CHAPTER 12

SOUTHERN ONTARIO HYDROGEOLOGICAL REGION

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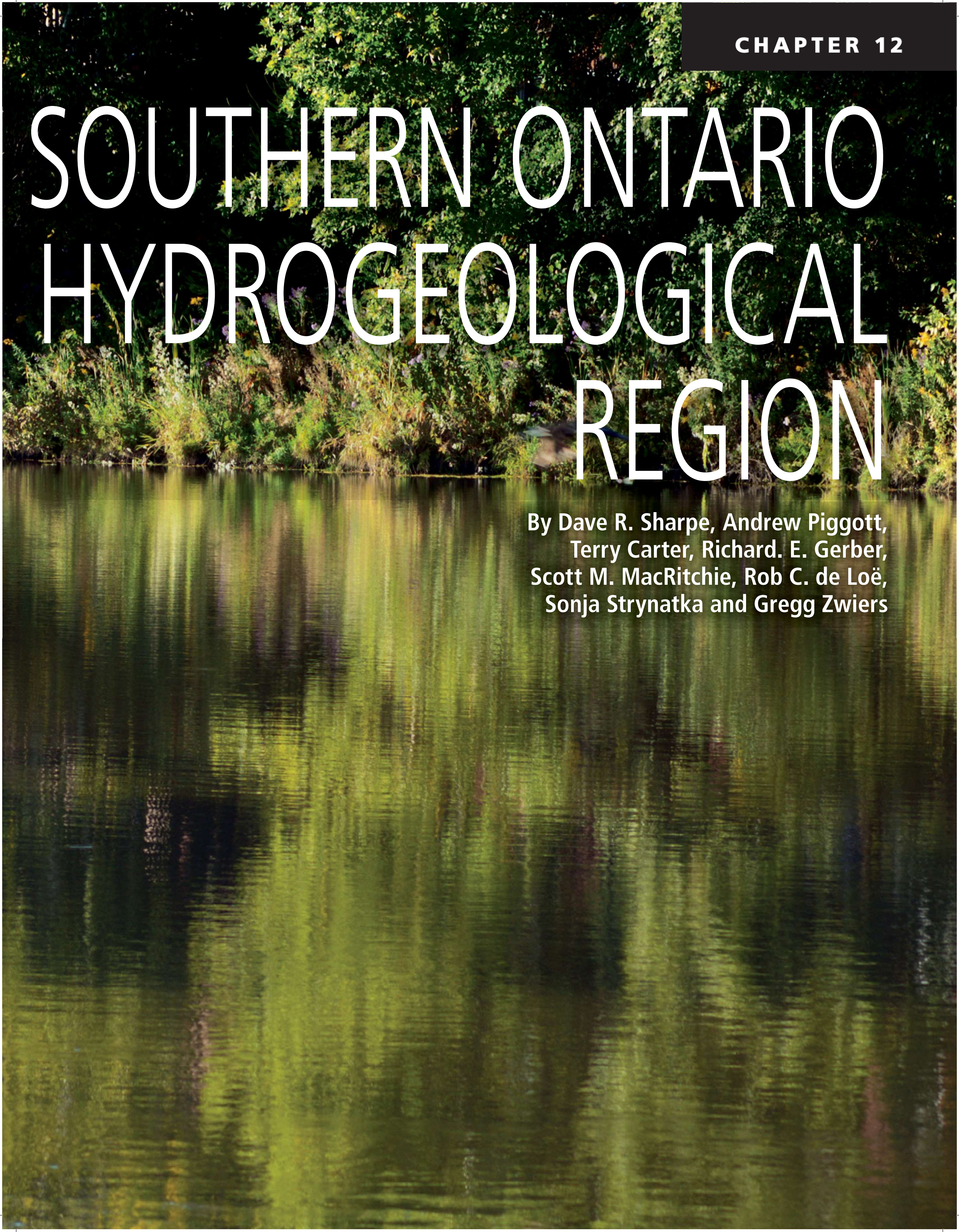

12.1 INTRODUCTION

Groundwater is vitally important to the quality of life enjoyed by the residents of southern Ontario and to the health of its economy and ecosystems. Groundwater is a significant source of water supply for agriculture, industry, and municipal and rural users. As a source groundwater is often more cost-effective than surface water. It is generally cheaper, needs minimum treatment, requires less costly pipelines, has uniform temperature, and has better water quality.

The goal of this chapter is to add to public understanding of groundwater resources in southern Ontario (e.g., Council of Canadian Academies, 2009). Water supply and quality issues are of increasing concern to Ontario's residents and there is growing awareness that lakes, rivers and streams are inextricably linked to groundwater systems. Driving this awareness are concerns about the long-term impact of climate change and the Walkerton tragedy in 2000 which put the spotlight on the issue of safety, security and sustainability of our water supply (see Box 12-1). Recent calls for action have come from the International Joint Commission (1999; which has jurisdiction over the Great Lakes basin) to protect water in the Great Lakes and to map groundwater in a systematic manner. As well, Ontario's Auditor General (2006) and its Environmental Commissioner (1997; 2000) have clearly identified the increasing needs and conflicts in water demand from urban, industrial and agricultural users, and the susceptibility of aquatic ecosystems to the impact of human activities in southern Ontario. These public concerns must be linked to groundwater science and considered in the management of our water resources.

How important is groundwater in southern Ontario (e.g., Cohen, 2006)? Current groundwater use in Ontario shows that a quarter of Ontario's residents, representing half a million households, are reliant on groundwater. About 1.3 million people use groundwater from private wells and 1.9 million from municipal supplies. Much groundwater use, other than drinking water supply, is for agriculture. For example, in agricultural counties of southwest Ontario, such as Middlesex and Elgin, about 25% of all groundwater use is domestic and municipal while agricultural use is closer to 30%. In those areas with significant sand and gravel operations, however, industrial use may be up to 35%.

About one-half of total streamflow in southern Ontario is estimated to be baseflow due to groundwater discharge. Surface aquatic habitats such as springs, streams, wetlands and many lakes depend on groundwater. The volume of groundwater discharge plays an important role in maintaining the depth of surface waters, or the "living space" used by aquatic organisms. With a constant temperature of 7°C to 9°C in southern Ontario, groundwater discharge maintains the conditions for cold-water fish such as brook trout. Groundwater sustains soil moisture along stream banks where healthy vegetation contributes to stream-bank stability. Groundwater can sustain food production, spawning areas, and connections along the channel and allow fish to access refuge areas during low-flow periods.

The analysis begins by looking at the climate and physical settings which provide the background necessary for understanding southern Ontario's groundwater resources. An examination of the hydrogeological framework which provides the geological overview for the water cycle and how it varies across different terrain conditions follows. The next section on groundwater resources

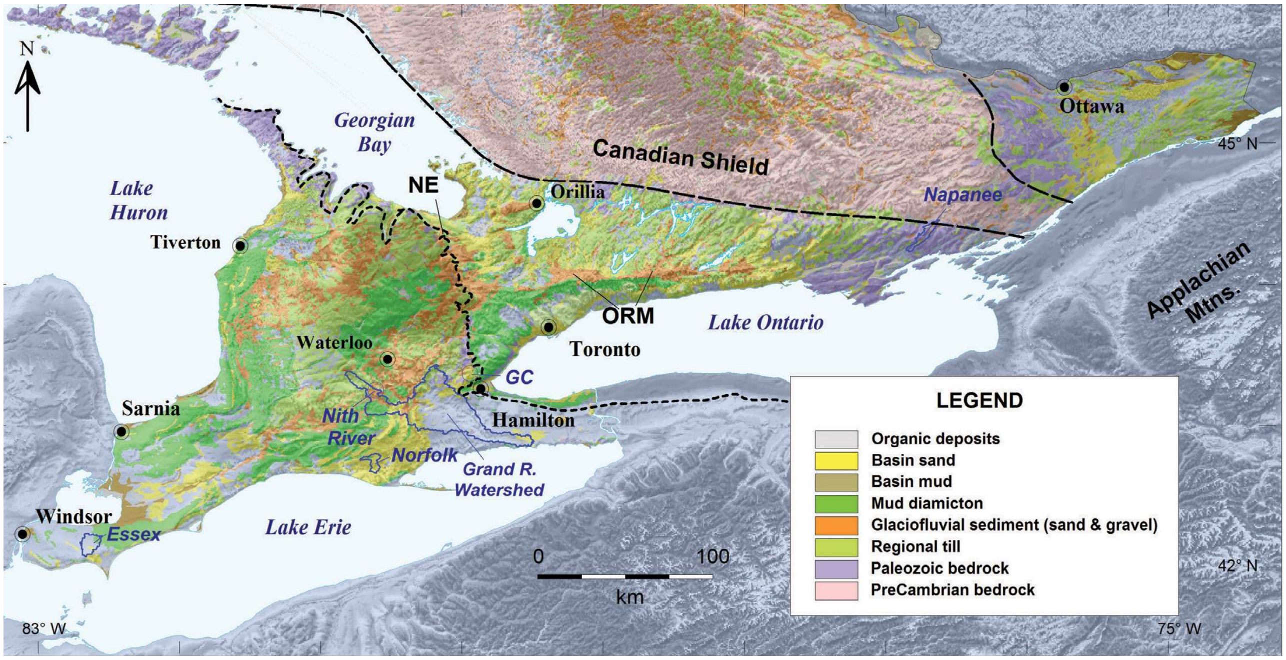

Figure 12.1 Geology guides the flow of groundwater.
The surface geology of southern Ontario, and adjacent areas such as the Canadian Shield, is draped on an elevation model to illustrate regional physiography. The generalized geology shows five main sediment types (sand, mud, diamicton or till, gravel and organic) plus the Paleozoic and Precambrian bedrock. It also illustrates that key hydrogeological terrains (blue outlines), to be discussed below, can be represented by the sediment types in which they are located. The Norfolk hydrogeological area is defined by sand; Essex by clay; Grey by till (east of Tiverton); Wellington by gravel (north portion of Grand river watershed); and Napanee by Paleozoic rock. Grindstone Creek (GC) and Nith River (NR) watersheds are also illustrated. NE= Niagara Escarpment; ORM= Oak Ridges Moraine. Tiverton is the site of a deep geological repository discussed later. Manitoulin Island is located in northern Lake Huron. Walkerton is located halfway between Waterloo and Tiverton.

offers a brief snapshot on groundwater availability and resource issues. Seven vignettes are interspersed throughout the text with a more detailed look at specific groundwater terrains and issues including 1. the Walkerton tragedy; 2. Norfolk sand plain, a sediment aquifer case study; 3. the Essex clay plain/ interface aquifer case study; 4. Napanee limestone plain aquifer case study; 5. fluoride and water quality; 6 the ecological significance of groundwater; and 7. Grand River watershed water budget (Figure 12.1).

12.1.1 Setting

Southern Ontario includes the sedimentary basins between Ottawa and Georgian Bay, bound in the south by the Great Lakes Huron, Erie and Ontario, and by the St. Lawrence River (Figure 12.1).

Southern Ontario covers an area of about 72,000 square kilometres, including Manitoulin Island, bounded by the Canadian Shield to the north and east, and by the Great Lakes to the south and west (Figure 12.1). The underlying bedrock is composed of Paleozoic marine sedimentary rocks deposited from the Cambrian through late Devonian time (~500 to 350 million years ago) and preserved in deep sedimentary basins. Hydrocarbon reservoirs are also present in the deeper parts of these sedimentary basins. Covering bedrock is unconsolidated sediment, mainly glacial, ranging up to 200 metres thick.

Southern Ontario has gentle topography, fertile well-drained soils, a warm growing season, and abundant rainfall, making it ideally suited to supporting extensive agriculture and woodlands.

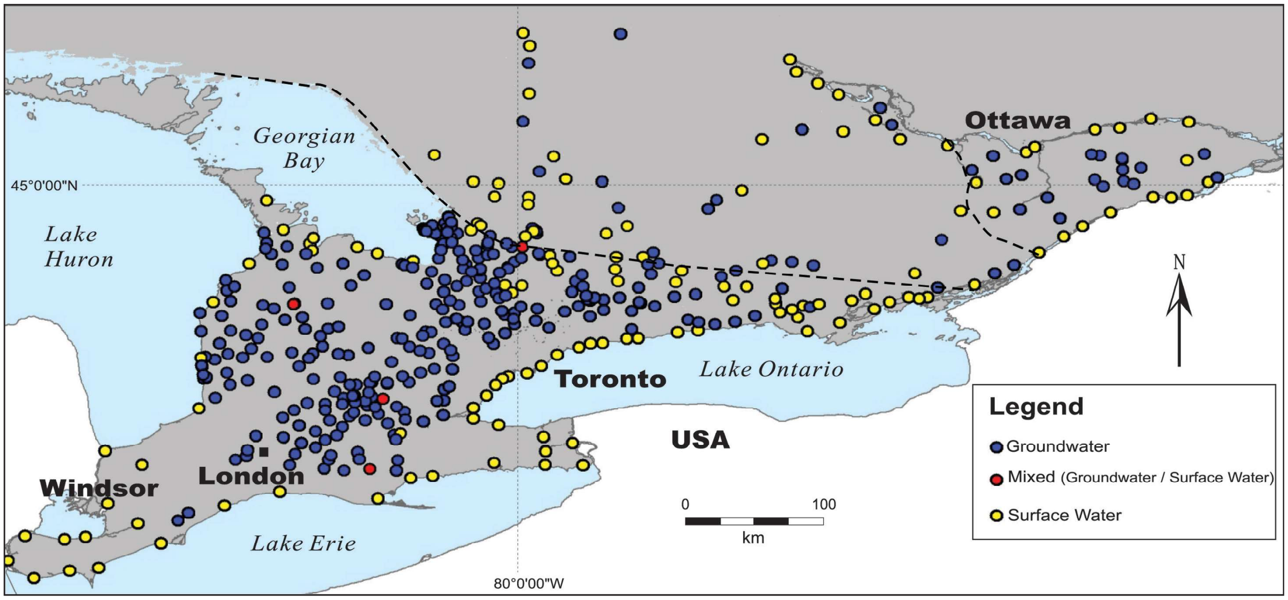

Figure 12.2 Do you use groundwater or surface water?
Municipal groundwater supply[1] is very prominent away from large, lake-based supplies. Water from Lake Ontario is used across much of the Greater Toronto Area despite the costs of treating this water and pumping it uphill to areas where groundwater is available. Map data was provided by the Source Protection Programs Branch, Ontario Ministry of Environment. London (black square) uses surface water from Lakes Erie and Huron (see also Ministry of the Environment, 2011).

The region is one of Canada's most important industrial hubs with a high population density: both factors affect land use and surface hydrology. Despite the proximity of abundant Great Lakes surface water, groundwater is a pivotal resource for agricultural and potable water use in inland areas, with about 90% of rural areas in southern Ontario and some 200 municipalities using groundwater as their primary water source (Figure 12.2).

12.1.2 Climate

Southern Ontario has a humid continental climate with warm to hot summers, cold winters, and reasonably uniform precipitation throughout the year (Brown et al., 1980). The Great Lakes modify the climate of the region, moderating temperatures inland from the Lakes and producing lake effect precipitation in areas east of Lake Huron and Georgian Bay (Figure 12.3). Average annual temperature varies (Figure 12.4) from 3.9°C in the north to 9.4°C in the south with a regional average of 6.1°C. Average monthly temperatures at Petawawa, west of Ottawa, vary from −12.9°C in January to 19.1°C in July. Temperatures at Windsor vary from −4.5°C in January to 22.7°C in July. Average annual precipitation also varies across the region (Figure 12.3), from 790 mm near Toronto to 1,200 mm in Bruce County, east of Lake Huron, with a regional average of 960 mm. Average monthly precipitation at Toronto varies from 43 mm in February to 80 mm in August. Precipitation at Paisley, near Lake Huron where lake effect precipitation is pronounced, varies from 70 mm in April to 150 mm in December.

12.1.3 Physiography

Topography and the types of soils and sediments at the surface are factors which determine how groundwater flows. Southern Ontario is part of

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[1] Map data provided by the Source Protection Programs Branch, Ontario Ministry of Environment, who provide guidance for the safe operation and security of municipal water supply systems.

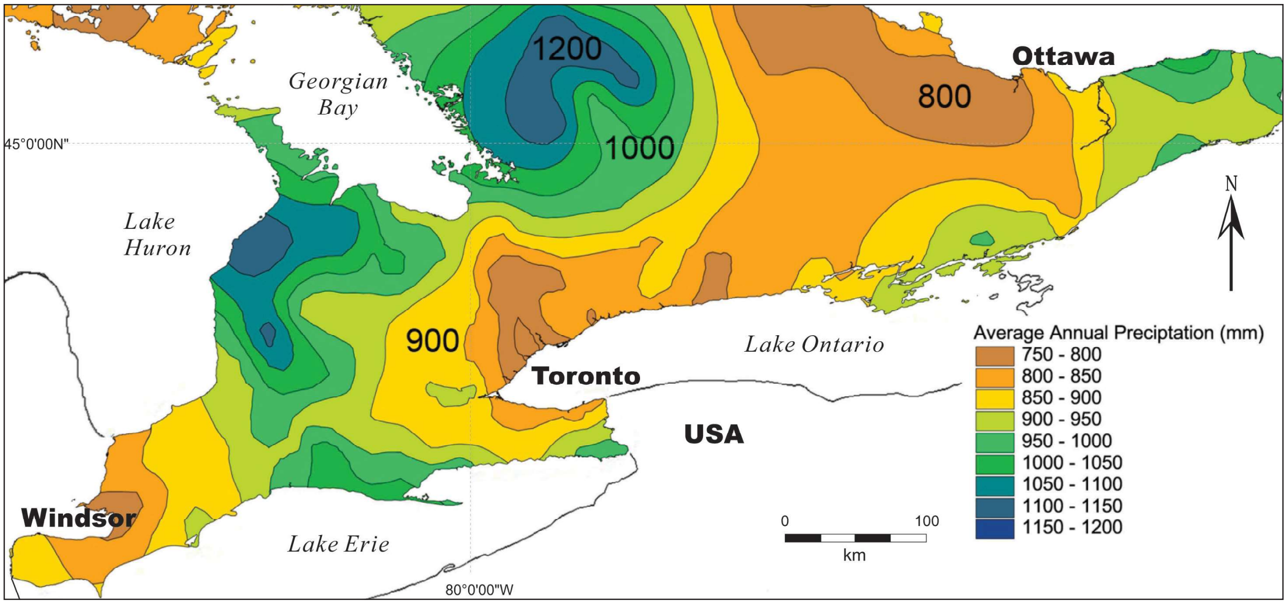

Figure 12.3 Precipitation nourishes streams and the groundwater system.
There is variation of average annual precipitation across southern Ontario. Data Source is Meteorological Service of Canada—Ontario Region; Internal Data Courtesy of National Climate Data and Information Archive.

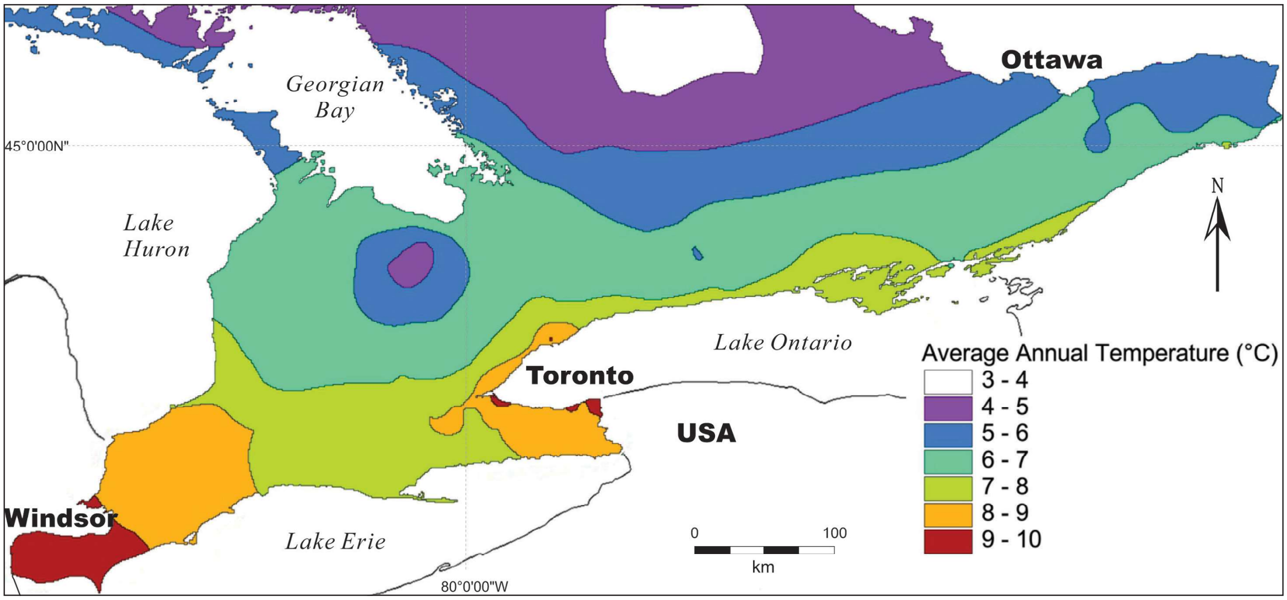

Figure 12.4 Temperature influences evaporation and transpiration, and hence the hydrologic cycle.
There is variation of average annual temperature across southern Ontario, particularly from southwest to northeast. Data Source is the Meteorological Service of Canada—Ontario Region; Internal Data Courtesy of National Climate Data and Information Archive.

the Great Lakes/St. Lawrence watershed that drains the lowlands between the Canadian Shield to the north and the Appalachian uplands to the south (Figure 12.1). This watershed is distinguished by low-relief bedrock topography interrupted by buried valleys and prominent escarpments. Southern Ontario's most significant high-relief feature is the Niagara Escarpment, a 725-kilometre-long, 100-metre-high bluff that extends from Niagara Falls to Tobermory at the tip of the Bruce Peninsula and to Manitoulin and Cockburn Islands, which separate Georgian Bay and northern Lake Huron. At its highest point, the Escarpment reaches about 500 masl and slopes gently southwest on inclined rock strata. The escarpment has been eroded over geological time which has led to enhanced fractures and cavities of the soluble escarpment cap rocks. More recently the escarpment has been eroded primarily by glaciation.

Southern Ontario's landscape is very much the result of the advance and retreat of the massive, kilometres-deep ice sheets that completely covered it until more than 10,000 years ago. Glaciers and their meltwater shaped the landscape largely by erosional and depositional processes during the Quaternary period. This 2-million-year era was a period of dramatic climate change with repeated cool episodes of glacial advance/retreat and intervening warm, inter-glacial periods. It was characterized by the accumulation of up to 200 m thick glacial, glacial-lake, glacial-river, and non-glacial deposits (Barnett, 1992).

Moraines, landforms containing undulating slopes formed as the ice melted and receded during the last ice age, are another important topographic feature found throughout southern Ontario. The Oak Ridges Moraine (ORM) is the largest and most significant rising up to 300 metres above Lake Ontario to form a series of mounds and ridges and a ~160 km long drainage divide between Lake Ontario and Georgian Bay (Figure 12.1). More typically moraines, and other common ice age landforms such as drumlins and eskers, provide lower-relief terrain and are 10–25 metres high. The ice age also left many prominent surface valleys with relief of 25–50 metres, largely developed as meltwater channels. Low-relief terrain, such as clay plains and sandy outwash deposits, have been incised by modern rivers to depths ranging from 10 to 25 metres as the land continues to rise following the melting of the thick ice sheets.

The varied and complex glacial deposits resulted in equally complex local groundwater flow patterns which can vary within 100s or 1000s of metres. Changes in the landscape wrought by the glaciers are still happening. Although the weight of thick glacial ice compressed the land, it is still rebounding at the rate of a few cms per century, which over time slowly disrupts drainage patterns. The load of the ice and the discharge of its meltwater during the glacial period also affected the flow of water deep below the land surface and changed the chemistry of this water.

