its two Southern North-American neighbors, the USA and Mexico, Canada does not have obvious problems as a consequence of the intensive use (or overexploitation) of groundwater. Canada mostly struggles to keep the quality of its waters, surface and ground, in the highest standard possible, and to overcome the knowledge gaps of its groundwater resources. In the process of assessing water quality, it has become obvious that both surface and groundwater resources are in most cases hydraulically inter-connected and the need for evaluating surface water/groundwater interactions are becoming urgent.

In addition to water quality issues and groundwater knowledge gaps, Canada is concerned about transboundary water issues, both between provinces and internationally, and more recently about water exports.

3.3.1 *Transboundary water*

There is no competition in Canada for groundwater resources between provinces or internationally. The most important cases of transboundary aquifers with potential competition are located in the Prairie provinces of Alberta, Manitoba and Saskatchewan. There are 19 aquifers spanning interprovincial boundaries in the Prairies (Plaster & Grove 2000). When an aquifer extends beneath the border of two jurisdictions, conflict may arise when one jurisdiction depletes groundwater resources that affect the quantity and quality of water available to the other jurisdiction.

The equitable and *reasonable* use of shared waters is the most essential principle considered when negotiating a groundwater apportionment method for the interprovincial aquifer of the Prairie Provinces. Other factors considered are: the priority use; the sustainable yield of the aquifer; the joint apportionment of surface water and groundwater (though a method for incorporating surface water/groundwater interactions is yet to be developed); the specification of pumping locations and amounts; the existing Prairies agreement (changes in surface water levels are included in water balances for aquifer interacting with interprovincial lakes or streams); and the provincial allocation methods.

The current international practices on transboundary aquifers in North America are managed by the USA-Canada International Joint Commission (IJC), and the USA-Mexico international Boundary and Water Commission (IBWC).

The International Joint Commission (IJC) was established under the 1909 Boundary Waters Treaty. The Treaty provides the principles and mechanisms to help prevent and resolve disputes, primarily those concerned with surface water quantity and quality along the international boundary between Canada and the USA. The 1909 Treaty did not mention groundwater; it was until 1977 that transboundary aquifers were first considered by the IJC.

There are two major transboundary aquifers between Canada and the USA: the Abbostford aquifer located between the Lower Fraser River Valley in British Columbia and the Nookack River Valley in Washington state; and the Poplar River aquifer, a third located in Southern Saskatchewan and two thirds in Montana along the international boundary.

Although the use of those shared international transboundary aquifers is important and has consequences for both countries (e.g. decline in water levels and water quality), there have not been major disputes or competition. Local tasks forces or sub-commissions have joined forces to jointly developed long-term strategies for the effective management of those highly sensitive international aquifers.

In recent years, focus has been shifted to the groundwater in the Great Lake region shared by

Canada and the USA. The International Joint Commission has emphasized the need for additional work to be done in the Great Lakes that may be required to better understand the implications of consumption, diversions and removal of surface water and shared groundwater from other basins along the boundary (IJC 1999).

The IJC report (1999) states the importance of groundwater's contribution to streamflow and lake levels of the Great Lakes. Groundwater recharge is mainly from percolation and precipitation in the Great Lakes basin. Withdrawal of groundwater at rates greater than the recharge rate causes water levels in aquifers to decline. If the amount of decline is sufficient, water may be drawn from streams or lakes into the groundwater system, thus reducing the amount of water discharging to the Great Lakes. This is indicative of the inextricable link between ground and surface waters.

Although there is uncertainty and a lack of adequate information about withdrawals of groundwater, it is estimated that about 5% of all withdrawals in the basin are from groundwater. Consumption of groundwater does not currently appear to be a major factor with respect to Great Lakes levels. It is nevertheless a matter of considerable concern and importance to the more than 20% of the basins population who rely on groundwater (IJC 2000).

Finally, it has been estimated that groundwater recharge into the Great Lakes, south of the border (USA), is done indirectly through streams and rivers flowing into the Great Lakes. The average groundwater component of streamflow ranges from 48% for Lake Erie to 79% for Lake Michigan (Grannemann *et al.* 2000). Lake Michigan is the one receiving the most of groundwater flow. Although small in comparison to the amount of water in storage in the Great Lakes, groundwater directly and indirectly contributes about 80% of the water flowing from the watershed into Lake Michigan. Groundwater is also very important to the Great Lakes ecosystem. In the basis of these data, it is evident that groundwater is an important component of the hydrologic budget for the Great Lakes Region. Data for groundwater input into the Great Lakes, north of the border (Canada), are scarcer.

3.3.2 *Water exports*

Estimates of Canada's supply of freshwater vary from 5.6%–9% to 20% of the world's supply, depending on how one defines *freshwater* –whether it means *available*, *usable*, or merely *existing*. One study says Canada has 20% of the world's freshwater –ranking it at the top– but only 9% of *renewable* freshwater.

It has been said that water will be *the oil of the 21st century,* or *liquid gold*, and that it will cause wars between nations. Whatever happens with regard to global water, and the environmental, economic and political fallout, Canada, no doubt, will be a major player. Talks have intensified during the past few years on whether Canada should take advantage of its bountiful supply of water by selling it for profit –like gas, oil and timber.