12.1.4 Geology

Ancient (Paleozoic) marine sedimentary rocks of the Michigan and Appalachian Basins are the dominant geological feature of southern Ontario and exert a controlling influence on groundwater storage and regional flow directions (Figure 12.5). The basins are separated by a northeast-trending basement ridge known as the Algonquin Arch (to the northeast) and by the Findlay Arch (to the southwest). The Findlay Arch, in turn, is separated by a structural depression known as the Chatham Sag. These arches likely formed during basin subsidence, and together with the basins, control groundwater flow directions. Strata dip gently at 3.5 to 12 m/km westward into the Michigan Basin north of the Algonquin and Findlay Arches, and southward into the Appalachian Basin on the arches' south side (Figure 12.5). Bedrock strata along the crest of the Algonquin Arch have a regional southwest dip of 3 to 6 m/km into the Chatham Sag (Armstrong and Carter, 2010).

East of the Niagara Escarpment, bedrock strata younger than Ordovician age have been eroded away exposing subcropping Paleozoic bedrock consisting of sandstone, siltstone, shale and carbonate rocks of the Ordovician (~488 to 444 million years ago) and late Cambrian age (~500 to 488 million years ago). West of the Niagara Escarpment, carbonate and evaporite rocks are prominent in Silurian age (444 to 416 million years ago) formations that extend from Lake Erie to Georgian Bay and Lake Huron. Younger carbonate and shale rocks of Devonian age (416 to 359 million years ago) occur to the southwest near Sarnia, and extend eastward to the Niagara River. In general, strata in the Appalachian Basin are more clast-rich in composition, while those in the Michigan Basin are more carbonate-rich. Thick evaporite and halite (salt) beds also occur within the Michigan Basin.

Paleozoic bedrock has variable porosity and permeability depending on grain size, lithology, sorting, depositional setting, lateral facies changes, fracturing, and post-depositional weathering and alteration. In general these bedrock tiers form a thick stratified succession of aquitards with a few thin, confined aquifers (underground water-bearing units) and erosional breaks; flow directions are controlled by regional dip of the strata (Figure 12.6). The dominant control on the occurrence and movement of water in these rocks, and in particular the carbonate and evaporite rocks, is their proximity to the present-day erosion surface and/or paleo-erosion surfaces represented by unconformities in the deep subsurface bedrock (Carter and Castillo, 2006). Chemical dissolution of carbonate and evaporite rocks at these unconformities has created major regional aquifers in the subsurface, at the present-day surface, and in areas of thin sediment cover (Brunton et al., 2008; see Figure 12.12). Where these same rocks have not been exposed to surface weathering and dissolution they form aquitards and even aquicludes (no water flow). The best example of this phenomenon is the Salina Group. The beds of halite, anhydrite, dolostone, limestone and shales in the deep subsurface that form the Salina Group have no effective permeability, and form aquicludes where thick beds of halite are still present. In the near-surface, the halite and anhydrite dissolve in the presence of fresh groundwater and meteoric water, and the rock is reduced to a karstic rubble of rock fragments with greatly enhanced porosity and permeability. Recognition of these surface karst terrains (see Figure 12.12) and subsurface karst intervals (Armstrong and Carter, 2010) is critical to understanding the movement of water in Paleozoic bedrock and development of accurate models of water movement in bedrock.

Southwestern Ontario is tectonically stable. Faults are widely spaced, with a maximum vertical displacement of ~100 metres on steeply dipping normal faults (Armstrong and Carter, 2010). Modelling of fracture systems by Sanford et al. (1985) indicates the greatest density of fracturing and faulting is along the crest of the Algonquin and Findlay Arches and in the Chatham Sag. Paleozoic rocks in the Ottawa area, have been affected by block faulting (Late Mesozoic) along the Ottawa-Bonnechere graben (tectonic zone). Faulting is most severe near the Ottawa River with vertical displacement of up to 1,000 metres on steeply dipping normal faults (Williams, 1991). Such faults received large amounts of fresh glacial meltwater which was forced deep into the bedrock (>100 m in depth) by thick glacial ice during glaciation, pushing brackish and saline water deeper into the basin. The glaciers eroded the bedrock

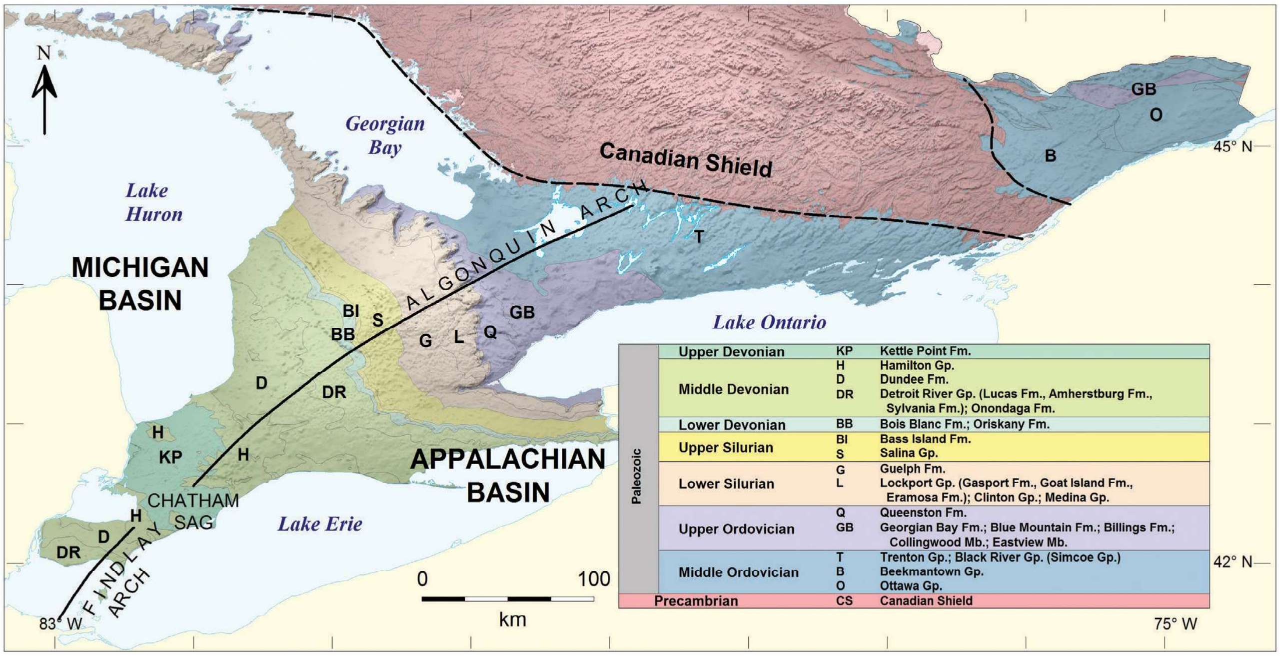

Figure 12.5 Geology and topography of the bedrock surface.
Geological setting and bedrock strata of southern Ontario[2] control groundwater flow at larger scales than does surface topography. Bedrock strata form barriers to downward movement of fresh water except where these rocks have been fractured, weathered or affected by karst. Bedrock strata may control the location of bedrock valleys due to differential erosion (see Figure 12.9). The map illustrates major structural elements (arches and basins), major formations (marked by letters) and major age groups (marked by colours) on an elevation model. Arch locations varied at different points in geologic time. It is important to note that the time-stratigraphic correlation of the Silurian is undergoing revision (Cramer et al., 2010) and the term "Amabel" has been abandoned and replaced by Lockport. The oldest rocks (Canadian Shield), in the north and east, are overlain by successively younger ancient marine rocks from northeast to southwest. The Niagara Escarpment occurs at the eastern margin of where hard carbonate rocks overlie soft, more erodible shale rocks (see Figure 12.9). Cambrian strata are not shown on this map, but are exposed on the eastern flanks of the Frontenac Arch of the Canadian Shield (narrow area east of Lake Ontario).

and partially covered the landscape with glacial sediment, which again altered groundwater flow patterns within the basin. In recent times, without glacial loads and pressures, fresh water typically reaches shallower depths (<100m) below ground surface (Figure 12.6).

Bedrock is covered by thin unconsolidated clastic sediments of glacial or recent origin in most of southern Ontario (Figure 12.1): its thickness ranges from zero to >200 metres, but is usually tens of metres thick. Sediment cover is thinnest near escarpments and along river valleys. The thickest sediment occurs along buried bedrock valleys, such as the Laurentian valley connecting Georgian Bay and Lake Ontario (Figure 12.9), and below major moraines such as the Oak Ridges Moraine. Thick sediment also fills or partially fills former meltwater channels important to regional groundwater flow. The variety of sediment types affects groundwater infiltration toward bedrock, and includes sand, clay, till uplands and sand and gravel channels that dissect uplands.

12.1.5 Key groundwater information sources

12.1.5.1 Province-wide reports

Understanding of regional groundwater systems and their related settings in southern Ontario comes from past geologic and hydrogeologic frameworks (e.g., Scott, 1967; Sibul et al., 1977; Turner, 1977; 1978; Barnett, 1992; Farvolden and Cherry, 1988;

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[2] Geology from Armstrong and Dodge (2007).

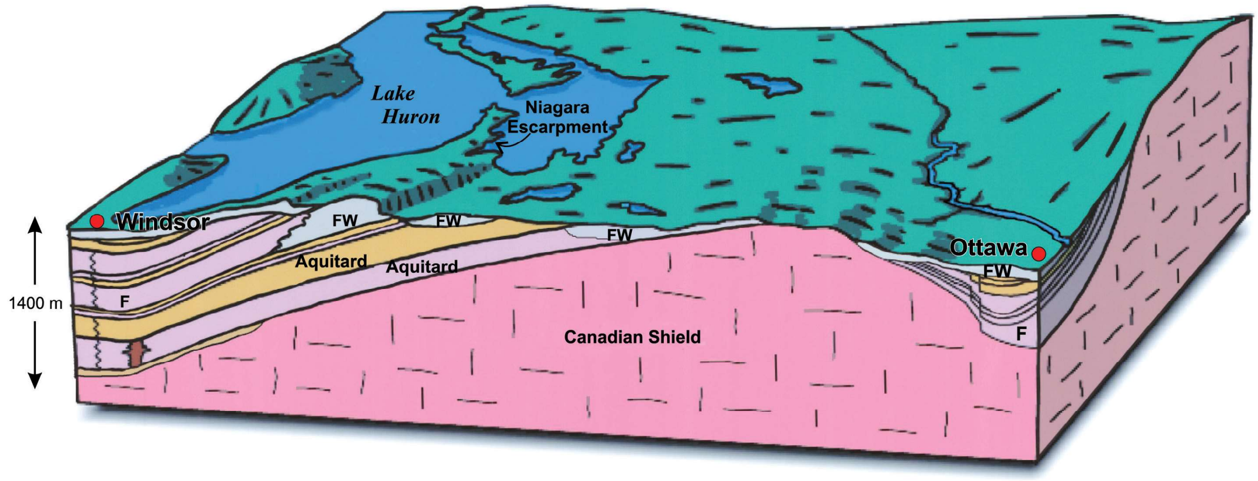

Figure 12.6 Geology below the surface and groundwater flow.
This geological cross section extends from Windsor to the corner of southeastern Ontario. It shows generalized bedrock lithology (purple—carbonate rocks, orange—shaley rocks) with a ~10–100 m thick sediment zone near the surface (light grey). The thicker grey zone indicates enhanced recharge and deeper flux of fresh water in karst and reefal shallow carbonate bedrock along the Niagara Escarpment area to depths beyond 100 m. Bedrock units identified as aquifers are only viable in the top 100–250 m below surface; deeper water becomes brackish to very salty. Note faults (F) in the Ottawa valley basin sequence. Geology is from Armstrong and Dodge (2007) and Sanford and Arnott (2010).

Novakowski and Lapcevic,1988; Johnston et al., 1992; Karrow, 1989; Singer et al., 1997; Eyles, 2002), and, from synoptic reports such as "Groundwater in Ontario" by MacRitchie et al., 1994 and "The Hydrogeology of Southern Ontario" by Singer et al., 2003; from a series of municipal groundwater studies (e.g., Oxford County, 2003) that preceded the serious water problems at Walkerton; and from Source Protection watershed assessment reports which followed the Clean Water legislation.

The MacRitchie report highlights major groundwater sources, quality, and management across Ontario. It identifies several major aquifers within the region (the Alliston, Oak Ridges and Waterloo moraine aquifers in sediment, the Lockport-Guelph and Detroit River Group carbonate aquifers, and the Nepean sandstone aquifer in eastern Ontario, for example).

The Singer report describes the occurrence, distribution, quantity and quality of groundwater on a regional scale in southern Ontario, based on more than 215,000 water well records. The report combined this data with physiography, geology and hydrogeological information to create synoptic maps of key parameters and regional relationships. Groundwater was analyzed according to major geological formations, and the occurrence of wells drilled in bedrock and/or in sediment. The wells were assigned as water sources, specifically as 18 bedrock aquifers and 164 sediment aquifers, including a number of well-known aquifer systems. New geological insights, in particular the recognition of a regional interface or contact zone aquifer system at the point of contact between bedrock and the unconsolidated sediments, has led to the realization that sediment and bedrock waters in the near surface are mixed and cannot easily be classified as strictly bedrock or sediment aquifers. Groundwater quality may form a continuum between bedrock and sediment settings.

Of particular note in Singer's report, data from 33 stream gauges indicated highest groundwater discharge during spring, with an ensuing decline until fall precipitation. This data was also used to estimate a long-term mean groundwater recharge of between ~83–285 mm per year, depending on soil and slope conditions. Groundwater quality, tested in over 1,000 samples and from well records, is generally very good across the region with some natural and man-made water quality issues. Anthropogenic effects have led to many problems in shallow aquifers which are poorly protected from near-surface contamination sources. The main concerns for groundwater quality and management are waste and sewage disposal, agricultural activities, and road salt application.

12.1.5.2 Municipal groundwater studies and Source Protection assessment reports

From 1999 to 2005, groundwater studies were produced for each Ontario municipality which utilized a groundwater supply for drinking water (see conservation authority or municipality websites). These studies examined groundwater resources at local and regional levels to identify potential risks. The studies included delineation of wellhead protection areas for municipal wells, mapping of groundwater recharge and discharge areas, and identification of sensitive groundwater areas. The resulting groundwater management plan was designed to manage activities which would reduce the risk of contaminating drinking water supply for each municipality.

The Clean Water Act (Province of Ontario, 2006) provides a framework for the development and implementation of local, watershed-based Drinking Water Source Protection plans. The Act also implements the Drinking Water Source Protection recommendations made by Justice Dennis O'Connor in Part II of the Walkerton Inquiry Report. The Act came into effect in July, 2007, along with the first five associated regulations (O'Connor, 2002).

To comply with the Act, municipalities and conservation authorities have conducted technical studies to delineate those areas around municipal drinking water sources (groundwater supplies) which are most vulnerable to contamination and overuse (Ministry of the Environment, 2004). Within vulnerable areas, the studies have identified historical, existing and possible future land uses that are, or could pose, a threat to municipal water sources. The resulting Assessment Report provides the scientific foundation to develop a Source Protection Plan for each region (Figure 12.7); such plans aim to eliminate significant threats and prevent new ones from developing.

Source Water Protection is focused on municipal water supplies, but rural residents also require groundwater advice and protection. Some 90% of southern Ontario's rural residents rely on groundwater and use ~750,000 private wells; ~20,000 new wells are drilled each year. There are an estimated 100,000 abandoned wells, and because these wells are not serviced, they may pose a contamination threat as they offer a preferential flowpath from surface land uses to the aquifer system.

While Ontario regulations require that all residential well owners keep their well accessible at all times for cleaning, treatment, repair and inspection, many homeowners compromise the integrity, reliability and safety of their wells, and possibly those of their neighbour's through poor practices. Indeed, a high percentage of wells in southern Ontario suffer from poor location, construction and maintenance. A recent survey of over 1,500 private well owners in Ontario, conducted by the Water Policy and Governance Group, found that many well owners do not understand how to protect their water supplies through testing and inspection (Kreutzwiser et al., 2010). The

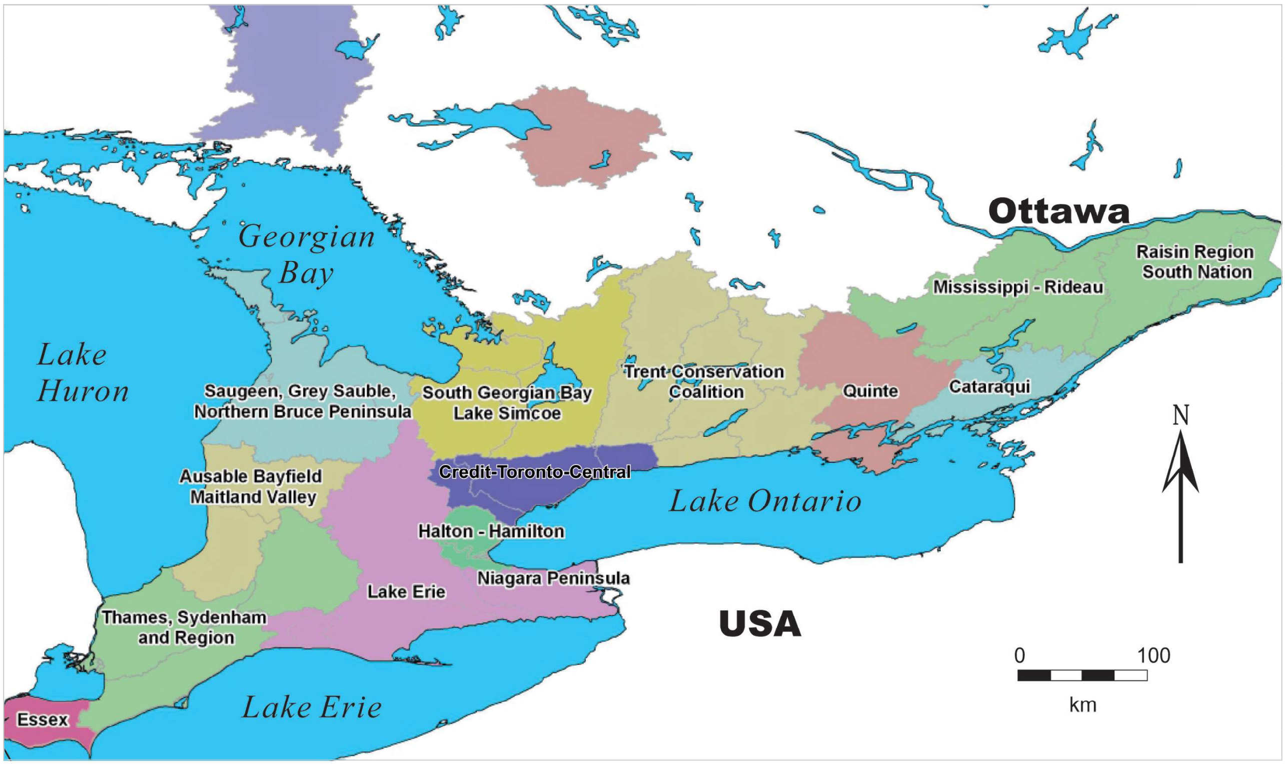

Figure 12.7 How is Ontario safeguarding groundwater following Walkerton?
Ontario is subdivided into a number of Source Water Protection Areas and Regions. Each area must prepare an assessment report and a Source Water Protection Plan (see Ministry of the Environment SWP website http://www.ene.gov.on.ca/environment/en/subject/protection). Source Protection Areas are grouped into Source Protection Regions led by a Source Protection Committee responsible for guiding the required technical studies, setting standards, and developing planning policies to protect drinking water supplies within each region.

Well Aware program (http://www.wellaware.ca/) provides a full range of practical information on safe practices in well construction, maintenance, decommissioning, and protection of groundwater to ensure that wells are in safe running order.

12.1.5.3 Groundwater monitoring, databases, and mapping

The Ontario Ministry of the Environment (MOE) operates the Provincial Groundwater Monitoring Network (PGMN) in partnership with 10 municipalities and all 36 Conservation Authorities (e.g., Ministry of the Environment, 2007). As of 2012, the PGMN consisted of 435 groundwater monitoring wells located in southern Ontario. These wells were selected to provide scientific information on groundwater quality and levels in the area. Water samples from the wells are collected annually and analyzed for a variety of chemicals. Groundwater levels and chemistry collected by the PGMN can be accessed on the MOE website http://www.ene.gov.on.ca/environment/en/resources/collection/data_downloads/index.htm#PGMN.

Groundwater quality is also monitored at selected municipal drinking water systems under the Ontario Drinking Water Surveillance Program, which provides information on the quality of raw (untreated) water and treated drinking water. The raw water quality data can be used to assess ambient environmental conditions, and complements information collected by the Provincial Groundwater Monitoring Network.

Two databases are the principal sources of basic information on the occurrence of groundwater and subsurface geology in southern Ontario. The Water Well Information System, maintained by the Ontario Ministry of Environment, contains over 600,000 records, including basic data on well location, sediment or rock type, water quality, quantity and static level, pumping rates and well construction. The Ontario Petroleum Data System, a relational database, is maintained by the Petroleum Resources Centre of the Ontario Ministry of Natural Resources. These records provide geological, drilling and engineering information on over 26,000 petroleum wells drilled in Ontario since the 1800s. Stored data includes well location, status, depths, geological formation tops, well construction, oil/gas/water intervals, logging and cored intervals, and drill samples. Water interval data includes depth, elevation, static level, water type and geological formation; the basic well data is available free of charge from www.ogsrlibrary.com, but oil/gas/water and geological data access is restricted to Library members. Water well data from across southern Ontario is publicly available for viewing at http://ontariogroundwater.com/.

Maps, reports and digital data on the surficial and bedrock geology of Ontario can be found on the Geology Ontario website available at http://www.geologyontario.mndm.gov.on.ca/. This website provides access to geoscience information from the Ontario Geological Survey, with its 1,000s of reports and 1,000s of maps which include digital field data, geophysical surveys and geochemical analyses for the region.

The Ontario Geological Survey has a program of aquifer mapping to characterize the geology and geochemistry of groundwater in southern Ontario. This includes 3D mapping of aquifers in sediments and bedrocks, mapping of karst and bedrock aquifers of the Niagara Escarpment (e.g., Bajc and Shirota, J. 2007; Brunton, 2009; Brunton and Brintnell, 2011), and characterization and mapping of the geochemistry of natural groundwater. Geochemical results from over 900 water wells (Hamilton, 2011) represent the largest and most complete regional database of ambient groundwater chemistry for southwestern Ontario, in addition to complementing data available from PGMN. The Geological Survey of Canada also has regional hydrogeological information available on its websites.

12.1.5.4 Accessible groundwater information

With growing public awareness and concerns about groundwater, information is in increasing demand from many of the above-mentioned government agencies. To meet this demand and to accommodate users' preference for web accessible information, a national Groundwater Information Network (http://gw-info.net) has presented a web-based system for mapping and analyzing water-well and monitoring data. This website enables users to find, view (in 3D), analyze, download and model their well and water resource data online. Decision-making requirements regarding groundwater resources are therby enhanced. It is hoped that this online groundwater resource centre, a cross-country collaboration of water agencies, will advance web-based groundwater data technology and improve knowledge of watersheds.

12.2 HYDROGEOLOGICAL FRAMEWORK

This section examines water movement through the landscape and seeks answers to several basic questions: What factors control the movement of water in southern Ontario once it reaches the surface or enters underground pathways? What are the important water-bearing (aquifers) and water-controlling (aquitards) formations? Where are these aquifers located and how can we assess them to improve knowledge of groundwater and related surface water flow? and, finally, is the quality of groundwater and surface discharge affected by southern Ontario's rock and/or sediment types through which the water flows?

Water-bearing formations must be assessed with respect to their elevation within the landscape and their soil or rock properties. Topography provides the gradient which drives water flow. Geology, through internal rock or sediment properties, controls how flow occurs through sediment or rock. A descriptive framework, therefore, begins with geology and topography. Next, we need to look at how water enters the subsurface (groundwater recharge), how it flows through the subsurface (hydrogeologic properties), and where it leaves the subsurface (groundwater discharge).

12.2.1 Bedrock topography and overlying sediment thickness

Variations in bedrock topography and overlying sediment thickness affect groundwater flow. These factors, along with the composition of bedrock and sediment units, affect the quality of water in the flow system. Bedrock irregularities occur where softer rock (e.g., shale, evaporite) was preferentially eroded, while harder rock (e.g., limestone) resisted erosion, leaving escarpments and troughs on the landscape. Sediment thickness and bedrock topography maps are consequently prime prospecting tools in the search for new aquifer water supplies in southern Ontario's thick sediment or shallow bedrock (Figure 12.8). These maps are also useful for identifying depth to the important contact zone aquifers.

The geographic distribution of southern Ontario's most important aquifers has been mapped by combining bedrock elevation and sediment thickness data, modified by water well usage in each of these main strata, bedrock and sediment (Figure 12.8b, c). Shallow bedrock and the contact zone between bedrock and sediment (contact zone aquifer) are targeted for groundwater in many areas except where sediment is thick, such as bedrock valleys and areas of stratified moraines. Thick sediment areas are the best areas for high-yield wells in unconsolidated sediment. The importance of bedrock aquifers may be qualified insofar that many wells drilled into bedrock obtain fresh potable water from overlying sediments. This contact zone aquifer has been identified as a discrete and separate bedrock aquifer in previous studies (e.g., Singer et al., 2003), but it is, in fact, a connected, complex, semi-confined or unconfined aquifer system of regional extent occurring at the contact between the Paleozoic bedrock and overlying sediments. A special case of a contact aquifer occurs where bedrock and sediment meet in a sediment-filled bedrock valley.

12.2.1.1 Laurentian buried valley

Buried bedrock valleys have been known in southern Ontario since the 1880s when geologist J.W. Spencer (1881; 1890) suggested that an ancient Laurentian river network might have helped form the Great Lakes. The Laurentian valley, 20 km by 80 km with sediments ~100–200 m thick, is located beneath the urban region west of Toronto and has considerable groundwater resource potential (Figure 12.9). Owing to the expense of collecting data from such depths, we have a poor idea of the form, geometry and nature of these buried valleys (Russell et al., 2007). Many municipalities across southern Ontario need to increase water supplies from groundwater, yet they lack the knowledge and tools to assess potential aquifers in buried valleys (Russell et al., 2007). Existing maps based on water well records show only general trends for prospecting (Figure 12.9). To improve mapping and to assess sustainable groundwater use require an enhanced geological framework provided by high-quality subsurface data.

A modern prospecting tool, the seismic survey, gathers reflected subsurface sound waves to provide amazing new cross–sections of buried strata down to bedrock (Figure 12.10). The Nobleton profile reveals a 1.5 km wide portion of the Laurentian bedrock valley overlain by a layered sequence of strata. A borehole, drilled into the bedrock along the profile to a depth of 192 m, yielded a continuous sediment core, downhole physical properties, and samples for particle size, water content, and sediment structure, all of which helped develop models of valley formation. This high-quality data provides a completely new picture of the

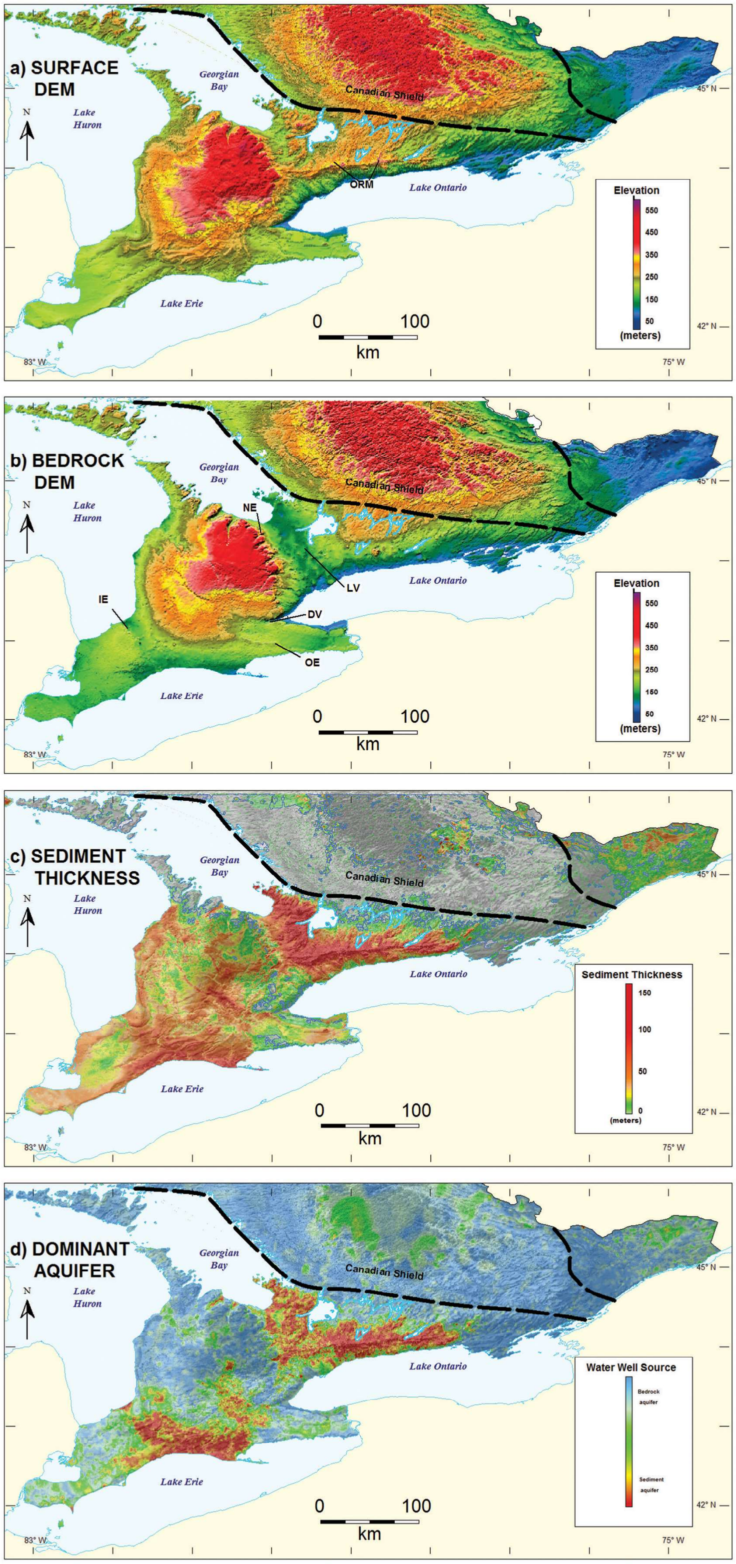

Figure 12.8 Slope and rocks determine how water moves through the landscape.
a) surface topography provides a gradient for surface runoff and groundwater flow to streams, ponds and lakes: the red areas represent high elevation and the blue areas low; b) shows the bedrock topography, with major escarpments: NE= Niagara, OE=Onondaga, IE=Ipperwash and valleys; LV=Laurentian, DV=Dundas; c) shows sediment thickness. Note that thick sediment occurs below major escarpments and in stratified moraines (e.g., Oak Ridges Moraine); d) shows dominant aquifers in sediment or bedrock based on the numbers of wells completed in each setting; these two regional aquifer settings are discussed in more detail later. In summary, groundwater tends to flow away from the topographic high near the Niagara Escarpment and to become stored in areas of thick sediment and along the contact between sediment and rock, and in areas where bedrock valleys occur (from Hinton et al., 2007). Note variation in colour bars.

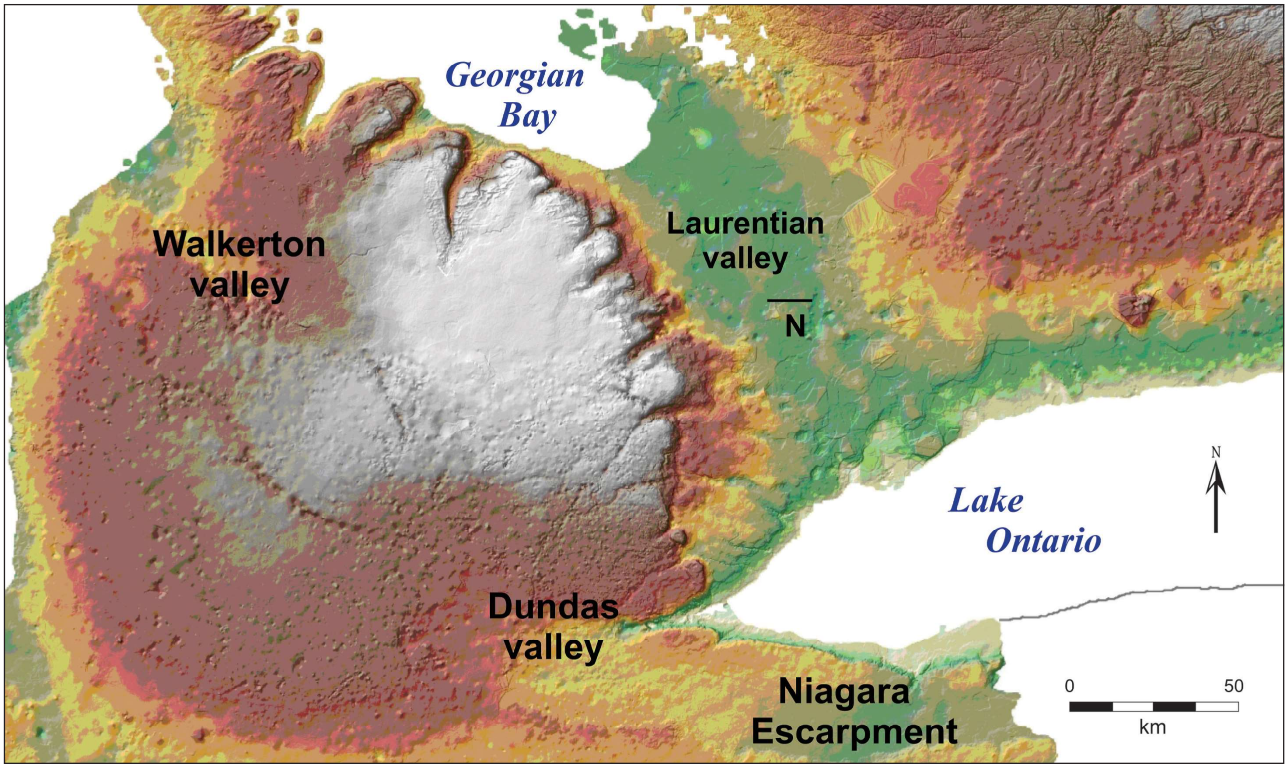

Figure 12.9 Where soft rocks meet hard rocks.
This bedrock topography map (from Gao et al., 2006) shows hard carbonate cap rocks of the Niagara Escarpment that resisted erosion, while the softer shale rock in the Laurentian (buried) valley to the east was heavily eroded to form a deep (~200 m) depression. The map also indicates the general location of other buried valleys, such as the Dundas valley and the Walkerton valley, as determined from water well records. Some bedrock valleys correspond to the subcrop location of easily eroded bedrock formations. For example, Walkerton Valley corresponds to the location of the evaporite rocks of the underlying Salina Group. N marks the location of the Nobleton subsurface seismic profile.

subsurface, context for water-level monitoring, and guidance for understanding groundwater flow patterns.

The movement of water in bedrock valley aquifers depends on many factors including the complex geology of the valley infill. Gravelly valley infill favours flow, but it may not be continuous along the valley floor. The lack of deep borehole data and no seismic profile leads to uncertainty with respect to potential connecting segments for bedrock valley aquifers. Water level monitors can record aquifer connection along bedrock valleys. Hydrographs for deep test wells at three locations along a valley tributary to Laurentian bedrock valley (Figure 12.9) show that many of the seasonal fluctuations observed in the shallow groundwater flow system are also evident in the deep bedrock valley system. This indicates that surface water is hydraulically connected to deep groundwater levels. Long-term groundwater pumping tests, temperature fluctuations and groundwater chemistry may indicate aquifer connection along these valley sites if there is a similar water level response to the groundwater pumping.

Buried bedrock valleys may contain very productive aquifers and their potential impact and value warrants the expense and time required to carry out exploring for them. Analysis and interpretation are needed to improve both the hydrogeological understanding of buried valleys, like the Laurentian valley, and the regional exploration for buried-valley aquifers (Davies, et al., 2008a,b).

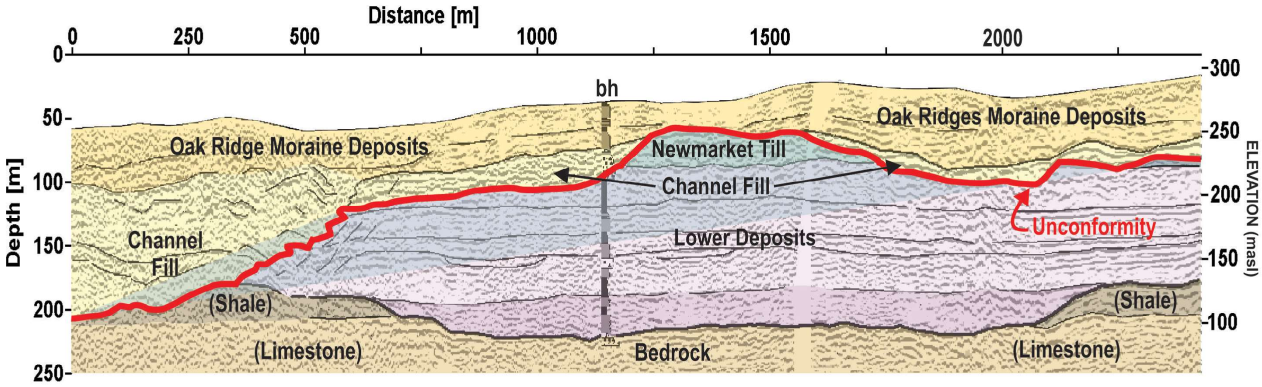

Figure 12.10 Sound waves map of a buried bedrock valley.
A section of the Nobleton west-east seismic profile depicts the Laurentian valley (bedrock channel) where it cuts through shale into limestone bedrock. A borehole core (bh, vertical line) records glacial sediments that fill Laurentian valley: aquifers (yellow) and aquitards (blue). This sequence is truncated by a younger, glacial channel erosion surface (red line), before glacial meltwater sediment filled the valley and built the Oak Ridges Moraine. This profile shows, for the first time, how groundwater strata are arranged below the Humber Valley watershed (west Toronto).

12.2.2 Hydrogeological settings

Four major hydrogeological settings describe groundwater systems in southern Ontario:

1. Sediment
2. Sediment-bedrock interface (i.e., contact zone)
3. Exposed or thin sediment-covered bedrock
4. Deep bedrock

Freshwater aquifers occur mainly in regional-scale, shallow or exposed carbonate bedrock, or in sediment complexes (mainly glacial sediments) with flow at local to intermediate scales. Exposed bedrock and thin sediment-covered bedrock occurs on Manitoulin Island, the Bruce Peninsula, the Niagara Escarpment, Lake Ontario shorelines, and along margins of the Canadian Shield (Figures 12.8; 12.11). Sediment aquifers are hydraulically linked to bedrock aquifers and help to capture water and recharge it to depth, particularly in porous sands, less so in clayey sediment areas. Important sediment aquifers occur below large major stratified moraines, as in the Oak Ridges and Waterloo moraines (Figure 12.1), and in sediment fills of buried bedrock valleys as described above. Stratified moraines have a number of key attributes that make them prolific water-yielding formations. Sediment aquifers are hydraulically linked to bedrock aquifers and help to capture water and recharge it to depth, particularly in porous sands, less so in clayey sediment areas.

Bedrock strata in southern Ontario consist of ancient layered sedimentary rocks of Paleozoic age (Figures 12.5, 12.6). Fractured bedrock is a unique hydrogeological setting because of its combination of relatively high hydraulic conductivity, or ease of flow, and relatively low storage capacity. Hydraulic properties (aquifer/ aquitard designation) might not necessarily agree with geologic strata as fractures may be present in some layers and not in others. As a result, changes in water quantity and quality can both be quite rapid (for example across formations) in fractured rock aquifers, as was the case at Walkerton. By contrast, sediment aquifers display lower conductivity but have a much higher ability to store and filter groundwater.

Deep bedrock settings, recorded by petroleum well records, do not produce or transmit much water. Most shale, evaporite and carbonate rocks can be considered to act as water-poor aquitards (Figure 12.6). Carbonate rocks and limestones of the Trenton Group and Black River Group, in

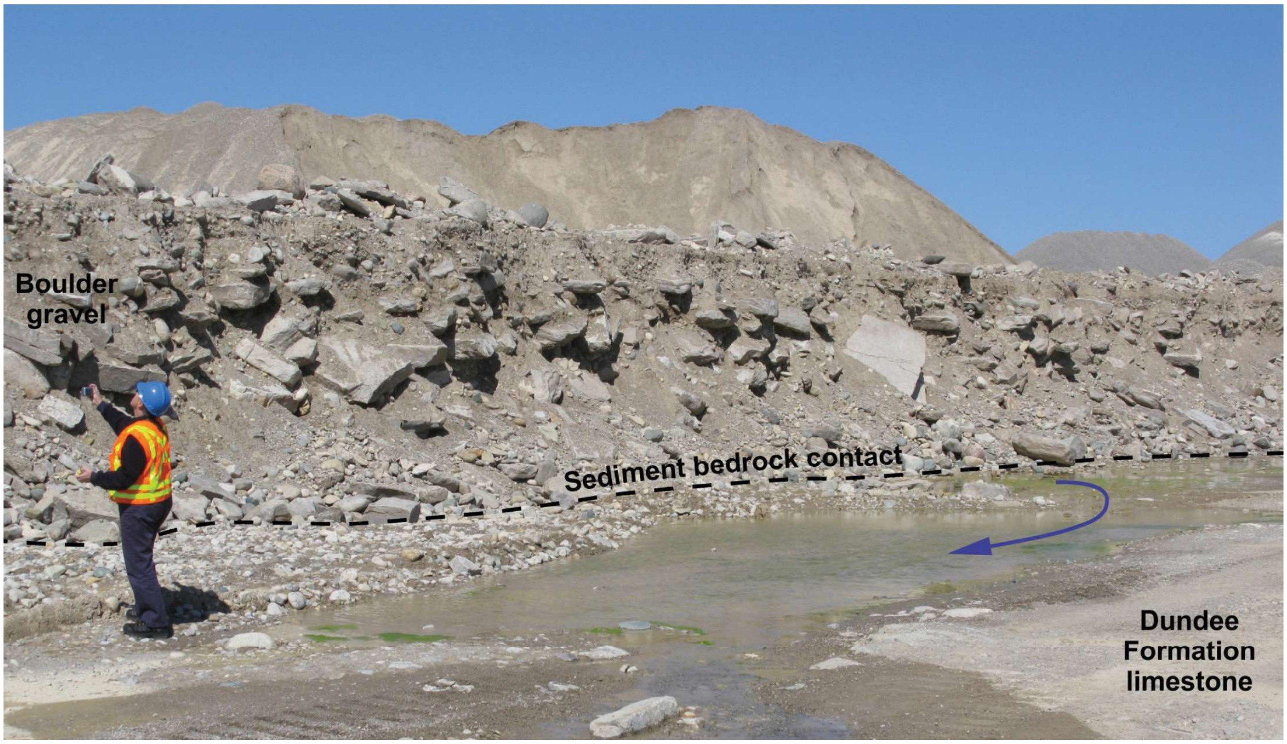

Figure 12.11 Groundwater flows from the interface or contact zone aquifer.
This Interface aquifer consists of boulder gravel directly overlying Dundee Formation limestone. Meteoric water has percolated downward through the highly permeable gravel to the upper surface of the nearly impermeable limestone, and is flowing toward the viewer on the slightly inclined bedrock surface. Note that sand and silt was removed from above the boulder gravel.

particular, form thick aquitards, with very low hydraulic conductivity or ease of flow. Thin aquifers of regional extent are confined within these bedrock formations; however, most of these aquifers contain non-potable formation water with very high salinities or high total dissolved solids; locally, they may contain reservoirs of crude oil or natural gas. In summary, potable water mainly occurs in thick glacial sediment, in exposed, karst-influenced carbonate bedrock, or in sediment-bedrock contact zone aquifers.

12.2.2.1 Sediment hydrogeological setting

Most of southern Ontario's major water-producing aquifers are found in sediment hydrogeological settings. Unconsolidated sediment (e.g., gravel to silt) provides enhanced infiltration of rainfall and snowmelt, and flow between sediment grains. Typical rates of flow, under a similar hydraulic gradient, range from ~1,000 to 0.0001 mm/day. Depending upon grain size and sorting, a sediment setting can have pore space that exceeds 40% to 50% of its total mass, resulting in a large groundwater storage capacity (Athy, 1930). Pore space flow also allows percolating water to take up the chemical character of the sediment as it flows toward the sediment-bedrock interface, or toward surface water bodies.

Variable sediment properties, thickness, type, and composition affect hydrological processes and the location of aquifers across southern Ontario (Figure 12.8). Thick sediment (50–200 m), for example, occurs in former meltwater channels and in valleys below escarpments (e.g., Niagara, Onondaga), and along the trend of buried valleys such as Laurentian valley. Thick glacial sediment, such as in moraines, has variable sediment type, geometry and internal structure; this usually results in complex aquifer systems with multiple layers (Sharpe et al., 2002). The higher groundwater infiltration, storage and flux associated with aquifers in sediment (Box 12-2) tends to yield good-quality water with low mineral content and few dissolved solids. Sediment aquifers, although smaller in size (tens of square kilometres) compared to bedrock aquifers (hundreds of square kilometres), are the source of most of southern Ontario's potable groundwater, and they are readily recharged from surface and atmospheric water that may mix with older glacial-age water (Husain et al., 2004) and/or deeper basin water.

12.2.2.2 Sediment setting case studies

The variable movement of water in unconsolidated sediments will be assessed by examining two representative sediment type case studies: i) the Norfolk sand plain (Box 12-3) and ii) the Essex clay plain (which also doubles as an interface aquifer; Box 12-4). Two other regional sediment types, till and gravel areas will be discussed for comparison. Sand, clay, till and gravel sediment areas combined, account for ~90% of the southern Ontario hydrogeological region (Figure 12.1); hence, these four sediment types summarize the shallow hydrological systems of most of the region.

Sand and gravel areas allow water to readily infiltrate, replenish and store groundwater in the accessible pore space between sediment grains. Less infiltration occurs in till, and very little occurs in clay, except by way of fractures, as is the case in most bedrock terrain. When saturated, both till and clay can store significant amounts of water, but these sediments do not transmit as readily as sand and gravel, and they discharge water more slowly. Differences in water level hydrographs between sediments and between sediment and bedrock are apparent. Each of the sediment case studies presented here is set in a low-relief location where topography provides modest yet differing gradients to water flow; the direction of flow is an important property as well but we will not discuss it until our Oak Ridges Moraine case study.

12.2.2.3 Sediment-bedrock interface hydrogeological setting

An important hybrid hydrogeological setting is found where sediment and bedrock meet. Water collecting at this interface forms a regional freshwater aquifer that underlies most parts of southern Ontario where sediment is thick (Figure 12.8).

Water and petroleum well records indicate that the top few metres of bedrock are often porous and permeable, regardless of rock type; this is caused by a combination of weathering and jointing, and in some places with sand and gravel at the interface. To some extent[3], all Paleozoic bedrock in southern Ontario exhibits regularly spaced vertical joints. These joints usually extend a few metres below the bedrock surface. The few metres of porous bedrock, together with the lowermost few metres of overlying sediment, form a "contact" or "interface" aquifer (Weaver et al., 1995; Husain et al., 1998, 2004; Carter, 2012). Below this porous bedrock, the unweathered and unfractured bedrock is several orders of magnitude less permeable than its overlying sediment, forming a barrier to

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[3] These joints are probably related to passive tectonic activity (Hancock and Engelder, 1989; Eyles et al., 1997) and formed in response to erosional unloading of younger sedimentary rocks or, more recently, to the melting and retreat of the one- to two-kilometre-thick continental ice sheets that covered southern Ontario at the end of the last ice age. Joints within the uppermost few metres of bedrock were also exposed to erosion and weathering during glaciation. Strata which contain evaporite minerals, in particular the Lucas Formation (Middle Devonian) and the Salina Group (Upper Silurian) may also have enhanced permeability at the sediment-bedrock contact due to dissolution of soluble evaporite minerals (e.g., salt, gypsum), forming a karst rubble.

downward percolation of fresh water. This contact aquifer (Figure 12.11) is part of a widespread sediment-rock system, and is the most regionally extensive freshwater aquifer in the southern Ontario hydrogeological region. Contact zone aquifers are also common in the Ottawa-St. Lawrence Lowlands (Cummings and Russell, 2007).