The House of Commons held televised hearings starting in September 2001 on *freshwater security* to examine the pros and cons of selling Canada's water to other countries. Canada sells bottled water to other countries, but shipments of bulk water are not allowed. There is also the issue of whether, under the terms of the General Agreement on Tariffs and Trade (GATT) and the North American Free Trade Agreement (NAFTA), water is a *vital resource* like the air we breathe, or a *commodity* to be sold and traded. There is a sharp divide on what to do about Canada's water.

In Canada the water resources belong to the provinces, thus the federal government has no jurisdiction on that matter. When it comes to water exports, however, the issue has to be dealt with internationally, thus bringing federal government into play. Nevertheless, some provinces are defying Ottawa and the rest of Canada with plans for bulk freshwater exports.

The province of Newfoundland, Eastern Canada, has made plans in early 2001 to sell water from the Gisborne Lake near the south coast of Newfoundland. About 500,000 m^3 would be skimmed from the lake each week and ship it in bulk to overseas customers. It is argued that "draining 500,000 m^3 of water would lower the lake an inch [1 inch = 2.54 cm], but that this would be replenished naturally within 10 hours" (CBC News 2001). The province government is very enthusiastic about the plans and would go for it alone, regardless of the federal government's opinion.

Environmentalist in Canada argued that allowing Gisborne Lake water to be sold in bulk would make Canadian water a *commodity* and thus subject to the terms and conditions of GATT and NAFTA.

A similar situation happened two years earlier when the province of Ontario issued a permit to a private company to collect Great Lakes water and ship it in bulk to Asia. The permit was issued to a private company, allowing it to ship up to 600,000 m^3 of Lake Superior water to Asia by 2002. There was such a public outcry –on both sides of the border– that the permit was withdrawn.

Other examples exist across Canada, and no doubt, they will continue to defy Canadian's position on water exports. Nevertheless, some critics regard the federal hearings as an indication that Canada is about to change its policy on prohibiting bulk water sales. Some Canadians even talk about diversion (e.g. diverting rivers flow to the south).

Other critics argue that debate over exporting Canada's water is a useless exercise. They say there is no international market for Canadian water. Even if there were, the cost of collecting and shipping Canadian water to distant markets would be prohibitive, far more expensive than drinkable water recovered by new-generation desalination plants.

Whatever the outcome, the provincial and federal governments are preparing themselves for future eventualities by trying to estimate the value of water (e.g. water prize), and by inventorying their other, hidden, water resource: aquifers.

4 SUMMARY AND CONCLUSIONS

The North American landscape emerged from the last ice age that ended some 20,000 years ago. During the retreat of the ice masses, surficial materials were deposited in Canada and in northern parts of the USA that became some of this region's most productive aquifers. During this time, climate patterns formed that provided the snow and rainwater that would establish a dynamic equilibrium between aquifer recharge, discharge and storage. And it was during this time that new populations of people migrated, settled and flourished throughout the continent. So, what, if anything, went wrong? A cynic might say, in considering the effects of the intensive pumpage in Mexico City and Florida described in this chapter, that it took mankind just decades to destroy what nature took tens of thousands of years to create. To a cynic's eye intensive groundwater development caused, among other things, some of the natural springs in Florida and Mexico City to dry up. An alternate viewpoint might be that water is a commodity and, as such, contributes to the overall well-being of the citizens of the community. The loss of natural springs, salt-water intrusion and land subsidence, then, are a relatively small price to pay for the socio-economic development that resulted from the use of community's groundwater resources. The latter argument seems to have merit given the incremental pace at which environmental degradation takes place. One hundred years is a small period of time when compared with geologic time but it is three generations of human lifetimes. Does it matter that grandfather's spring dried up now that grandson has tap water to rely on? The fact that Canada, arguably the most water-rich country in the world, is now engaged in a national dialogue about the need for a nation-wide water-management plan, and that Florida, the USA and Mexico are currently improving policy and regulations to protect their water resources, suggests that the answer to the question is a resounding, *yes!* It matters because groundwater is more than a commodity. It matters because the intensive use of groundwater, as currently practiced, cannot be sustained without adverse impacts on the environment.

A lesson learned from the case studies in this and other chapters of this book, is that a greater recognition is needed about the essential role groundwater plays in the hydrologic cycle and its value as a *common good*. Groundwater storage serves to prevent salt-water intrusion and supports the land itself. Groundwater discharge to surface waters helps to maintain the water level of lakes, the base flow in streams, and ecosystem function. Such functionality has social and economic value. We must develop methods to estimate the *common good* value of groundwater in order to fully understand the tradeoffs of its use as a commodity.

Groundwater will continue to be used as a commodity. Sustaining such usage will require that surface and groundwaters be managed conjunctively in order to meet demands during droughts or periods of exceptionally high usage. Faced with increasing demands for water resources, and with the uncertainty caused by the effects of regional and global climate change, better predictive models are needed to select appropriate water management options. Predictive models that integrate socio-economic and natural system processes are particularly important as policymakers and water managers debate the efficacy of implementing new water treatment, and artificial recharge and storage options.

Groundwater is, by far, the largest source of freshwater on Earth –other than that stored in glaciers and ice caps– but probably the least understood. Knowledge about its occurrence, distribution and quality is needed in order to make informed decisions about its availability for use. Education is needed so that citizens will understand the consequences of the casual disposal of wastes or the inappropriate placement and use of wells. It is recognized that social and economic realities may force a country to exploit the commodity valuation of its groundwater. It is hoped, however, that lessons learned in North America can help bring about alternate solutions to ensure the sustainability of groundwater resources in harmony with the natural environment.

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