Flow direction in the contact aquifer is influenced by bedrock topography, and flow can follow buried bedrock valleys wherever the hydraulic gradient is sufficient. Regional flow directions inferred from bedrock topography indicate a flux from Niagara Escarpment highlands, south of Georgian Bay, toward topographic lows in lakes Erie, Huron and Ontario.

Reports of "bedrock" aquifer yield in water well records can be misleading as much of the potable water comes from sediment overlying the bedrock, rather than from the rock formation itself. About 58% of the so-called "bedrock" water wells in Essex region, for example, terminate within three metres of the bedrock surface (Strynatka et al., 2007), and draw water from the interface zone in a sand bed (Figure 12.13). The same is true for most areas of southern Ontario. The Essex clay plain (Box 12-4) is a good example of a contact zone aquifer as little aquifer potential exists deeper in the limestone bedrock or in the thick overlying clay sequence. This setting also illustrates the different hydrology of a clay plain as compared to a sand plain.

Water from the contact aquifer has a hybrid composition, reflecting the dual effects of travel through and residence time within both sediment and bedrock. Contact zone waters have lower mineral content, are less saline and hence more potable than water from confined deep bedrock aquifers. Conversely, contact zone waters are usually more mineralized than water from wells completed entirely within sediment, and they may have distinctive chemical characteristics, presumably reflecting the mineralogy of bedrock water with a longer residence time being drawn in.

Methane is also commonly found in contact aquifers, wherever the local bedrock is black organic-rich shale, notably in the Kettle Point Formation. This so-called "shale gas" is probably biogenic in origin, the result of the interaction of anaerobic microbes in the groundwater with organic material in the shale (Hamblin et al., 2008).

In areas dominated by carbonate bedrock, the joints at the bedrock surface may be solution-widened and extend to depths much greater than a few metres. In these areas the contact aquifer is connected to and transitional with the karst aquifer setting described below.

12.2.2.4 Exposed, thin sediment-covered bedrock hydrogeological setting

This setting is widespread, occurring where Paleozoic sedimentary rocks are exposed at the surface, or thinly covered by sediment (Figure 12.1), although paleo-karst features in areas of thick sediment cover are also possible. Rocks such as carbonate, sandstone and shale allow precipitation and snowmelt to readily run off to streams, or, to infiltrate fractures and joints. Carbonates, in particular, are very susceptible to erosion by acidic rainfall and groundwater. Infiltration into this setting contributes to regional groundwater recharge and storage, as ease of surface flow into rock openings allows penetration of fresh water to much greater depths than is usually observed (Hurley et al., 2008). This raises the importance of groundwater protection by constraining certain land uses in this setting. Recent and ongoing studies by the Ontario Geological Survey (Brunton et al., 2008;

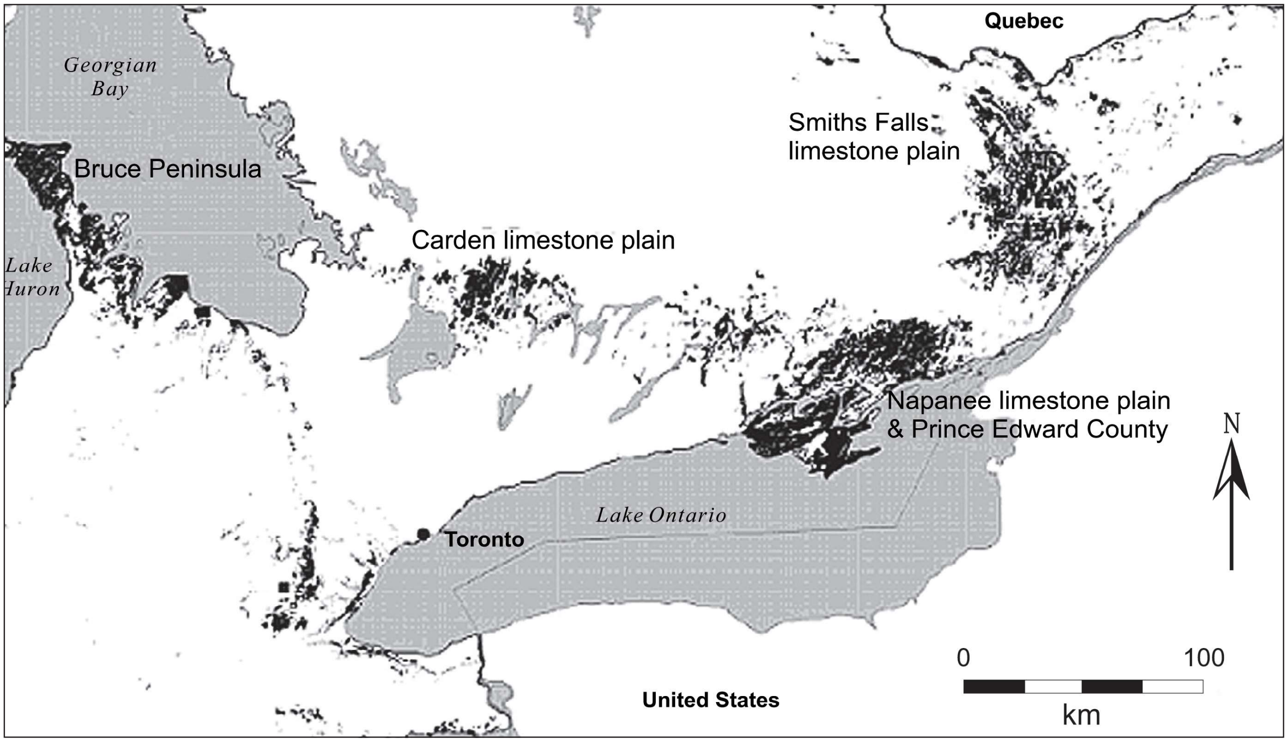


Figure 12.12 Cave-like karst openings allow more water to flow faster.
Carbonate rocks (limestone, dolostone) and evaporite rocks (anhydrite, gypsum, salt) are susceptible to dissolution by acidic surface water and groundwater resulting in solution-widened fractures and joints through which surface waters readily flow down to aquifers. These are called karst terrains and are widespread in southern Ontario (from Brunton et al., 2008).

Brunton, 2009; Brunton and Brintnell, 2011) have documented the importance of karst in controlling groundwater flow in exposed bedrock and the thin drift areas of southern Ontario.

Karst-influenced flow is of particular importance in the exposed bedrock setting (Figure 12.12) (e.g., Worthington, 2002). Karst is formed as a result of weathering and the chemical erosion of exposed or thinly covered carbonate bedrock by acidic surface and groundwater over thousands of years or more. This process enhances permeability, especially by solution-widening of joints or fractures in the upper tens of metres of exposed or thinly buried bedrock. The result is pipe-like groundwater flow both vertically and laterally. The greater connectivity between surface waters and groundwater aquifers makes these aquifers more susceptible to biological and chemical contamination from surface sources (e.g., Perrin et al., 2011). Water interval records from petroleum wells have reported fresh water at depths of up to 250 metres in karst-influenced bedrock.

Karst terrains in southern Ontario (Figure 12.12) display distinctive features including closed, surface depressions, well-developed underground drainage systems, and few surface streams. Other key features like sinkholes, sinking streams, caves and large springs may result from solution interaction with circulating groundwater and related streamflow. Larger, pipe-like, karst dissolution influences the amount, timing and distribution of groundwater recharge, as well as the depths and lengths of active groundwater flow systems. The Napanee limestone plain (Box 12-5) illustrates such water flow in the exposed, thin sediment-covered bedrock setting.

The Napanee karst-rock aquifer setting usually contains potable water, like that found in the Trenton Group limestones (Figure 12.5). The original saline formation water has been replaced by infiltrating fresh water of atmospheric or glacial meltwater origin. Almost all limestone units east of the Niagara Escarpment display good joint-fractures in outcrops with variable degrees of dissolution (Brunton et al., 2007). Larger groundwater flow that occurs in cave openings is common in Gull River Formation rocks and is controlled by proximity to the Paleozoic-Precambrian boundary (Figure 12.1), to rivers and swampy areas, and to margins of mini-escarpments between major rivers.

Other significant potable groundwater sources in karst carbonate bedrock, west of the Niagara Escarpment, are the Guelph-Lockport aquifer extending from Hamilton to the Bruce Peninsula, the Lucas Formation aquifer west of London (Figure 12.5), and the Detroit River Group (MacRitchie et al., 1994). The Lucas and Guelph-Lockport karstic aquifers are recharged at their outcrop edges with down-dip flow within the strata west of the Niagara Escarpment (Figures 12.5, 12.12). Down-dip penetration of fresh water is limited by the dense saline formation waters within the deep subsurface (Figure 12.13).

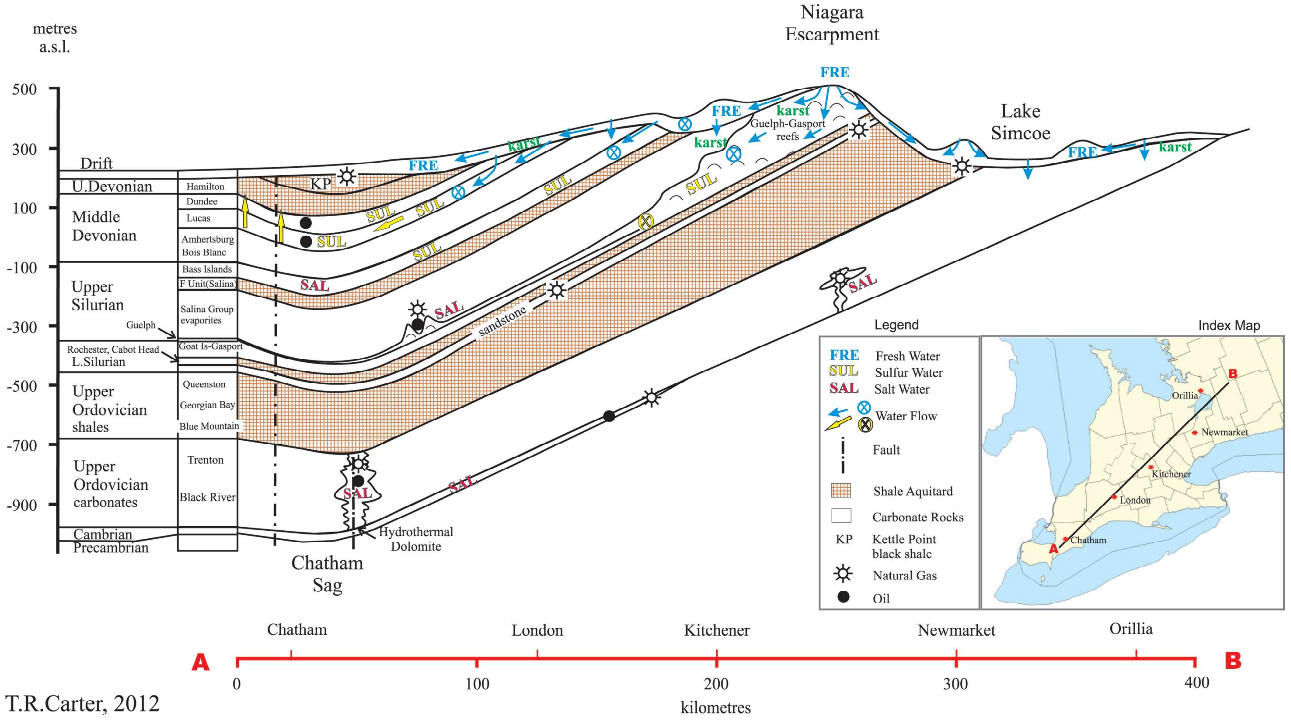
12.2.2.5 Deep bedrock hydrogeological setting

A system of thick regional aquitards and thin confined aquifers defines the deep Paleozoic bedrock setting of southern Ontario (Figure 12.13). Shale forms thick regional aquitards within the sequence; the thickest and most extensive of these are the Upper Ordovician Queenston, Georgian Bay and Blue Mountain formations (Figure 12.5) with combined thickness >300 m. The Salina Group evaporites with halite also form regional aquitards with combined thickness >230 metres. Most carbonate rocks may form aquitards as well, particularly in the thick limestones of the Trenton and Black River groups. Several regional aquifers, containing non-potable formation water of moderate to very high salinity, are confined between these aquitards. Potable water only occurs within these bedrock aquifers where porous bedrock formations outcrop at the surface or immediately beneath sediment in the contact aquifer zone (Figure 12.11).

Regional confined aquifers of saline water are found within the Middle Devonian Lucas and Dundee formations, the Upper Silurian Bass Islands Formation, in the Upper Silurian Guelph Formation, within fault-related hydrothermal dolomite zones in the Upper Ordovician limestones of the Trenton and in the Black River groups and in Cambrian sandstones (Figure 12.13). The deeper strata contain extremely high concentrations of total dissolved solids (140–390 g/L) dominated by sodium and calcium chlorides (Dollar et al., 1986; 1991). The Devonian and shallow Silurian strata contain brackish to saline waters (3–50 g/L TDS) of similar composition.

Sulphur water (dissolved H_2S) occurs regionally at intermediate depths in the Devonian and Silurian aquifers, and is usually found from a few metres beneath top of bedrock to ~500 metres depth. Sulphur water is also locally common in sediments overlying bedrock.

Groundwater chemistry changes with depth below surface; from fresh water, to brackish - saline sulphur water to deep saline water. This geochemical zonation was recently recognized in southern Ontario, and has been clearly documented at the proposed deep geological repository for low to intermediate level nuclear wastes at the Bruce



T.R.Carter, 2012

Figure 12.13 How does groundwater flow in a sedimentary basin?
A scaled geological cross section across southern Ontario showing regional southwesterly dip of bedrock formations and occurrence of water, oil, and natural gas in these layered rocks (Carter, 2012). Bedrock consists of marine strata: carbonate, sandstone, shale, siltstone, and evaporitic rocks, up to 1,400 m thick. Fresh water (blue-FRE) is confined to a relatively thin veneer (<250 m) of glacial sediment and very shallow bedrock. Saline water containing dissolved H_2S (sulphur water—SUL), shown in yellow, occurs at intermediate depths to ~ 500 m, and the deepest rocks contain saltwater with no dissolved H_2S (orange—SAL). Interpreted flow is downgradient from topographic highs and down regional dip of confining geological formations. Fresh water forms a three-dimensional flow system in upper part of confined aquifers (circles with × symbols), while saline water will remain confined in lower part due to its higher density. There is likely little or no actual movement of water in the deep subsurface strata. This sketch is based on petroleum well records and drill core and cuttings maintained by the Ontario Ministry of Natural Resources at its Oil, Gas and Salt Resources Library in London.

Nuclear power station at Tiverton (www.nwmo.ca/dgrsubmission).

The Nuclear Waste Management Organization is conducting detailed hydrogeological studies of Paleozoic bedrock at their proposed Deep Geologic Repository, for low- to intermediate-level radioactive waste at the Bruce nuclear station near Tiverton (Jensen et al., 2009; Gartner Lee Limited, 2008). Deep drilling indicates that there has been no penetration of fresh surface water below depths of ~250 metres. Flow model simulations indicate that groundwater velocities below a depth of 200 metres are extremely low or stagnant. Dissolved constituents move mainly by molecular diffusion. This very low-flow regime, and evidence from geochemical tracers, indicate that water in these rocks likely represents evaporated seawater that has resided in the bedrock for about 300 million years (e.g., Hobbs et al., 2008; Sykes et al., 2009; 2011, www.nwmo.ca/dgrsubmission). This new understanding will be used in support of site design investigations with a proposed waste repository to be situated 680 metres deep in the Cobourg Formation limestone (upper Ordovician).

Deep bedrock aquifers do not produce potable water because fresh recharge from recent precipitation does not readily percolate beyond shallow (1–200 m) depths depending on location (Figure 12.6). The deeper saline aquifers, however, have other important uses. Saline formation water is a nuisance by-product of crude oil and natural gas production. This "oil-field fluid" is safely disposed of by injecting it, using disposal wells, into deep bedrock aquifers, often the same formations from which it was produced. Some brines have compositions (e.g., high-calcium content) that make them of commercial value, and these are retrieved using special brine production wells. Deep saline aquifers may be targeted for possible future injection and permanent storage of carbon dioxide captured from large industrial point sources (Carter et al., 2007; Bachu and Adams, 2003).

Crude oil and natural gas are present in the Devonian, Silurian, Ordovician and Cambrian aquifers (Figure 12.13); economic accumulations occur in isolated reservoirs. Natural gas occurs in a continuous distribution in the Lower Silurian sandstones, escaping to the surface along the face of the Niagara Escarpment. Cumulative production to the end of 2006 was 86 million barrels of crude oil and 1.3 trillion cubic feet of natural gas (Lazorek and Carter, 2008).

12.2.2.6 Summary of hydrogeological settings

Most potable water is derived from sediment, exposed bedrock, or from sediment-bedrock (interface) aquifer geological settings. Water in deep aquifers is too saline for potable uses. The distribution and type of surface sediment determines the flux of water to the other three hydrogeological settings. Because the generalized geology of southern Ontario (Figure 12.1) shows wide variation in sediment type for the five main geologic areas or terrains (sand, clay, till, gravel and bedrock), case studies of this control on surface and groundwater were examined. Additional hydrogeological case studies (Norfolk sand, Essex clay and Napanee limestone plains) show hydrograph patterns and fluxes that reveal distinct hydrologic conditions for Grey County till uplands, and Wellington gravel valleys, landscapes that cover large areas (40%) of southern Ontario.

The five selected geological areas of Figure 12.1 characterize about 90% of the southern Ontario hydrogeological landscape. These areas vary approximately as follows: clay= 20%; sand= 20%; carbonate rock= 15%; sand and gravel= 5%; till uplands= 35%. As a result, we can generalize the main characteristics and hydrological behaviour of these sediment/ rock types (terrains) represented in the hydrograph trends for each illustrated case study (e.g., Boxes 12-3, 12-4, 12-5). Hence, clay plain behaviour in Windsor is comparable to clay plain hydrological behaviour near Ottawa. If we know how clay plains move water and how they differ from sand plains, till plains, gravel valleys and limestone plains, then we improve our regional understanding of surface water and groundwater movement in similar terrain types across southern Ontario (Figure 12.1).

Clay plains, for example, promote surface runoff to streams, inhibit groundwater recharge and, as a result, their watersheds experience low baseflow as groundwater discharge during dry seasons. Aquifers in clay plains reside at the sediment-bedrock interface. In contrast, gravel areas show no overland flow and induce considerable groundwater recharge: consequently, streams in those watersheds show large year-round discharge of cool groundwater to streams. Sand plains and till uplands show conditions between these two end member landscapes.

Other factors, such as sediment thickness, and/or the sequence and variation of sediment type, play a role in determining groundwater flow deeper below the surface within sediment setting.

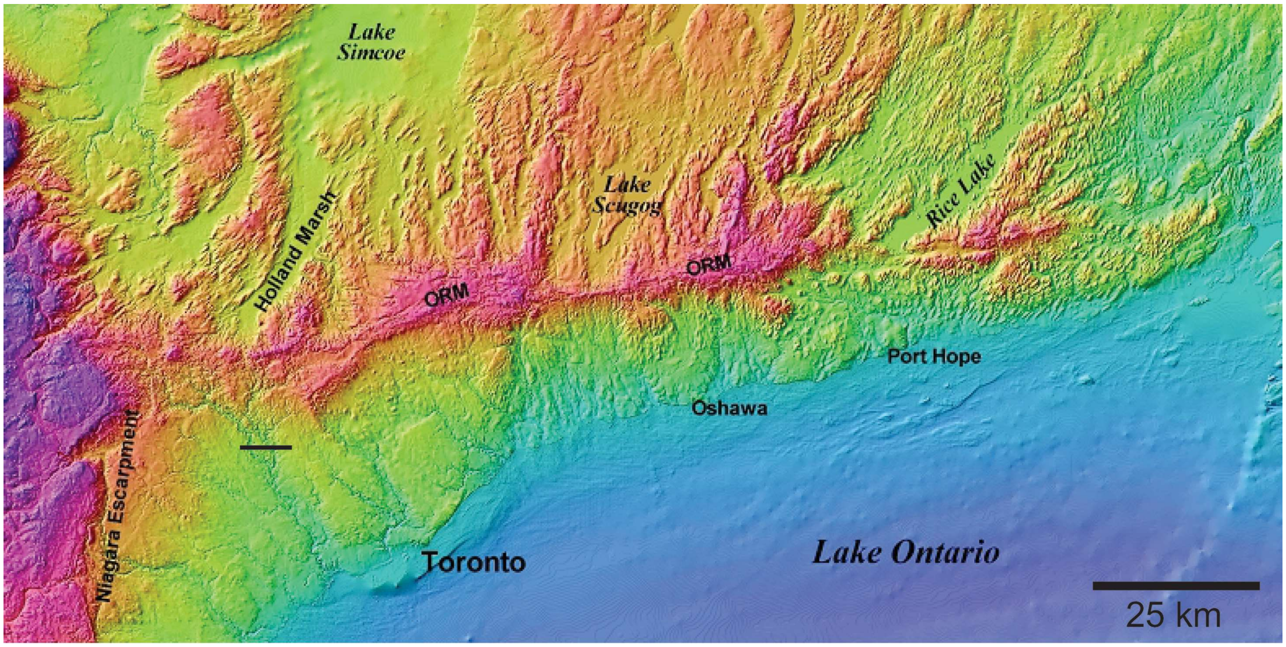


Figure 12.14 Oak Ridges Moraine surface topography is a window into the subsurface.
An elevation model shows blue in lower areas such as the shoreline of Lake Ontario (blue) to higher areas such as the ORM and Niagara Escarpment (purple). Surface channels such as the Holland Marsh extend beneath the ORM southward as shown on the seismic profile (see Figure 12.10). A 2.5 km seismic profile located near Nobleton (black bar) reveals subsurface geology south of the ORM, for example, the southern extension of the Holland Marsh channel and related channel aquifer sediments deposited on the channel floor. A 192 m deep borehole (east end of black bar) was cored from surface to the top of bedrock within a 1.5 km wide bedrock valley. Borehole details are shown on Figure 12.15.

12.2.3 Oak Ridges Moraine: Thick sediment case and the need for high-quality data

Our profile of the Oak Ridges Moraine, a thick sediment terrain, is based on high-quality subsurface information collected to address key groundwater issues associated with municipal water supply and land use planning (e.g., Gerber and Howard, 2002).

The Oak Ridges Moraine (ORM) is a prominent glacial landform located north of Lake Ontario within the Greater Toronto Area (Figure 12.14). It is a 5 to 20 km wide ridge of sandy hills extending from the Niagara Escarpment eastward beyond Rice Lake. These 50 to 100 m high hills rise more than 200 m above Lake Ontario. As a result, direct ground and surface water flows south to Lake Ontario and north to Lake Simcoe. The ORM occupies a significant and sensitive position in relation to the hydrology, hydrogeology and ecology of southern Ontario as it forms a major drainage divide and is the headwater for more than 40 streams, many with vibrant cold-water fisheries. As well, it is one of the most important aquifers in southern Ontario providing water supply to more than 200,000 people. Groundwater discharge from the ORM provides more than 50% of streamflow across the region.

Management of urban growth in the Greater Toronto Area requires an advanced understanding of groundwater flow systems within the ORM and across an area of 10,000 km^2. Key information includes a digital elevation model of the ground surface, geophysical probes, sediment cores and data from multi-level water monitoring devices in key strata. Such high-quality information leads to a sound 3D conceptual geological model (Figure 12.15a). Detailed geological mapping of the interior structure and complex sediment sequences in the

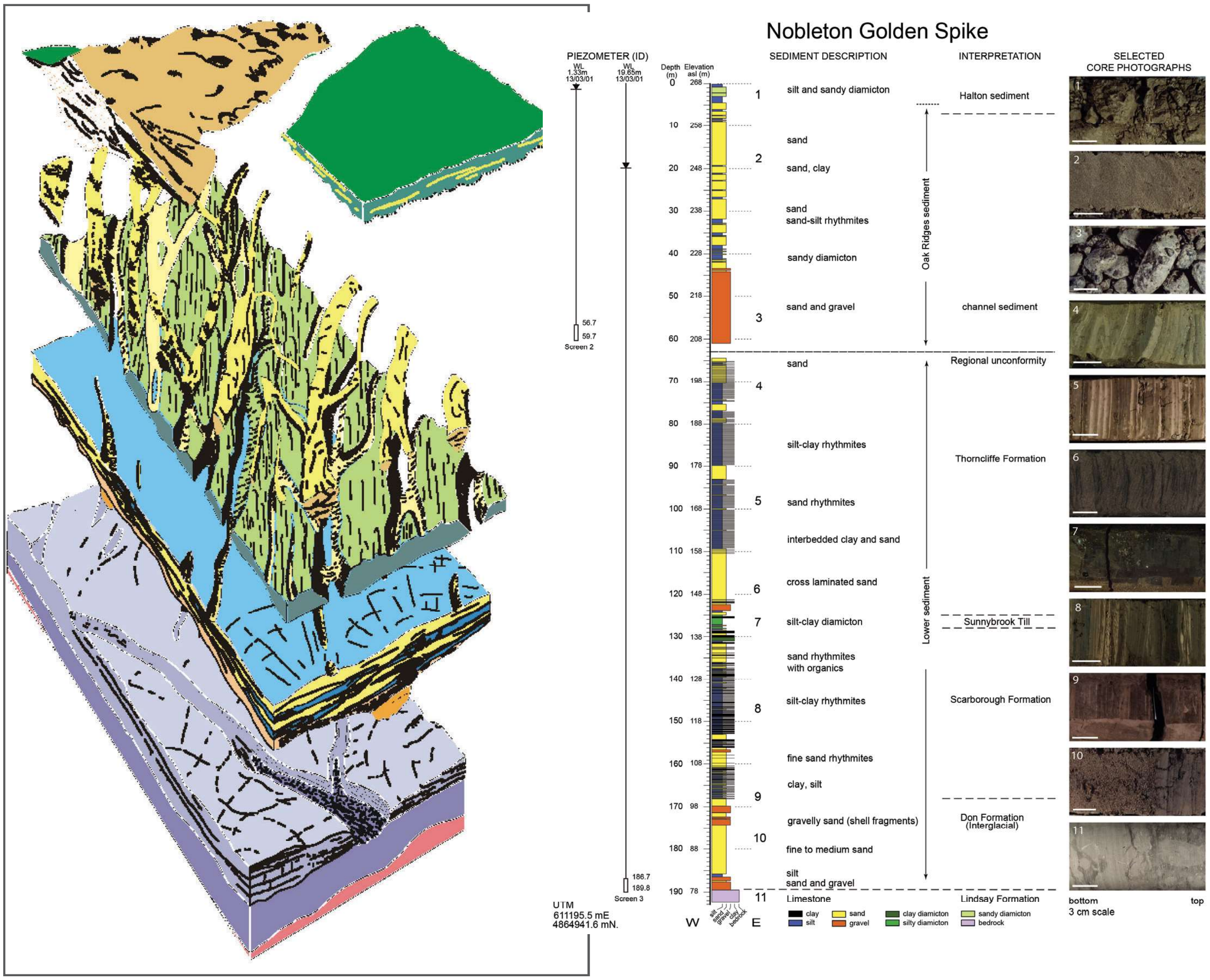


Figure 12.15 Oak Ridges Moraine 3D geological model and groundwater system.

The ORM 3D conceptual model consists of six main strata from oldest to youngest: i) bedrock, ii) lower sediments, iii) Newmarket Till, iv) channels Fill, v) ORM, and vi) Halton Till. These strata contain a number of stacked aquifers shown as yellow and oranges layers; blue-green layers transmit much less water. Layers in the model were observed on seismic profiles and confirmed by continuous sediment core drilled to bedrock. (b) shows a continuous sediment core with key photos of the main ORM strata (Knight et al., 2008). One can visualize the ORM 3D geological model by linking the elevation model (Figure 12.14 to detailed geological mapping (Sharpe et al., 1997) and then build a 3D hydrogeological framework across this 10,000 km^2 area (Logan et al., 2006).

ORM (Figure 12.15b) help identify the main geological elements controlling groundwater recharge, flow and discharge (Sharpe et al., 2007).

Regional groundwater flow occurs through a number of aquifers at different levels within the ORM model. Flow is driven by topographic gradients and is enhanced due to preferential flow in sand and gravel along connected channel networks. Channel sand also intersects sand sheets and deeper channels in the regionally extensive lower sediments. Lower sediments can be viewed at the Scarborough Bluffs on Lake Ontario and traced inland using seismic profiles and drill core results. These data dramatically improve confidence in the conceptual model and related numerical groundwater flow models (e.g., YPDT-CAMC and Earthfx Inc., 2006).

A critical feature of the ORM is its extensive

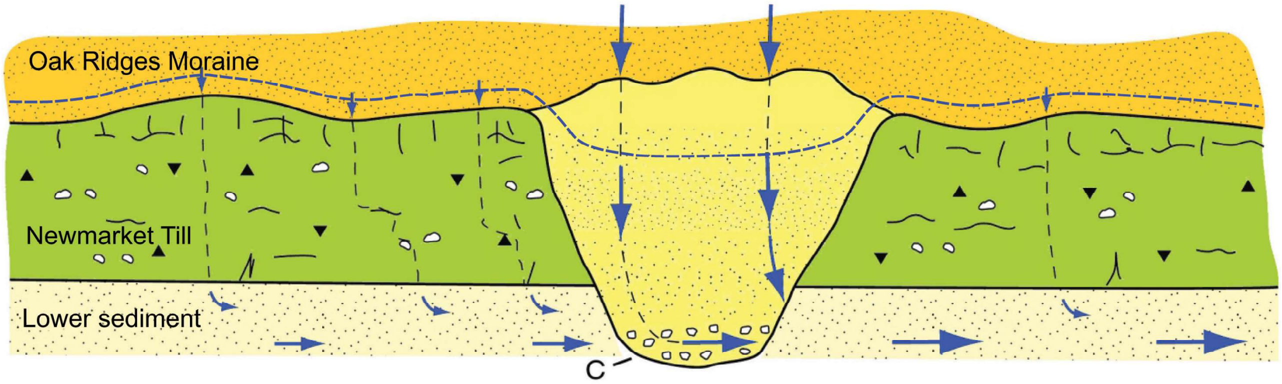


Figure 12.16 How does groundwater flow through channels or uplands under the Oak Ridges Moraine?
Water infiltrating the ORM may encounter Newmarket Till through which flow will be slow (small vertical arrows), or less likely, it may encounter channel sand (which breaches the Till) through which groundwater flow may be much faster (large vertical arrows) depending on permeability of the infill sediments and vertical hydraulic gradients. Flow along both the "slow" and "fast" routes is improved when there is drainage to lower water levels such as a river or lake (increasingly large arrows in the lower sediment aquifer unit). Note that the water table (dashed blue line) is lower over the channel breach.

network of north-south-trending valleys, such as the Holland Marsh, that underlie thick sandy hills (Figures. 12.15a). The size of valleys like the Holland Marsh, 1 to 5 km wide and more than 100 m deep, is about ten times larger than valleys eroded by modern rivers and about one hundred times larger than modern precipitation regimes could have created. These valleys were likely eroded when large glacial floods periodically released very large volumes of water stored under the glaciers. The valley network extends for 10 to 50 kilometres north of the ORM and south toward and beneath the ORM. North of the ORM, the valleys are visible utilizing digital elevation models. Many valleys are known to underlie the ORM, based on seismic research which shows these valleys to be 1 to 3 kilometres wide and greater than 100 m deep. In places, the valleys can be filled with a silt-sand-gravel sediment sequence, from surface to bedrock. Understanding the dimensions, depth and how these subsurface valleys or channels are filled is significant to understanding local, watershed and regional scales of groundwater flow.

These buried channel valleys may direct infiltrating water deeper into the subsurface. They may help to replenish deeper aquifers, depending on valley sediment fill and vertical hydraulic gradients (Figure 12.16), which can vary in direction and magnitude seasonally and with groundwater pumping. Deeper flow occurs where water flows readily through sandy channel sediments and the direction and magnitude of flow directs drainage downward. Over much of the ORM area, where shallow and deep aquifer systems are separated by the Newmarket Till, there are large water level differences between aquifers. The resistance to flow in the Newmarket Till limits downward flow and results in the higher water levels. Downward flow through the Newmarket Till to deeper aquifers is estimated to be less than 35 mm per year on a regional basis (Gerber and Howard, 1996; 2000; Gerber et al., 2009) in an area where climatic data indicate that 350 mm per year may be available for recharge. As a result, areas of channel erosion with higher-permeability infill sediments may be very important to regional groundwater flow and sustainable water supply. Where the Newmarket Till is breached by channel erosion and infilled with

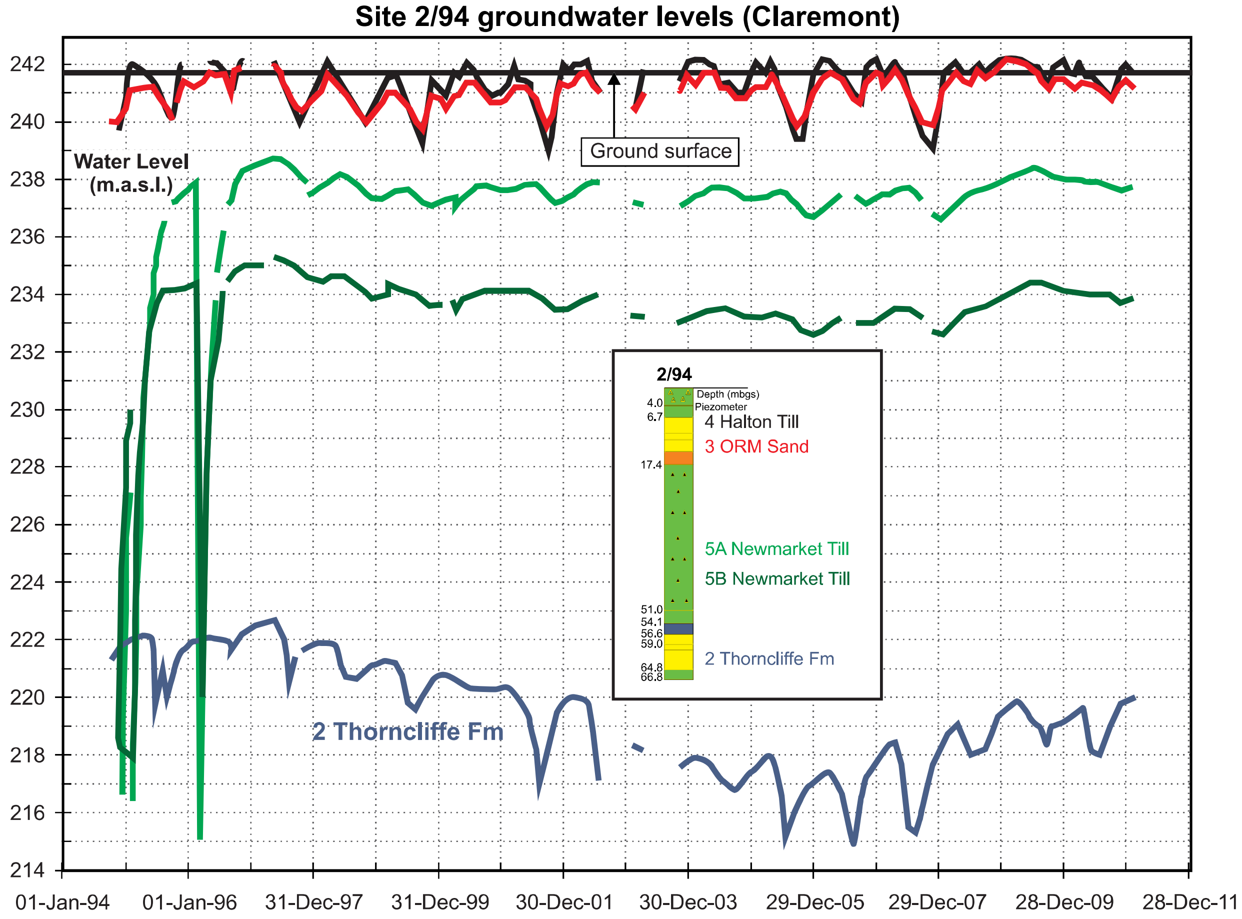


Figure 12.17 The pulse of the ORM plumbing system—different levels in different strata.
Water levels in the top two strata (Halton and ORM) at Site 2/94 (red and black lines), Claremont, are in direct hydraulic communication and indicate seasonal rhythms (2– 3 m), recharge and lateral groundwater flow from upgradient on the ORM. In contrast, water levels in lower strata (Newmarket Till, green lines, and Thorncliffe Fm, blue line) are 4 to 20 m lower than upper levels with a weaker annual rhythm, ~1 to 2m. These monitors indicate two components of the ORM groundwater flow system: one shallow with local recharge and discharge and the other deep with more widespread recharge and remote discharge further downgradient. Note that Thorncliffe levels show decline from ~1996 to ~2006 likely due to pumping (see general location on Figure 12.14).

sandy sediment, water level differences are less than in till-covered areas, due to less resistance to flow. This key finding makes it clear that in areas with sandy channels, it is particularly important to protect the quality and flux of water from land uses where this water is likely to recharge deep aquifers.

Groundwater levels are monitored at a number of locations across the ORM as part of the Provincial Groundwater Monitoring Network (PGMN). Key, longer-duration groundwater monitoring occurs at two sites situated south of the ORM. These are linked to the geological framework, which allows researchers to place monitors accurately, relate their water level trends to specific water-bearing units and better understand the flow of groundwater from recharge to discharge areas. One of the sites, monitor 2/94 (Figure 12.17), is situated where surface till overlies shallow ORM aquifer sand and a deeper aquifer.

This well-monitored site (Gerber and Howard, 2002) is situated on the south flank of ORM (Figure 12.14), where ORM aquifer sediment pinches out and is confined by overlying Halton Till (Figure 12.17). Water levels within the shallow ORM aquifer are near or above the ground elevation. Levels vary seasonally by up to 3 m and demonstrate good near-surface hydraulic connection. Annual fluctuations within a deeper aquifer are ~2 m, but they fluctuate in rhythm with near-surface hydrographs, and demonstrate some connection to and recharge from the shallow ORM aquifer. Lower fluctuations may be affected by groundwater discharge to nearby streams such as Duffins Creek, and by pumping, indicated by the ~10 year decline in trend (1996–2006) and seasonal level changes of ~4 to 5 m.

Detailed water budgets can be estimated for ORM watersheds (Gerber and Howard, 2002). These budgets sum all water flux into and out of the watershed, including creeks that drain southward into Lake Ontario from headwater areas situated along the ORM south flank. According to these water budgets, approximately 60% of the groundwater discharge emanates from the south flank of the ORM; about 75% of the groundwater discharge occurs from relatively shallow aquifer systems, while the remaining groundwater discharge occurs from deep aquifers in the southern parts of the watersheds. Most of the groundwater discharge is to rivers and creeks within the watersheds, with little groundwater discharge directly into Lake Ontario (Grannemann et al., 2000).

This brief description of the ORM highlights several key issues in assessing groundwater resources in southern Ontario. Understanding groundwater flow in areas of thick sediment requires high-quality data. Such data, in turn, enables detailed three-dimensional interpretation of hydrostratigraphic units and their interaction within the flow system (e.g., Sharpe et al., 2002). The identification of new hydrogeological features, such as buried channels in sediment and bedrock, has proven of economic significance in finding and protecting sources of water supply, waste disposal sites and directing land-use planning. Further, the use of improved geological models to advance groundwater science, methods, and collaboration has assisted in a number of developments in the ORM. For example, it has helped in setting out formal plans (e.g., 2001 Oak Ridges Moraine Conservation Act) to protect groundwater source areas. These models have also provided guidance in the development of the Clean Water Act and source water protection strategies. A coalition of municipally funded conservation authorities and local municipalities is building upon the groundwater science, education and outreach for the ORM. They hope to influence public awareness and local planning decisions related to groundwater systems and management (www.ypdt-camc.ca).

12.3 GROUNDWATER RESOURCES

How important is groundwater in southern Ontario and what issues arise to manage it well? Groundwater is critical to the quality of life of residents of southern Ontario and to the health of its economy and ecosystems. It is very cost-effective and forms a significant water supply for agriculture, industry, municipal and rural users.

Does land use affect the amount and quality of groundwater? How accessible is groundwater, and can it service and sustain current and increased use in the future, particularly with potential changes in climate? Increasingly, watershed managers are recognizing that groundwater and surface water, as the water cycle shows, is one connected resource.

12.3.1 Groundwater quantity and availability

There is considerable variation in timing of hydrological processes across southern Ontario, and these variations have a major impact on how groundwater moves. Mean annual temperature here varies by more than 5 °C. This variation affects rates of both evaporation from water bodies and transpiration water losses from plants (and, hence, reduced infiltration to the water table). Deviation in mean annual precipitation of ~500 mm means that annual runoff can vary from 190 to 590 mm, for an average of ~380 mm/year. As a result, assuming that there is no pumping from groundwater storage, overall streamflow water quantity changes throughout the year. It is important to note that about 40% of precipitation forms streamflow (total streamflow includes flow derived from overland runoff and from groundwater discharge), while the remaining 60% is returned to the atmosphere by evapotranspiration. Overall, ~45% of the total streamflow comes from shallow groundwater storage and discharge. This discharge is greater in areas with more permeable sediment and bedrock, lower in areas with less permeable material, such as is found in clay basins (e.g., Essex) and areas covered by thick till. Overall, variation in groundwater levels is less compared to that in streamflow levels.

12.3.1.1 Water availability in a typical setting—a Nith River watershed

Snow accumulation and melting and evapotranspiration (the combination of evaporation of water from the landscape and transpiration of water from plants) alter the availability of water throughout the year. Figure 12.18 illustrates average monthly precipitation and streamflow for a watershed of the Nith River located 30 km northwest of Kitchener and Waterloo. Both precipitation as rain and snow, and precipitation adjusted for snow accumulation and melting are depicted. The streamflow data is summarized as the total volume of streamflow during each month and per unit area of the watershed so that it can be compared to precipitation. Precipitation distribution is reasonably uniform; however, precipitation is slightly below average during January to March and slightly above average during August, September, and November. Snow accumulation and melting reduce water availability during November to February, when there is net accumulation of snow, and increase availability during March and April, when there is net melting of snow. Evapotranspiration modifies the relation between precipitation, adjusted for snow accumulation and melting, and streamflow, which closely matches precipitation during January and February when temperatures and plant activity are low. Streamflow becomes an increasingly small fraction of precipitation from March to a minimum in July and August as temperatures and plant activity increase, and, then, an increasingly large fraction from September to December when temperatures and plant activity decrease. Average annual precipitation and streamflow are 990 and 390 mm, respectively, and therefore 600 mm of precipitation is returned to the atmosphere by evapotranspiration or otherwise removed from the watershed.

Figures 12.19 and 12.20 illustrate the variation of average annual precipitation and streamflow across southern Ontario using data for 336 watersheds. Precipitation is largest immediately to the east of Lake Huron and Georgian Bay and generally decreases to the east. Streamflow follows the same trends but also reflects factors such as temperature and land cover, which influence evapotranspiration (e.g., Fernandes et al., 2007). In some cases, groundwater flow across watershed boundaries and human processes such as water use and diversion may also influence streamflow. The averages of precipitation and streamflow for the watersheds

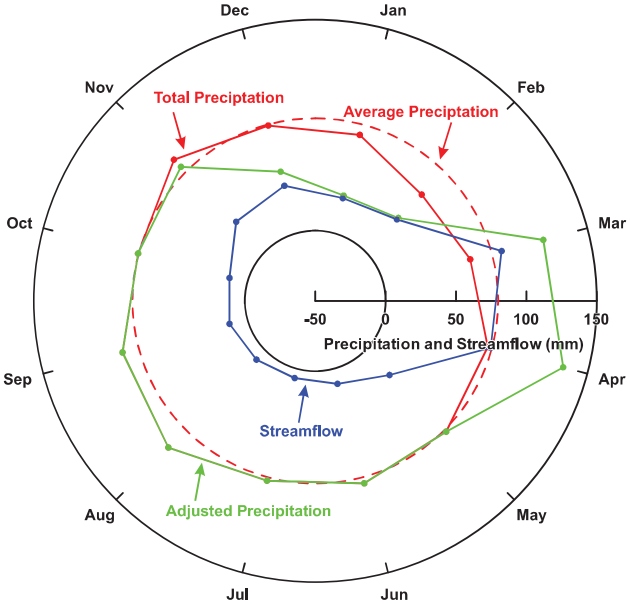


Figure 12.18 Is water available evenly throughout the year?
This graph illustrates the annual cycle of water availability for a watershed of the Nith River. Monthly average precipitation (red points and solid red line) is compared to the average for all months of the year (dashed red line). Precipitation, adjusted for snow accumulation and melting (green points and line), is compared to streamflow (blue points and line). Note that both precipitation and streamflow are high in the spring.

are 950 and 380 mm, respectively, and therefore evapotranspiration (approximated as precipitation minus streamflow) is roughly 570 mm on average.

Average annual groundwater recharge (the amount of water that enters groundwater flow systems from precipitation) varies across southern Ontario because of variations in precipitation, evapotranspiration, geology, and terrain (Figure 12.21). The highest levels occur in areas with coarse textured sediments such as sand and gravel in the shallow subsurface while the lowest levels occur in areas with fine-textured sediments such as clay.

A monitoring well in Wellington County near Acton sampling a gravel aquifer overlain by deposits of clay and silt illustrates a local water cycle, based on precipitation, streamflow, and groundwater level data (Figure 12.22). Precipitation data is adjusted for snow accumulation and melting. The streamflow data is from a watershed of the Eramosa River located approximately 15 km

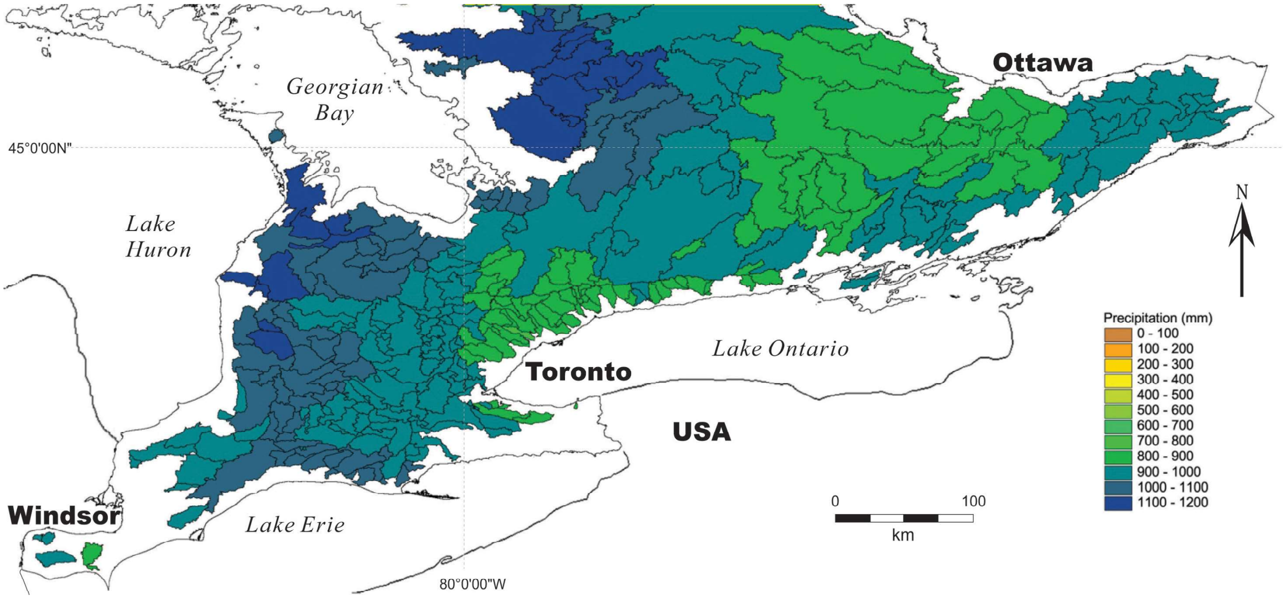


Figure 12.19 Precipitation drives the water cycle.
Average annual precipitation for 336 watersheds in southern Ontario varies from highs of 1,200 mm to lows of 800 mm. Note "lake-effect" in higher precipitation levels east of Lake Huron and Georgian Bay. Note: Precipitation, streamflow, and recharge are shown for a selection of 366 gauged watersheds. These watersheds do not provide complete coverage of southern Ontario and therefore precipitation (Figure 12.19), streamflow (Figure 12.20), and recharge (Figure 12.21) are not shown in some (white) areas.

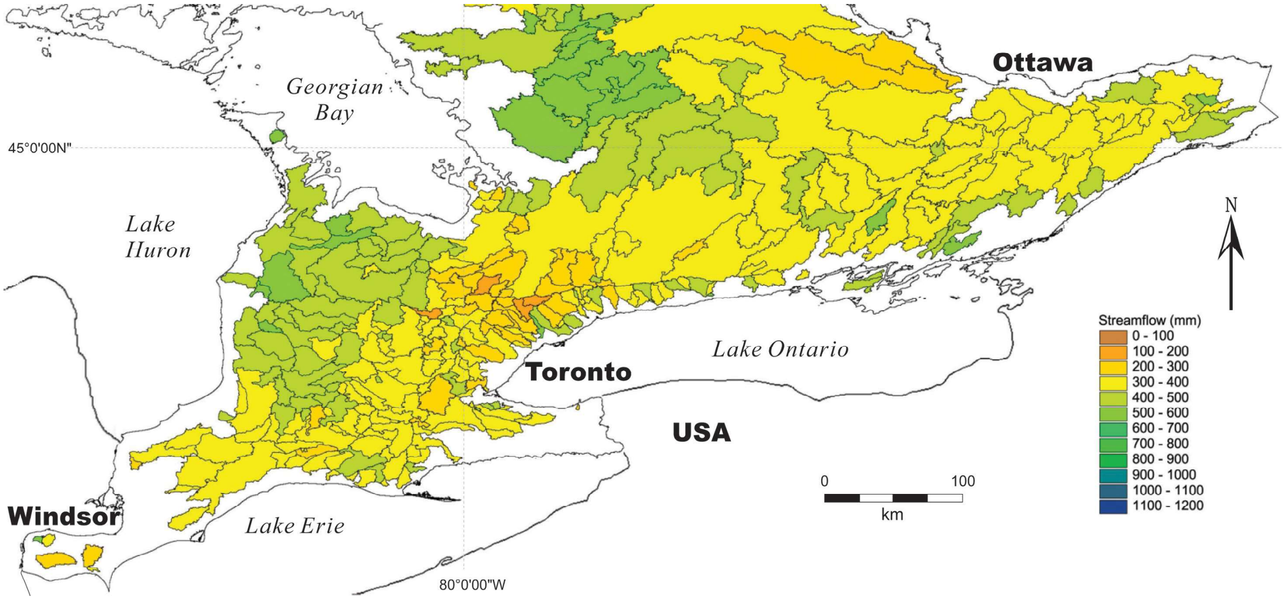


Figure 12.20 How much water flows in steams and where does it come from?
Average annual streamflow for 336 watersheds in southern Ontario varies from highs of 600 mm to lows of 200 mm.

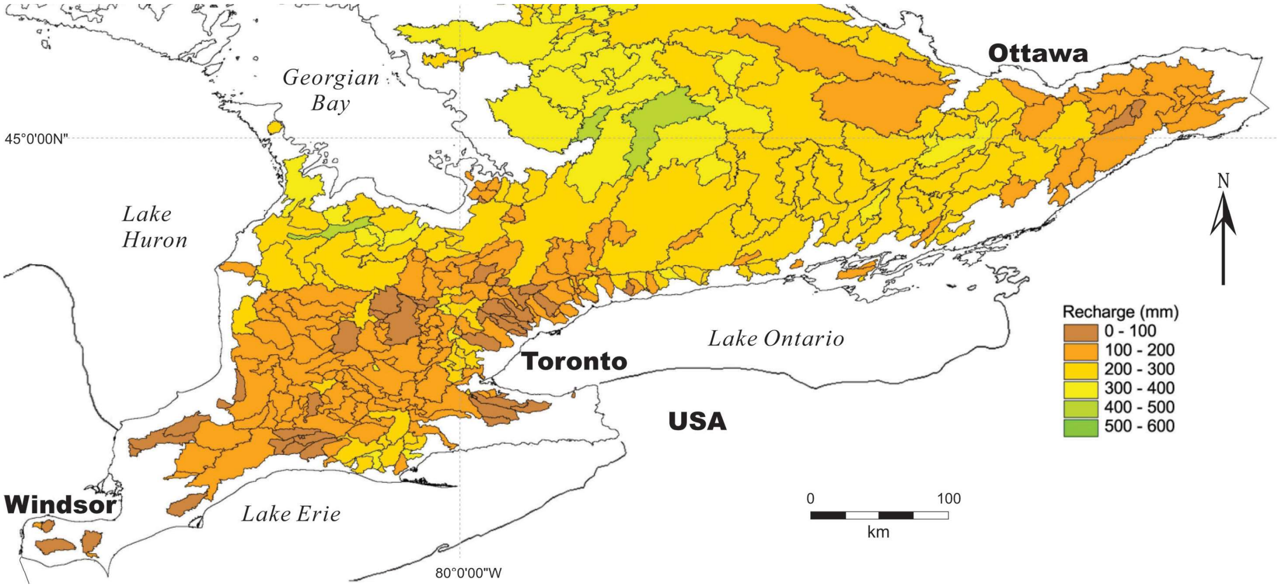


Figure 12.21 How much water goes into the ground?
Average annual groundwater recharge for 336 watersheds in southern Ontario varies from highs of 400 mm to lows of less than 100 mm.

northeast of Guelph. This data has been summarized as the total volume of streamflow during each day and per unit area of the watershed so that is can again be compared to precipitation.

The rapidly varying streamflow data consists of total streamflow, the actual flow in the river (m^3/d), while the slowly varying data is the baseflow component believed to be due to groundwater discharge to the river (Figure 12.22). The departure of streamflow from baseflow conditions reflects runoff across the ground surface and directly into the river following precipitation and snowmelting events.

Groundwater levels increase significantly following events in January to May and November

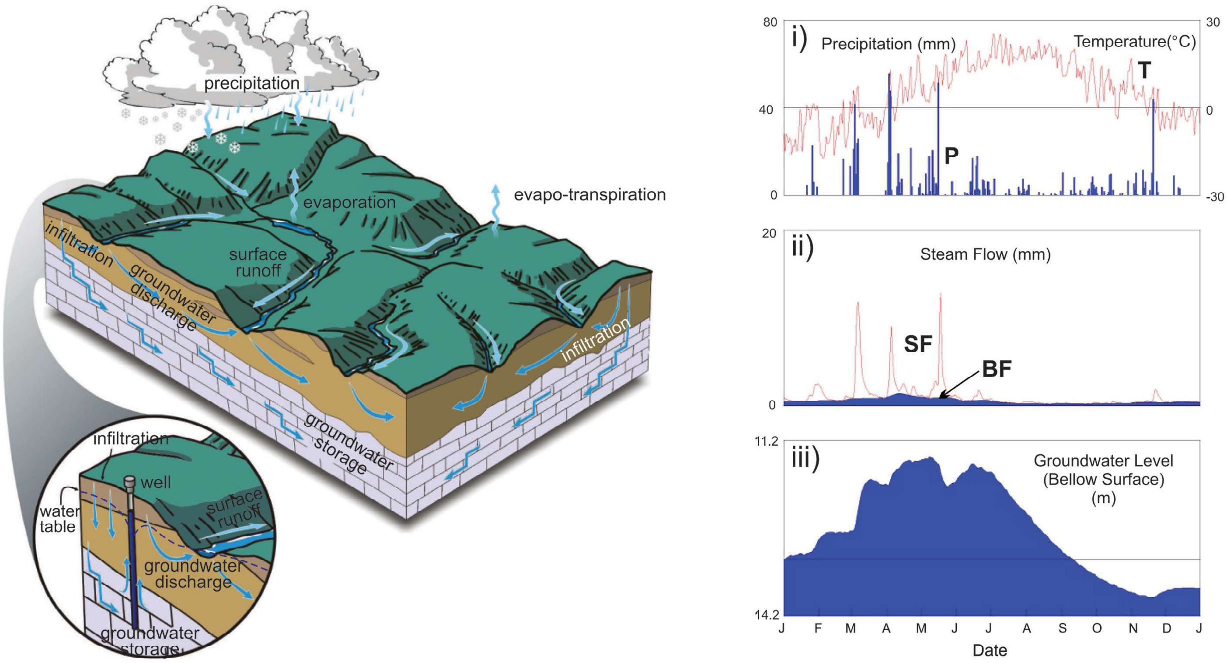


Figure 12.22 Streamflow and groundwater response to precipitation.
Streamflow (SF, ii) and groundwater level (iii) both respond to the larger precipitation events (i) that occurred in January to May and in November. Declining groundwater levels (iii, August to November) reflect groundwater discharge to surface water, which forms baseflow (BF) throughout the year (ii).

(Figure 12.22), which indicates that another portion of available water recharged the groundwater flow system. The decline in the levels following these events and during the summer and fall reflects the discharge of groundwater to the river, which is the source of baseflow. The ratio of baseflow to streamflow, in this case 59 percent, indicates the contribution of groundwater discharge to streamflow and the partitioning of precipitation into surface runoff and groundwater recharge.

12.3.1.2 Groundwater occurrence and regional aquifers

As we have seen in southern Ontario, groundwater occurs widely in sediment, bedrock and at their interface, particularly in ancient marine carbonate rocks. The exception is those locations with very thick sediment cover (e.g., near escarpments). We know this, in part, from the very abundance and even distribution of water wells in each of these settings (Figure 12.8) including the interface between sediment and bedrock. Indeed, a key feature of water use in southern Ontario is the fact that most rural homes have a well. Southern Ontario's main aquifers can be linked and defined by three key hydrogeological settings: i) exposed bedrock, ii) sediment-bedrock interface, and iii) thick sediment (Figure 12.8d). Groundwater within a deep bedrock hydrogeological setting is generally not used for water supply due to water quality issues and the cost of the deep drilling.

12.3.1.3 Groundwater recharge, flow, and discharge

Groundwater discharge is important from a human perspective. It maintains streamflow, and therefore surface and/or stream water quantity and quality, between precipitation and snowmelting events. It is also important from an ecological perspective because, for example, some aquatic species are highly dependent on water temperature, which is moderated by groundwater discharge during both the winter and summer.

There are several ways to estimate groundwater discharge. One is to calculate the baseflow component of streamflow using a mathematical process known as hydrograph separation. The resulting baseflow is the slowly varying component of streamflow (Figure 12.22) and is an estimate of groundwater discharge in many areas not affected by surface water body flow regulation devices (e.g. dams). Streamflow is monitored across southern Ontario and therefore it is possible to estimate groundwater discharge across the region in a reasonably seamless and consistent manner. To do this, it is convenient to first summarize streamflow and baseflow as baseflow index, which is defined as the long-term average of baseflow divided by the matching average of streamflow. Baseflow index is a number between zero and one where increasing values indicate increasing baseflow and groundwater discharge. If values of baseflow index are interpreted with geological mapping, then it is possible to derive an estimate of baseflow index for each geological unit across southern Ontario (Figure 12.23).

Figure 12.23 illustrates the results of this approach using 1:1,000,000 scale mapping of the surface geology (Figure 12.1). The estimated values of baseflow index vary from 0.15 for fine-textured sediments such as silt and clay (e.g., Essex), to 0.73 for coarse-textured sediments such as sand and gravel (e.g., Norfolk). Areas with the smallest values of baseflow index tend to be larger and more continuous than those areas with the largest values of baseflow index. On average, approximately 50 percent of streamflow is estimated to be due to groundwater discharge. Thus, roughly one-half of streamflow in southern Ontario has first flowed through the subsurface as groundwater, often for years to centuries and longer. Groundwater is a hidden resource that is difficult, costly, and time-consuming to investigate using methods such as those developed for the Oak Ridges Moraine. Methods such as separating baseflow from streamflow are simpler and economical, while providing useful information when used at appropriate scales.

As we have seen in the hydrographs provided in our case studies, climate, streamflow, and groundwater levels have a dynamic interaction in the hydrological cycle. Central hydrological processes, which are complex functions of geology, terrain, land and water use, include: partitioning precipitation between surface runoff and groundwater recharge, streamflow that combines surface runoff and groundwater discharge, and groundwater flow from recharge to discharge. Approximate estimates of groundwater discharge (baseflow) across the Great Lakes basin and across southern Ontario made use of geology (Neff et al., 2005; Piggott and Sharpe, 2007) to help assign streamflow components. Subsurface hydrology, groundwater, is expensive to study, yet it is inexpensive to study its relationship with discharge by measuring streamflow.

12.3.1.4 Climate stress

Groundwater, as an important component of the water cycle, responds to changing climate and is linked to water availability. The analysis of a temperature rise and precipitation fall can be tied directly to a decrease in groundwater discharge in a southern Ontario stream, and this means that simple climate and streamflow data may serve as an early warning for possible climate change impacts on sensitive watersheds. For example, precipitation change affects the volume of water

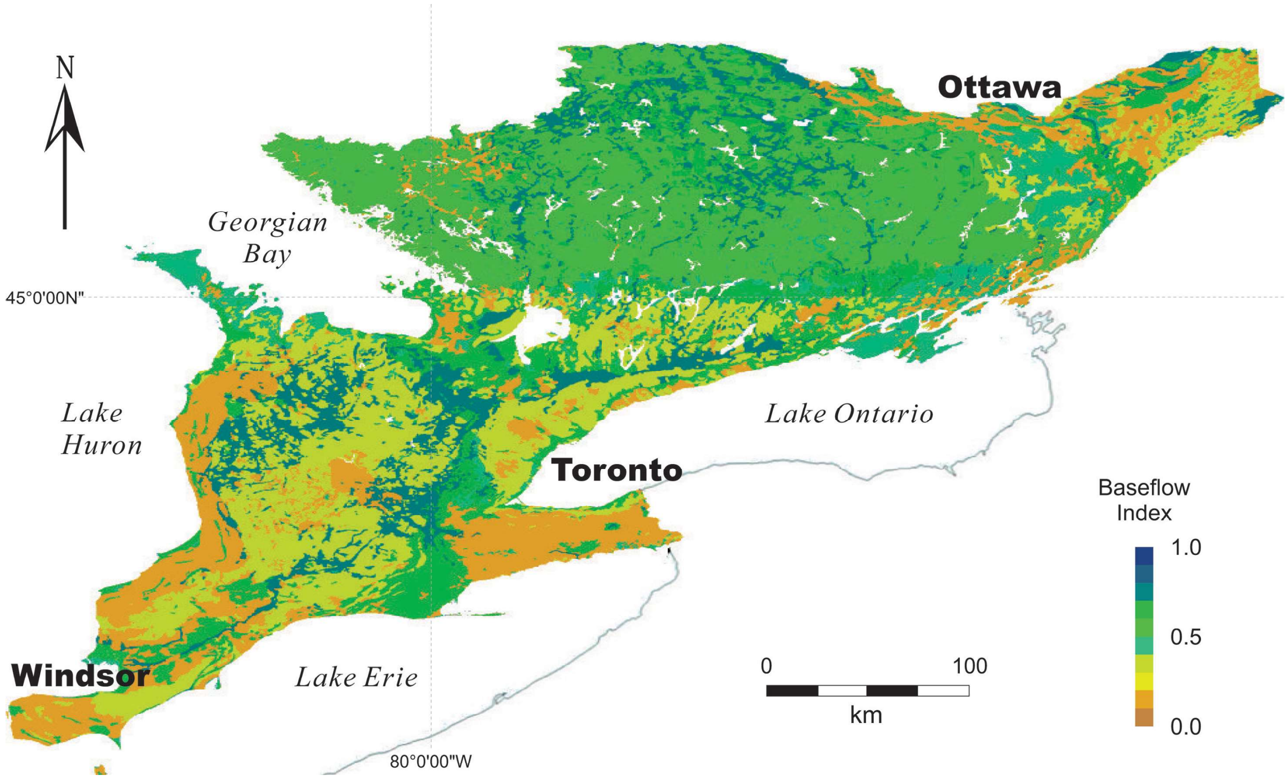


Figure 12.23 Can groundwater flow to streams be compared across the region?
High values of baseflow index (>0.5) relate to areas of permeable sediment and rock with sufficient groundwater storage such as glacial meltwater channels (blue tones), or morainic areas like the Oak Ridges Moraine north of Toronto. High values in Shield terrain relate to the number of lakes and wetlands that contribute stored water to streamflow.

available for groundwater recharge, flow and discharge. Temperature change will also affect snowmelt, accumulation, the timing of groundwater recharge, as well as recycling water to the atmosphere. The potential impacts of climate change on groundwater conditions in southern Ontario are varied and have recently been summarized by Environment Canada (2005; 2007) as changes in annual streamflow and water levels linked to geological and topographic setting.

Assessing impacts of climate change on groundwater is difficult because of limited data on subsurface hydrology, uncertain knowledge of the geology and flow systems, and projected variability of climate change trends at the provincial and watershed scales. This is further complicated by the fact that we also need to assess a range of factors such as stresses on groundwater resources caused by urban growth, increasing water use and intensified agriculture.

The diversity of groundwater discharge across southern Ontario implies that impacts of climate change will be similarly variable. Grindstone Creek (GC, Figure 12.1) for example, a waterway with a high baseflow index (high groundwater discharge), but a quick drop-off in baseflow during the year (from a lack of groundwater storage), illustrates the estimated impact of warmer and drier climate conditions. The low-flow conditions in Grindstone Creek resulted in loss of aquatic habitat and restricted migration of many species of fish to sustainable aquatic conditions. Some of the lost fish likely had survived under some stress for several years, but this watershed proved to be vulnerable to climatic stress. Even though Grindstone Creek had an above-average baseflow index, the lack of groundwater storage and the quick decline of both groundwater levels and discharge made the watershed susceptible to moderate drought conditions. This tangible example of climate impact is a signal to improve understanding of watershed flows, levels and timing in order to maintain and manage future groundwater/surface water resources. Ontario Ministry of Environment has prepared guidelines on how to conduct climate change assessments to assist in managing water resources within Ontario in a new publication "Sensitivity mapping and local watershed assessment for climate change detection and adaptation monitoring".

12.3.2 Groundwater quality

Both natural and human-induced changes in groundwater quality can affect the safe use of groundwater (Environment Canada and EPA, 2005). Groundwater can dissolve elements and compounds from the sediment and rock that it flows through. These natural constituents provide a baseline water quality for comparison with groundwater that may have picked up man-made chemicals.

Groundwater quality may also change due to natural chemical evolution along a flowpath, such as acidic rainfall which can dissolve calcium carbonate as it seeps into limestone rock, and more as it flows along the limestone fractures. Such trends may provide valuable insight into the dynamics of groundwater flow systems (e.g., tracers showing connection between aquifers or lack of connection in aquitards that reduce or deflect flow). Monitoring allows identification of changes in water quality. Natural groundwater may be of low quality for some uses (Rudolph et al., 1998; Goss et al., 1998); groundwater with a salt content, for example, would not be suitable as drinking water, but could be of acceptable quality for industrial uses. In addition, pollution from urban growth, industrial uses and agricultural activity may significantly degrade groundwater quality over portions of southern Ontario, diminishing safe use of groundwater and damaging aquatic environments.

12.3.2.1 Ontario drinking water objectives

Under Ontario's Safe Drinking Water Act, the Ontario Drinking Water Quality Standards are legally enforceable limits on constituents in drinking water. These standards are designed to protect public health by limiting the amount of specific constituents allowed in drinking water. Three different types of constituents, some of which may be contaminants, are covered briefly below: microbiological, chemical, and radiological.

Microbiological standards are for *E. coli*, fecal coliforms and total coliforms, and they should not be detectable in drinking water. Coliforms are those bacteria that come from human and animal waste. Operators at drinking water treatment plants are required to test regularly for coliform bacteria. Disinfection of drinking water by chlorination is designed to eliminate these harmful bacteria.

Chemical water quality standards for both inorganic and organic chemicals are expressed in milligrams per litre (mg/L), e.g., for lead as maximum concentrations allowed in drinking water. Some chemicals can cause health problems if, over a lifetime, they are consumed in drinking water at levels above limits. Mercury, for example, can cause kidney damage.

Radiological standards are for natural and artificial radionuclides, expressed as maximum allowable concentrations in becquerels per litre.

Radiological contaminants include natural radionuclides, such as radium 228 that result from the erosion of naturally occurring rocks and sediment, and radionuclides released anthropogenically, such as tritium released into water and vapour by nuclear power plants.

Ontario does not regulate cosmetic or aesthetic problems such as taste and odour in drinking water. Odour and taste, as well as colour and clarity, are considered to be aesthetic parameters, and not a risk to health.

Ontario's Drinking Water Quality Standards can be accessed at http://www.e-laws.gov.on.ca/html/regs/english/elaws_regs_030169_e.htm.

12.3.2.2 Groundwater quality monitoring and related studies

12.3.2.2.1 Provincial Groundwater Monitoring Network

In 2000, the Ontario Ministry of the Environment (MOE) began the Provincial Groundwater Monitoring Network (PGMN) in partnership with 10 municipalities and all 36 Conservation Authorities. As of 2012, the PGMN consisted of 474 groundwater monitoring wells located across the province. Of the 474 monitoring wells, 360 are routinely sampled for water quality. The PGMN helps to establish baseline groundwater conditions by monitoring groundwater levels and sampling groundwater to determine its chemistry. This information is used by the MOE, conservation authorities and municipalities responsible for managing groundwater.

Water quality results for sampled monitoring wells are compared to the Ontario Drinking Water Quality Standards (ODWQS). When a parameter is above the ODWQS, MOE sends a notice to local health unit and conservation authorities. A preliminary hydrogeological report helps determine why the parameter is above the ODWQS, and sets an agenda for pertinent parties to discuss the report findings and next steps.

Many measured parameters are believed to be naturally occurring and their sources are linked to the geological setting and natural groundwater conditions.

12.3.2.2.2 Water well records

Groundwater quality can be reviewed for several regions across southern Ontario using a few simple measures such as chemical composition, taste (saline), smell (sulphurous), appearance (iron-staining), as well as through readily available public water well records (Figure 12.24).

Because groundwater reflects and inherits the chemical composition of the sediment and rock units through which it percolates or through which it is drawn, its quality mirrors the geology of southern Ontario. Groundwater can be mapped for its aesthetic qualities such as taste, smell and turbidity. The Ontario Ministry of Environment developed such a map in 2007 (Ministry of the Environment, 2007) using water well records from across the region. The map shows areas of fresh and saline water, and areas affected by sulphur, gas, iron and high-mineral content (Figure 12.24), based on qualitative drillers assessments. Fresh well water appears to be most common in sediment aquifers and in the Canadian Shield. Sulphur gas is common and is most likely to be found in wells that penetrate bedrock in areas north of Lake Erie, south of the Shield margin, and in the Ottawa-St. Lawrence Valley.

12.3.2.2.3 Ambient chemical characterization of regional aquifers

Regional data across southern Ontario shows broad

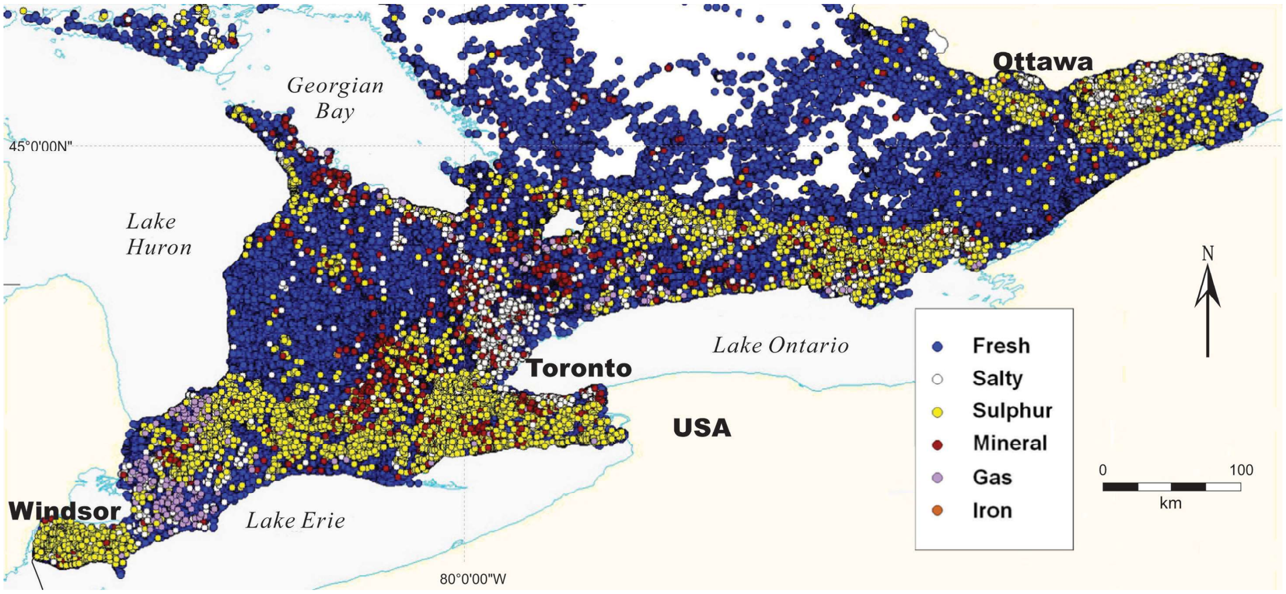


Figure 12.24 Aesthetic groundwater quality in wells across southern Ontario.
Fresh water was reported in ~85% of all wells: less-potable water was found in the other 15%. Each dot represents a group of wells with similar aesthetic water quality based on Ministry of Environment water well database.

areas with differing water chemistry measured in those groundwater wells located in sediment and in bedrock (e.g., Waterloo Hydrogeologic Inc, 2008). These patterns can be viewed within a regional framework of basin water chemistry (Figure 12.25). In general, calcium-bicarbonate-rich water is characteristic of surface infiltration or young groundwater where calcite, common to limestone terrain or limestone-rich sediment, is dissolved (Figure 12.25). Thus calcium-bicarbonate water appears in most areas with calcite-rich sediment or near-surface limestone bedrock. In some areas, water which is largely saline is associated with key formations such as the Salina Formation with its concentrations of halite (salt), or with local upwelling of deeper basin brines (which produce calcium-chloride-rich waters where freshwater mixing occurs). Sodium bicarbonate water occurs in several areas where sodium from saline waters has also mixed with infiltrating carbonate-rich water (e.g., from deep basins). There is also a reasonably close association between the water chemistry in sediment and in rock: this association varies only by geological locality, and may indicate good hydraulic connection between water percolating through sediment to mix with water resident in bedrock fractures. The association may also indicate that chemistry of well water in bedrock reflects more mixed water found in "contact zone" aquifers.

A regional cross section of the southern Ontario (Figure 12.13) sedimentary basin reveals water quality changes as water moves from surface to deeper into the subsurface through three defined zones:

1. **Shallow zone:** low-salinity surface water and young groundwater dissolves calcite to produce a calcium-bicarbonate water (Ca-HCO_3); Mg-HCO_3 can also occur in dolostone bedrock.
2. **Intermediate zone:** medium- to high-salinity water dissolves gypsum or anhydrite to yield a calcium sulphate water (Ca-SO_4), or dissolves halite (salt) to produce a Ca-Cl water.
3. **Deep zone:** basin brine water mixes with

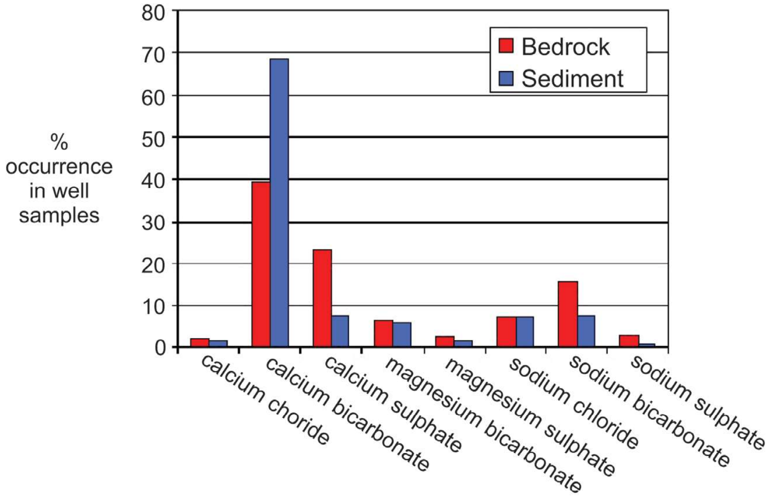


Figure 12.25 Comparing groundwater qualities in sediment and bedrock wells. Type of water sampled (%) in sediment aquifers (blue) and in bedrock aquifers (red) from ~300 wells. Note the relationship between similar water chemistry in sediment and bedrock wells, although this will vary by region. Calcium bicarbonate is an exception; infiltrating, young groundwater dissolves the calcite found in carbonate grains within sediment. Calcium sulphate water is more common in bedrock because gypsum found in rock dissolves to free sulphur.

seawater to produce a sodium- or calcium-rich(Na-Ca-Cl) brine with very high salinity.

In southeastern Ontario and elsewhere across southern Ontario, water that occurs a few metres into bedrock is strongly influenced by the chemistry of water that percolates from overlying sediment (Figure 12.25). This relationship is summarized in regional groundwater quantity and quality attributes, as discussed earlier in this chapter.

12.3.2.2.4 Ambient groundwater geochemistry data for southwestern Ontario, 2007–2010

In 2007, the Ontario Geological Survey initiated a multi-year groundwater sampling program to establish baseline groundwater geochemical conditions in southwestern Ontario. From 2007 to 2010, samples were collected from both domestic water wells and PGMN wells on a grid with 10 by 10 km nodes, with 1 sediment well and 1 bedrock well within each node. Temperature, dissolved oxygen, pH, conductivity and oxidation-reduction potential were measured during sampling using a multi-parameter instrument equipped with a flow-cell (Hamilton et al., 2010). The laboratory analyses of the groundwater samples included groundwater quality parameters, metals, and coliforms (Hamilton, 2011).

The result is a gridded, high-quality groundwater geochemical database which will be used to

1. Establish baseline groundwater geochemistry in major rock and sediment aquifers
2. Relate natural variations in water quality to these rock and sediment aquifers
3. Interpret and integrate other groundwater geochemical datasets
4. Model chemical species

Results show ranges of concentration for all parameters measured in sediment and bedrock. For example, areas of high dissolved oxygen are associated with known subsurface karst (Bruce Peninsula, Beaver Valley and Walkerton areas). Both karst and breathing wells are associated with high dissolved oxygen near Exeter (Hamilton and Freckelton, 2009). Maps and geochemical results can be downloaded from http://www.geologyontario.mndm.gov.on.ca/mndmaccess/mndm_dir.asp?type=pub&id=MRD283.

12.3.2.2.5 Ontario farm groundwater quality survey

Ammonium nitrate is a fertilizer widely used to provide nitrogen to soil in agricultural areas. Nitrogen provided to the soil promotes rapid growth, increased seed and fruit production, in addition to improving the quality of leaf and forage crops.

Nitrate is very soluble and can infiltrate through soil, and move readily into the groundwater system. The ability of nitrate to move through soil may depend on the soil's biological activity, soil type, and, on the nitrate concentration in infiltrating water. The Ontario Drinking Water Quality Standard (ODWQS) for nitrate is set at a maximum concentration of 10 mg/L (10 parts per million) as nitrogen (nitrogen is the main chemical element of nitrate). This concentration was established to prevent any incidence of methaemoglobinaemia, a blood disorder that occurs when red blood cells are unable to carry oxygen to other cells within the body, due to a change in haemoglobin. This condition is most commonly found in infants under 6 months of age.

An Agriculture Canada groundwater quality study sampled ~ 1,300 Ontario domestic farm wells in 1991 and 1992 for nitrate, and fecal coliforms, plus several pesticides (Rudolph et al.,1998).

Nitrate concentrations exceeded the standard of 10 mg/L in water samples from ~15% of the domestic farm wells. Results indicated:

- most nitrate contaminated wells were shallow, dug or bored wells
- nitrate concentrations tend to be higher in areas of high-permeability soils
- nitrate concentrations were consistent at the same location and did not show a seasonal variation
- nitrate concentrations decreased linearly with depth

An Oxford groundwater study in 2000 found nitrate concentrations above the 10 mg/L-N standard, in water samples from 10 of 83 (12%) sampled shallow sediment wells (Golder Associates Ltd., 2001). In Woodstock, nitrate concentrations in groundwater pumped from the Thornton well field have reached and exceeded the 10 mg/L-N standard. Nitrate contamination is likely due to agricultural activity west of the well field.

12.3.2.2.6 Road salt management

The use of road salt as a deicer on roads and parking lots is the preferred method to promote safe motor vehicle and pedestrian travel during winter months. As in all of eastern Canada, road salt is a source of groundwater contamination. Up to 50% of all complaints about well water quality at regional and district offices are related to road salt. Maximum desirable chloride concentrations are 250 mg/L (Ontario Drinking Water Standards), yet concentrations as high as 14,000 mg/L have been found in shallow groundwater near highways in Toronto (Howard and Maier, 2007).

Salt in groundwater may make it unsuitable for human consumption and some industrial applications. Groundwater contaminated with salt may also discharge to urban streams causing degradation of surface water quality. Sodium has been strongly linked to hypertension and associated indirectly with hyper-natraemia (Howard and Haynes, 1993; Howard and Beck, 1993).

Salt contamination of drinking water is generally limited to wells near paved roads (less than 30 m away), and is more likely in areas with many wells along the roadside, areas with heavy salt application (i.e., urbanized areas), and where topography favours contamination (e.g., steep, hilly terrain). Additional factors include shallow, dug or poorly constructed wells, and thin or permeable sediment (MacRitchie et al., 1994).

Over the past few decades, increasing chloride levels in groundwater have been observed in many urban municipal wells (Figure 12.26). Results tracked from two well fields in the Regional Municipality of Waterloo since the mid-1970s clearly reveal the impact of road salting, its link

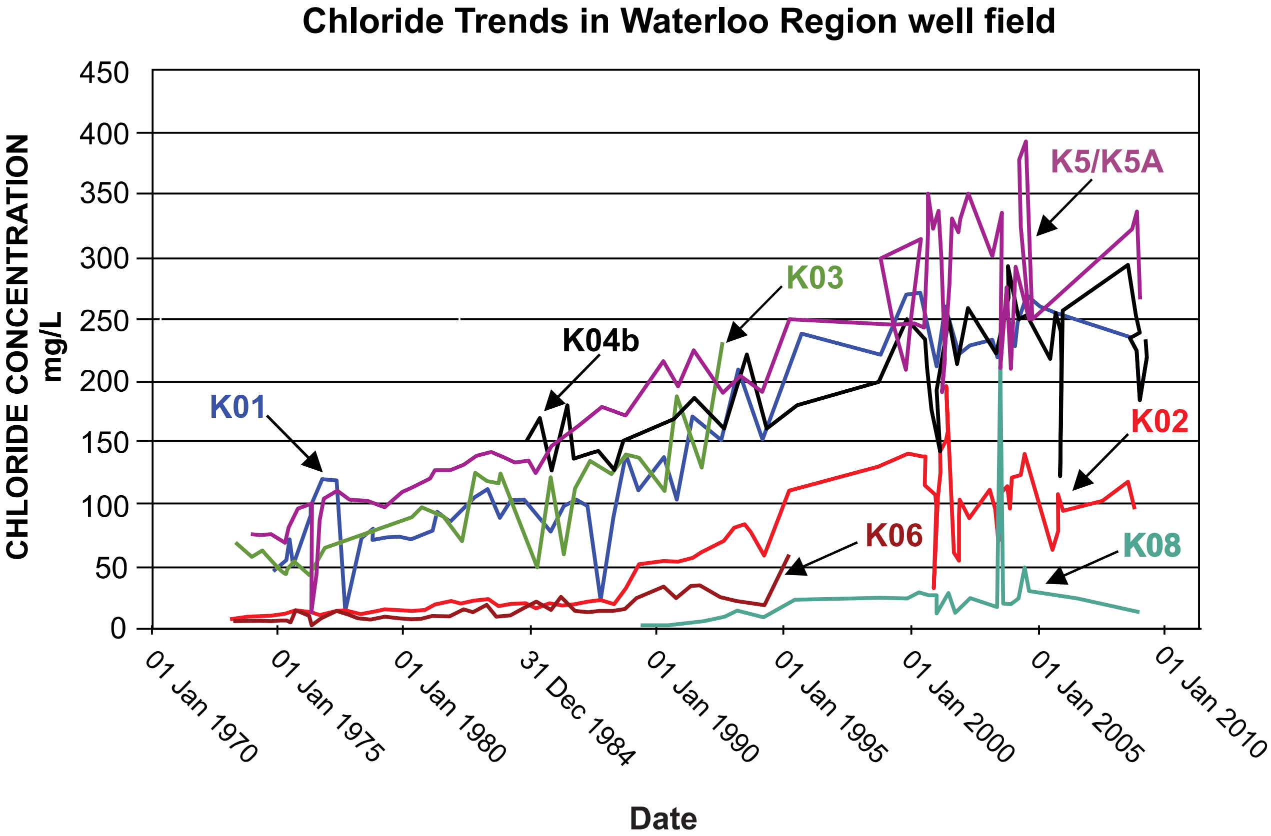


Figure 12.26 Road salt and water quality trends.
Road salt has been identified as a major threat to the groundwater supply of the Regional Municipality of Waterloo (which includes Kitchener, Waterloo, and Cambridge). Some well fields supplying drinking water have chloride concentrations above the 250 mg/L standard. A Road Salt Management and Chloride Reduction Study was initiated in 2003 to stabilize or reduce salt access to the groundwater supply; a field study in 2008 found a 45% reduction in average total mass of chloride. Labels K01 etc. represent individual municipal wells. Y-axis is concentration in mg/L (Figure courtesy of Regional Municipality of Waterloo).

to increased urban growth, and the number of roads in the region. Salt content increased three to four times in five municipal wells, located in two well fields, over a 25-year period. Rural wells also show evidence of increased sodium and chloride concentrations, albeit at lesser levels. The Ontario Drinking Water Objective for chloride (250 mg/L) is an aesthetic guideline, but increasing chloride levels can be a signal of potential land-use impacts.

A three-dimensional groundwater transport model was developed to evaluate the impact and risk to groundwater from winter road salt in Waterloo. The model showed chloride plumes originating mostly from arterial roads and migrating through a complex system of aquitards and aquifers, and into the water supply. Various scenarios of road salt application were postulated for the next 50 years and applied to the model. It was concluded that the impact of road salting on groundwater could be severe and that its reduction or elimination should be considered (Bester et al., 2006).

It should also be noted that the Region of Waterloo is largely underlain by the carbonate and gypsum-bearing rocks of the Salina Group. Where these rocks are buried to greater depths further west, they include beds of halite (rock salt). It is expected that formation waters in these rocks have a naturally elevated salt content. Thus, increasing salt content in water in the high-volume municipal water wells within the area may be due to withdrawal of saline formation water from deeper in the aquifer. Increased salts in Waterloo municipal water may result, in part, from more roads being deiced, and from high urban water consumption, requiring groundwater to be drawn from the deeper, naturally saline waters. This example illustrates the need to understand the groundwater flow system and how water quality may change due to natural and human-induced changes.

12.3.3 Groundwater use

Some 25% of southern Ontario residents rely on groundwater for their drinking water (e.g., Environment Canada, 2005; 2007). Indeed, some communities such as Orangeville and Guelph are entirely dependent on groundwater. Other major municipalities draw on a mix of surface and groundwater sources. The Regional Municipality of Waterloo takes 80% of its water from groundwater sources, with the other 20% from the Grand River. Kingston and Ottawa, depend mainly on surface water sources, but use some groundwater. The reliance on groundwater is much higher in rural areas, with 90% of rural residents using it as their drinking water source. The estimated total value to Ontario users of groundwater for drinking water is at a minimum, hundreds of millions of dollars a year (e.g., Nowlan, 2005; Figure 12.27). However, there is not enough data to be able to estimate accurately how much groundwater is used. The price of water does not include its value in dollars, just the service (cost of delivering reliable groundwater supply). Additionally, dollar valuation of water based on human uses only ignores the enormous value of groundwater for ecosystems.

Many industries rely on groundwater, with some served by groundwater-based municipal water supply systems and others using their own wells (Scharf et al., 2002). Water bottling is an industry that has grown dramatically during the past decade, with resulting conflicts. For instance, a 2007 application to increase water-bottling operations near Guelph produced intense opposition despite its potential economic value. Gravel pits and quarries are other important rural industries using groundwater. To extract aggregate below the water table, large quantities of groundwater must be pumped and may be discharged into nearby surface water bodies or lost to evaporation. In agriculture, farmers use groundwater for many purposes, the most important being irrigation of crops and watering livestock. While agricultural withdrawals of groundwater tend to be small, they can have a large impact locally because agriculture, in contrast to most municipal uses, consumes most of the water it withdraws. Golf course operators also consume groundwater for irrigation, which can add to land-use stress on groundwater-surface water systems.

While human uses are important, groundwater is also essential to the health of southern Ontario's ecosystems by providing baseflow in rivers and streams. For example, during the hot, dry conditions in late summer, water flow in many streams and rivers in southern Ontario comes completely from groundwater. Without this steady, cool groundwater flow, fish and other aquatic life would be in distress and their survival in jeopardy. A critical point in assessing groundwater use is the necessity of recognizing that humans have to share available supplies with aquatic environments. It is essential that human uses be balanced against the needs and limits of aquatic systems. More research is needed to clarify the ecological significance of groundwater (Box 12-7),

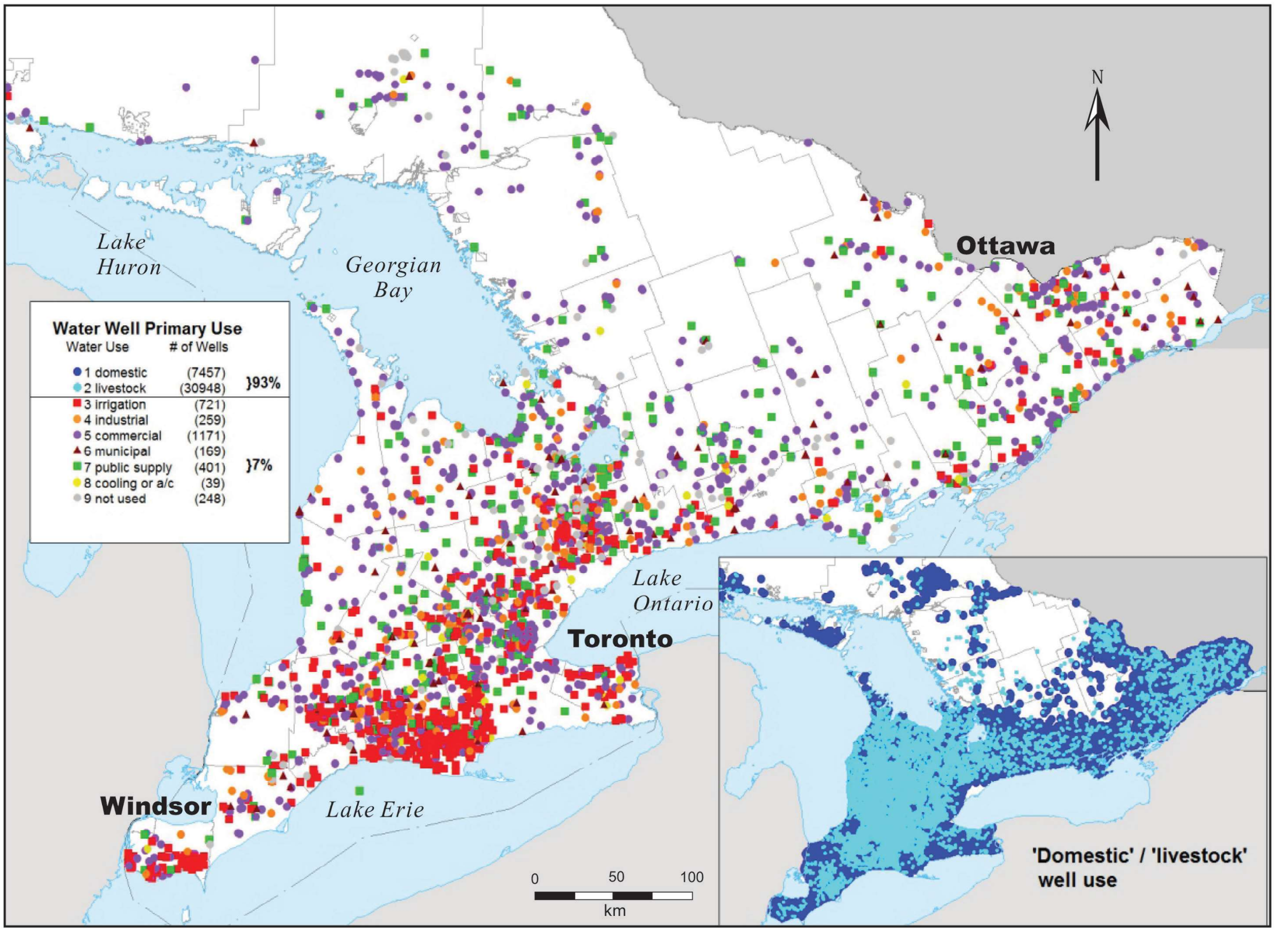


Figure 12.27 Who uses groundwater?
Groundwater use in southern Ontario based on major water uses reported in water well data from Ontario Ministry of the Environment. Note that the inset figure illustrates that there are many more livestock wells than domestic wells.

followed by public awareness building about this shared resource aspect.

12.3.3.1 Patterns and trends

Generally speaking, our understanding of water use in southern Ontario is poor, but improving (de Loë, 2005). There is a wide variation by sector and region in the completeness of water-use data. Data reporting for groundwater is particularly poor, as most levels of government neglected this role until recently (de Loë and Kreutzwiser, 2005). Preparation of aquifer and groundwater susceptibility maps ceased prior to the 1990s due to low budgets and reduced groundwater staff. Groundwater use is in decline in some large centres, like the GTA, due to increase use of piped lake water.

Encouragingly, since the Walkerton Inquiry findings were made public in 2002, there has been an increased emphasis on groundwater resources. Water-use reporting has improved through provincially funded groundwater management and protection studies. New groundwater studies have focused primarily on threats to groundwater quality and groundwater availability. Other initiatives, as well, are contributing to a better understanding of groundwater in the region. These include

- A Provincial Groundwater Monitoring Network

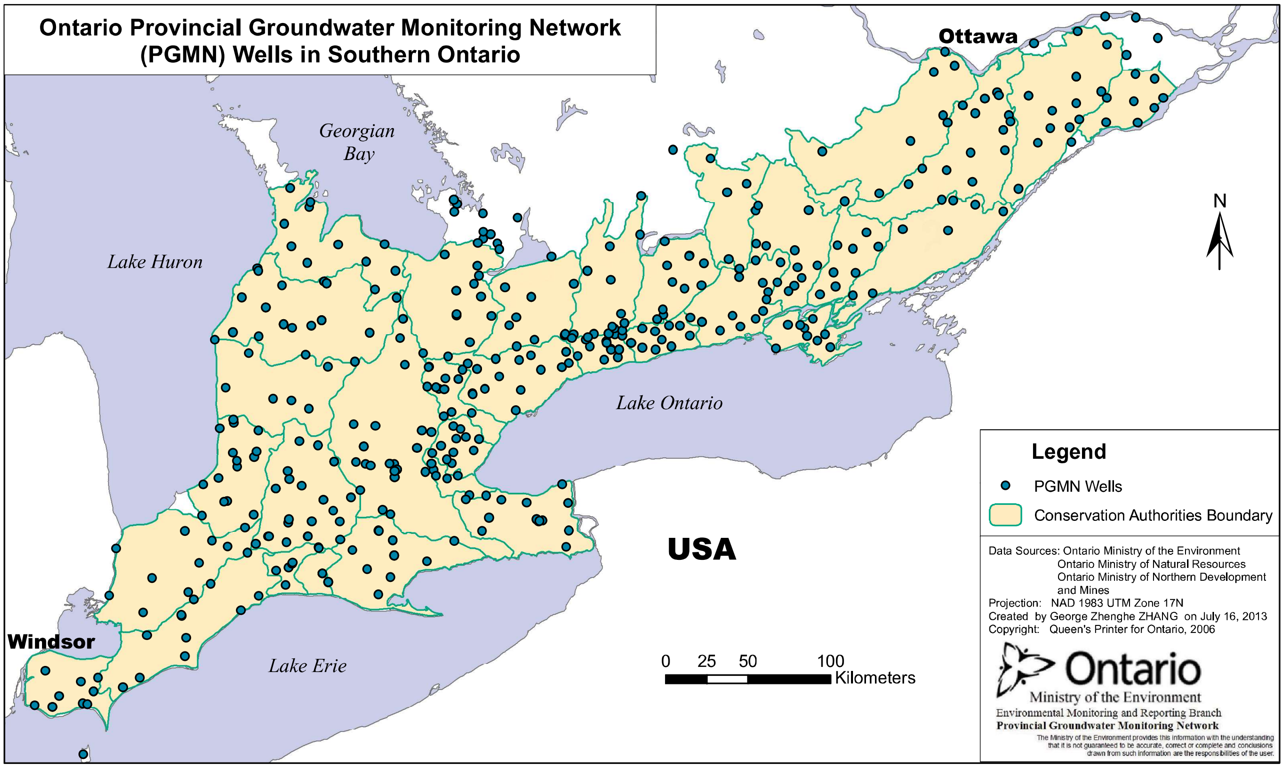


Figure 12.28 Measuring the pulse of the groundwater system.
The Ontario Ministry of the Environment Groundwater Monitoring Network covers most of southern Ontario region with monitoring wells set within the boundaries of conservation authorities, which manage water at the local scale. Note that some wells occur in the Canadian Shield hydrogeological region.

established in 2002, which collects and manages data on groundwater levels and quality in key aquifers across Ontario, including 400 monitoring wells in southern Ontario (Figure 12.28).

- Changes to the Permit to Take Water program (PTTW), Ontario's water allocation system, provides access to higher-quality water-use data. The Water Taking and Transfer Regulation under the Ontario Water Resources Act now requires that permit holders (those using more than 50,000 L/d) collect and record data on the volume of water taken.
- Permits now distinguish surface water from groundwater use. Thus over time, water-use data will improve. Water users who do not require a permit (use of < 50,000 L/d) for domestic use and livestock watering without storage are not counted, and this will create gaps in the database.

In summary, groundwater in southern Ontario is a subject that has been overlooked in the past, and our knowledge of this important resource is poor. In the wake of the Walkerton tragedy and bolstered by growing public awareness about the need to protect water resources, the forecast is improving for better groundwater management based on high-quality data from improved monitoring of this resource.

12.3.4 Understanding groundwater systems within the Grand River watershed

Work on one of the most characterized groundwater systems in Ontario, the Grand River watershed, provides a good example of how to assess, integrate and manage groundwater information and resources for all users. A watershed-wide groundwater flow model has been developed to incorporate new data and information with each model-iteration (e.g., Holysh et al., 2001; Waterloo Hydrogeologic Inc., 2005; AquaResource Inc., 2009). Model results have been very useful for determining a watershed-wide water budget (see Box 12-8) and for determining areas of groundwater recharge and discharge. The groundwater flow models also allow for better understanding of groundwater–surface water hydrologic linkages within the Grand River watershed and help tackle key questions including

1. Where does predicted groundwater recharge water go, to local or deep flow?
2. How are areas of high groundwater discharge evaluated?

These questions are addressed by using forward and reverse flowpath analyses within the groundwater flow model. Flowpaths are used to estimate where groundwater enters, travels through, and exits the groundwater flow system. These results can be tested with focused field data, stream gauging and ecological indicators, to better understand watershed hydraulic linkages. For example, areas of groundwater discharge have been correlated with coldwater fisheries (Figure 12.29).

Understanding and maintaining groundwater discharge is pertinent to ecological function. Groundwater discharge not only maintains baseflow and moderates stream temperature, but overall water quality is improved. Whitemans Creek thus provides habitat to the Silver Shiner, a fish species of special concern.

12.3.4.1 The quality of groundwater within the Grand River watershed

Groundwater within the Grand River watershed is considered to be of good quality where wells are used primarily to serve domestic and livestock uses (Environment Canada and EPA, 2005). Naturally elevated concentrations of inorganic constituents (e.g., calcium, magnesium, sodium, chloride and sulphate) are often found within the watershed's sediment and bedrock aquifers, and hard water is common throughout the watershed. The City of Guelph's wells yield water with hardness three to four times the aesthetic Ontario Drinking Water Objective of 80–100 mg/L.

Of the water wells with reported natural groundwater quality problems, 90% are in bedrock, compared to only 10% within sediment wells. Elevated sulphur concentrations are the most commonly reported problem within these wells; they are often associated with location within Salina or Guelph formations. As discussed in Box 12-6, fluoride can also have high natural concentrations in the groundwater of southern Ontario.

Human-induced changes to groundwater quality in the watershed are associated with urban sprawl, agriculture and industry (Sawyer et al., 2005). Common localized contaminants include organic compounds and bacteria from livestock, and more widespread impacts due to nitrates from agricultural fertilizers and septic systems. Chloride in road salt occurs in urban (Figure 12.26) and rural areas of the watershed.

Industrial contaminants known as volatile organic compounds (VOCs) have caused major problems in municipal groundwater supplies within several communities of the Grand River watershed. By 1998, for example, five of the City of Guelph's 24 wells were permanently removed from service due to low-level VOC contamination. This was a serious problem as these wells produced about 15% of Guelph's permitted water-taking

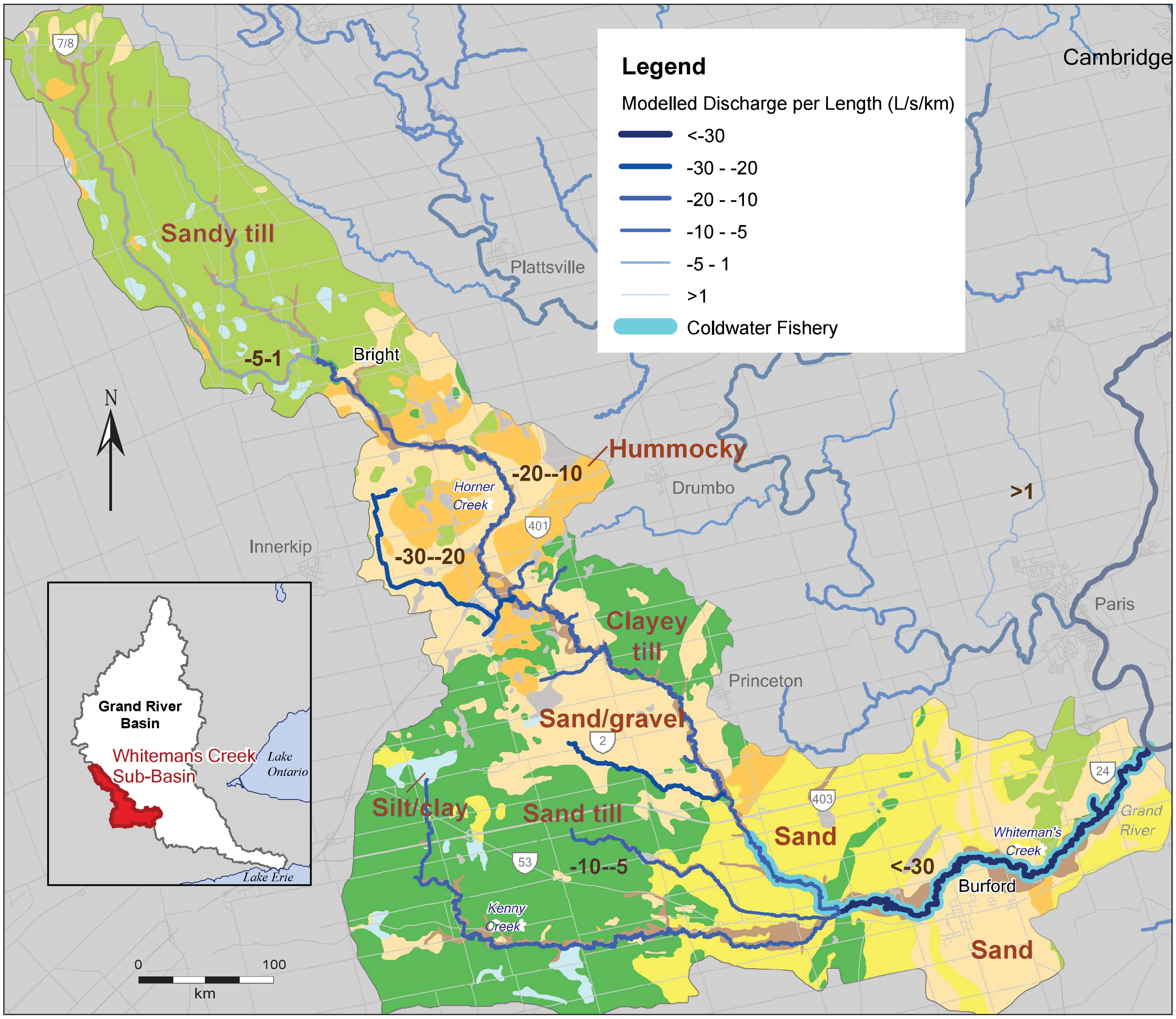


Figure 12.29 Geology controls groundwater discharge.
Variable sediment type in Whitemans Creek sub-watershed relates to areas of higher groundwater discharge and mapped areas of cold-water influx. The local shallow flow regime of the Norfolk sand plain discharges ~30–60 L/s/km of groundwater to Whitemans Creek, a high groundwater discharge zone within the Grand River watershed. Mapped cold-water fish distribution within Whitemans Creek compares well with modelled reaches of groundwater discharge with cold-water regimes.

capacity. Ultimately, new well fields were developed and water conservation measures implemented. In the community of Elmira, both a shallow, sand and gravel aquifer (Elmira Moraine) and a deeper municipal aquifer were contaminated with a variety of chemicals from nearby industrial plants. Elmira now receives its water supply from the Regional Municipality of Waterloo and nearby townships within the region.

12.3.4.2 Groundwater and land use: Agricultural impacts

Agriculture, covering ~67% of the total land area, is the major land use in the Grand River watershed. Agricultural activity can affect groundwater quality in many ways: use of pesticides, application of fertilizer or manure on fields, and improper storage, disposal or spills of animal waste or chemicals.

A significant problem arises from the application of excessive quantities of nutrients to agricultural land. Excess nitrogen is converted to nitrate, then picked up by infiltrating water and transported to the water table, where nitrate can affect groundwater quality. Land use and nitrate levels, measured in surface water from two sub-watersheds, illustrate the effects of agricultural activities on groundwater and surface water quality. In Whitemans Creek, ~78% of the area of groundwater infiltration is used for agricultural purposes, while ~20% is forest cover. In Eramosa River, ~60% of recharge land is for agricultural use and ~34% is forest cover. In both sub-watersheds, rivers receive significant quantities of groundwater discharge. The average annual concentration of nitrate measured in Whitemans Creek (1997 to 2003) was 2.5 to 8 times higher than that measured in Eramosa River. The higher nitrate levels measured in Whitemans Creek show the link between increased agricultural activity and groundwater contamination, and have implications for surface water quality. These high levels may also be a result of the larger number of rural communities in Whitemans Creek, with a correspondingly high density of septic systems leaching nutrients to the subsurface. In addition to nitrates, manure spreading on fields, runoff from waste disposal sites, and septic systems can all provide a source of bacteria to groundwater. Bacterial contamination in wells located within agricultural areas is common. This contamination is often due to poor well construction or maintenance, which allows surface water to enter the well (thus not indicative of widespread aquifer contamination). Shallow, dug wells are most vulnerable to bacterial contamination (Conservation Ontario, 2003).

The Grand River watershed population may increase by ~300,000 by 2020. Urban expansion and industrial development associated with this population growth will place increasing pressure on groundwater quality. Intensification of agriculture may also aggravate pollution caused by nutrients, bacteria and pesticides. Potential effects of climate change may put pressure on groundwater availability, which in turn could concentrate existing contaminants. Protecting groundwater resources will require multi-faceted strategies including regulation, land-use planning, water-resources management, voluntary adoption of best management practices, and public education, as well as improved understanding of the groundwater flow system fluxes and composition.

12.3.4.3 Integrated water management within the Grand River watershed

Conservation Authorities co-ordinate, focus and streamline water management using integrated approaches that extend across jurisdictional boundaries. The Grand River Conservation Authority's Rural Water Quality Program aims to improve water quality by implementation of best management practices. Farmers have access to financial assistance for eligible projects and over 1,600 projects have already been supported. The Authority has also organized a Low Water Response Team that declares low water conditions for each part of the watershed using three low water conditions specified by the Ministry of the Environment. Finally, the Authority has 27 wells which are part of the Provincial Groundwater Monitoring Network. Data from these wells assists in understanding long-term trends in groundwater conditions, and in establishing baseline geochemical characteristics at each site.

12.4 SUMMARY

We have touched on many issues linked to groundwater in southern Ontario in this chapter. We have seen how contamination of groundwater can have tragic consequences, or even close parts of a municipal well system, as in Guelph. We have touched on the issue of groundwater as a shared resource between humans and the rest of the ecosystem. And we have talked about competing demands for groundwater resources, and how these could become a major issue during extended dry spells. To sum up, we identify a few key issues that require pertinent scientific context. The goal is to assist public engagement in an active and informed dialogue regarding science-based approaches to groundwater protection in southern Ontario. This includes key legislation and some important outreach activities that are reshaping the management of groundwater.

12.4.1 Summing up groundwater science

Groundwater is generally abundant, of good quality and occurs in a diverse set of aquifers and aquifer systems across southern Ontario. Shallow bedrock and contact aquifers are important and widespread across the region. The best of these occurs in carbonate rocks west of the Niagara Escarpment, particularly where flow is enhanced by karst. Water quality can be an issue where shale and gypsum rocks occur in shallow bedrock units. Wells that only penetrate a short way into bedrock may, in fact, draw much of their water from the sediment rock interface. Deep bedrock is not a significant source of potable water in southern Ontario as most deep strata retard water flow. Deep regional aquifers occur in a few bedrock formations, either in sandstone or in carbonate rocks with karst zones; however, most deep water is saline and locally sulphurous.

Sediment aquifers are also common, widespread, and their natural water quality is almost always very good. These aquifers are very prominent where sediment is thick, such as in sandy moraines (Oak Ridges Moraine, Waterloo Moraine), in buried valleys (Laurentian valley), and on the north shore of Lake Erie. Different sediment types affect the flux, chemistry and annual movement of water.

In general, clay plains such as the Essex clay plain are characterized by high surface runoff and little infiltration of rain or snowmelt that seeps to groundwater in deep sediment-bedrock interface aquifers. Groundwater levels change very slowly over the year. Sand plains, on the other hand, such as near Norfolk, allow rain and snowmelt to readily infiltrate the surface and transmit water to the water table, where it is stored as groundwater, particularly in the spring. This stored water releases slowly throughout the summer, as discharge to streams, when rainfall inflow is low. Groundwater levels vary in response to these seasonal events. Water levels in wells drilled through till uplands in Grey County behave differently than wells in either the clay plain or sand plain, partly due to the more complex geology and slopes in this region. A dissected till upland in thick sediment in Wellington County is cut by channels containing glacial meltwater sediment, sand and gravel. In such terrains, stream baseflow is high due to enhanced permeability and storage in coarse sediment of the groundwater catchment. Groundwater levels also respond to precipitation and snowmelt events, yet with slightly delayed responses due to the fact that water is stored in near-surface, valley sediment, or wetlands. In addition, streamflow in limestone plains responds rapidly to precipitation and snowmelt that runs off the limestone surface.

Groundwater levels also respond rapidly to these events as karst-enhanced fractures capture some runoff. Groundwater storage levels vary by many metres over the season as karst enlarged chambers fill and empty from spring to late summer. The different hydrogeological settings are important because we can generalize understanding from one setting to similar settings across southern Ontario. We can also improve understanding by comparing or contrasting the type settings to other settings using a simple geological map of type settings across the region.

While general water quality and availability is good, there are some areas where groundwater supply and quality are poor. Agencies are starting to improve understanding by collecting better hydrogeological data, and by providing guidance on interpretation and monitoring. Overall, there is still much work to do to improve the collection and integration of high-quality data into publicly accessible groundwater databases.

12.4.2 Improved information and improved access

Southern Ontario is fortunate to have a considerable amount of regional hydrogeological data relative to most aspects of water resource management. Nevertheless, we need to achieve a better understanding of how groundwater functions at the regional scale, based on climate data, and more high-quality streamflow, water level, geology and borehole records, set within a modern information framework. Such an enhanced framework would aid the systematic mapping of groundwater throughout southern Ontario, including links to surface water. Ideally, the information framework and groundwater understanding can be connected to key properties of the regional hydrogeological system.

The Walkerton tragedy focused much needed attention upon groundwater and triggered the implementation of Source Water Protection as part of the Clean Water Act. This is a good first step, but there is still more that can be done, particularly in the area of quantitative water use and monitoring. Provincial programs, such as the Permit to Take Water program, need to be further integrated with land use information to develop a comprehensive water management strategy for Ontario.

12.4.3 Collaboration

Improved information, understanding and management of groundwater in southern Ontario rely on an ongoing need for cooperative efforts among local watershed authorities, municipalities, provincial ministries, the private sector and, possibly, federal experts. One very effective partnership is the Conservation Authorities Moraine Coalition, an amalgamation of the York, Peel, Durham and Toronto regional municipalities, and nine conservation authorities, with its focus on improving the public's basic understanding of surface water–groundwater resources. Additional similar partnerships would be beneficial at all levels of government. Single agencies in some cases, such as the Grand River Conservation Authority, have developed the vision and commitment to address water resource issues with up-to-date knowledge and understanding. Again, this is a model that could be adapted throughout southern Ontario.

12.4.4 Groundwater topics of interest

Events such as the tragedy in Walkerton have increased public and political interest in groundwater. They have also focused greater attention on a wide range of concerns and topics regarding the sustainability of groundwater resources of southern

Ontario. Science-based approaches must be used to determine the potential for detrimental impacts. In urban settings, for example, there are concerns that the increasing extents of impervious surfaces such as roads and parking lots may reduce recharge and baseflow while also requiring increased use of road salt that could contaminate groundwater. Deteriorating infrastructure such as sewers, water mains, and underground storage tanks certainly have the potential to impact groundwater. In rural settings, there are concerns about agricultural practices such as manure storage and spreading, and the use of chemical fertilizers and pesticides, the disposal of sludge from wastewater treatment plants, and how the increasing number of quarries impact groundwater supplies and dependent habitat and species. Waste disposal facilities such as landfills and the wells that are used to inject liquid wastes into the deep subsurface continue to cause concern, as do the many industrial and commercial sites that handle hazardous materials. Water bottling and other consumptive uses of groundwater, such as the irrigation of crops and golf courses, are topics of discussion in some areas. In others, pipelines are now being used to supply water to homes and businesses that were previously dependent on groundwater. Geothermal heating and cooling systems have the potential to decrease fossil fuel dependence and carbon dioxide emissions, but these installations may also impact groundwater. Climate change may alter the timing and magnitude of recharge and result in more frequent and severe precipitation events. Sequestration of carbon dioxide and the burial of radioactive waste in deep geological formations, and the tracking of shale gas from wells that have been stimulated using hydraulic fracturing, are emerging topics for improved knowledge and discussion.

ACKNOWLEDGEMENTS

We appreciate the assistance of a number of contributors who are not listed as co-authours: Andrea Bradford contributed to the Box 12-7 on the ecological significance of groundwater; Eric Hodgins provided the figure on salt trends in municipal wells, Regional Municipality of Waterloo. Reviews by Bob Betcher, Frank Brunton, Emil and Michael Frind, John Gartner and Bob Leech helped greatly to improve the chapter. Graphic assistance was provided by John Glew (drawings), Richard Franklin (drawing standardization), Rachelle Lacroix, and Charles Logan. Elizabeth O'Discoll provided edits from a lay person perspective. Christie Vodden revised an early draft of the chapter and made recommendations for publication to a general audience.

BOX 12-1 THE WALKERTON TRAGEDY IN 2000

After a heavy rainstorm on May 12, 2000, Walkerton's groundwater supply was contaminated with *E. coli* when surface water washed cattle manure into a town well where it quickly entered the public water system. Seven people died, while another 1,286 were struck with debilitating illness all because an unreported, faulty chlorinating system in the town well failed to kill the bacteria. The tragic events at Walkerton were a turning point in terms of groundwater understanding, policy and management.

One of the key recommendations of the Walkerton Inquiry report, released in 2002 (O'Connor, 2002), was that science-based Source Protection plans be developed for all Ontario watersheds. Ontario's Clean Water Act, passed in 2006, requires that all communities, through local Source Protection Committees, assess existing and potential threats to their water. The Act also empowers communities to take action to prevent any threats from becoming significant. This requires the development of a local Source Protection plan, based, in part, on public input. The Clean Water Act is guiding progress in understanding the availability of groundwater and its annual flow within a watershed under variable conditions such as spring floods and summer droughts. Accordingly, provincial and municipal governments as well as conservation authorities now require accurate and timely regional scientific data and expertise to support their groundwater management plans. These plans are to be coupled with a continuing public dialogue on water science and policy. Further information on the policies and the science behind Drinking Water Source Protection is web-accessible (http://www.ene.gov.on.ca/environment/en/subject/protection/index.htm). Information on Source Protection is also provided in sections 12.1.5 and in 12.4.2.

BOX 12-2 LINKING HYDROGEOLOGICAL SETTINGS TO HYDROGRAPHS

To understand the regional hydrogeological variability in southern Ontario, we link geology to hydrographs with available case studies (Figures 12.30, 12.31, 12.32). These studies are depicted by a conceptual sketch that shows the water movement in key southern Ontario landscape types. Three graphs provide climate data, streamflow and groundwater levels for informed comparisons, all of which are referenced to the same climate year. We note that total streamflow, groundwater recharge/discharge, and groundwater/water level fluctuations are not always directly related to total annual precipitation, owing to seasonal climatic effects. These effects determine the form of precipitation (rain/snow) and the movement of water between the atmosphere, surface and subsurface reservoirs. The well numbers and associated groundwater level data are from a Ministry of the Environment monitoring network that operated from 1974 to 1980. Many of the wells from this historical network have been re-activated since 2001 for inclusion into a recently established Provincial Groundwater Monitoring Network (PGMN). Note that in all hydrographs, streamflow is expressed in millimetres (mm) as a daily volume of flow per unit area of gauged watershed. This allows the data to be directly compared with millimetres of precipitation, and also helps to enable data comparison for different watersheds. Groundwater levels are in metres below ground surface (m bgs; Piggott, 1999).

To help compare hydrogeological settings, relatively small watersheds, of less than 1,300 km^{2,} were chosen in order for the hydrological data to be better linked among weather stations, stream gauges and observation wells.

BOX 12-3 NORFOLK SAND PLAIN: SEDIMENT AQUIFER CASE STUDY

A 23.8 m deep well (413A) samples a sand aquifer in a low-relief sand plain (Figure 12.30). Streamflow in Venison Creek rapidly responds to precipitation and snowmelt, but relatively low peak flows are generated (Figure 12.30c). This, plus the relatively high baseflow, is indicative of significant groundwater recharge and discharge. Baseflow forms a substantial portion of streamflow throughout the year, and likely reflects relatively high permeability and groundwater storage. Adequate storage in sandy strata helps to maintain baseflow, while permeability of the flow system is moderate so that storage is not discharged too quickly. Rapid infiltration of precipitation, through regionally extensive near surface sand, appears to increase the efficiency of groundwater recharge during periods of elevated evaporation and transpiration, and contributes to maintaining baseflow. Groundwater

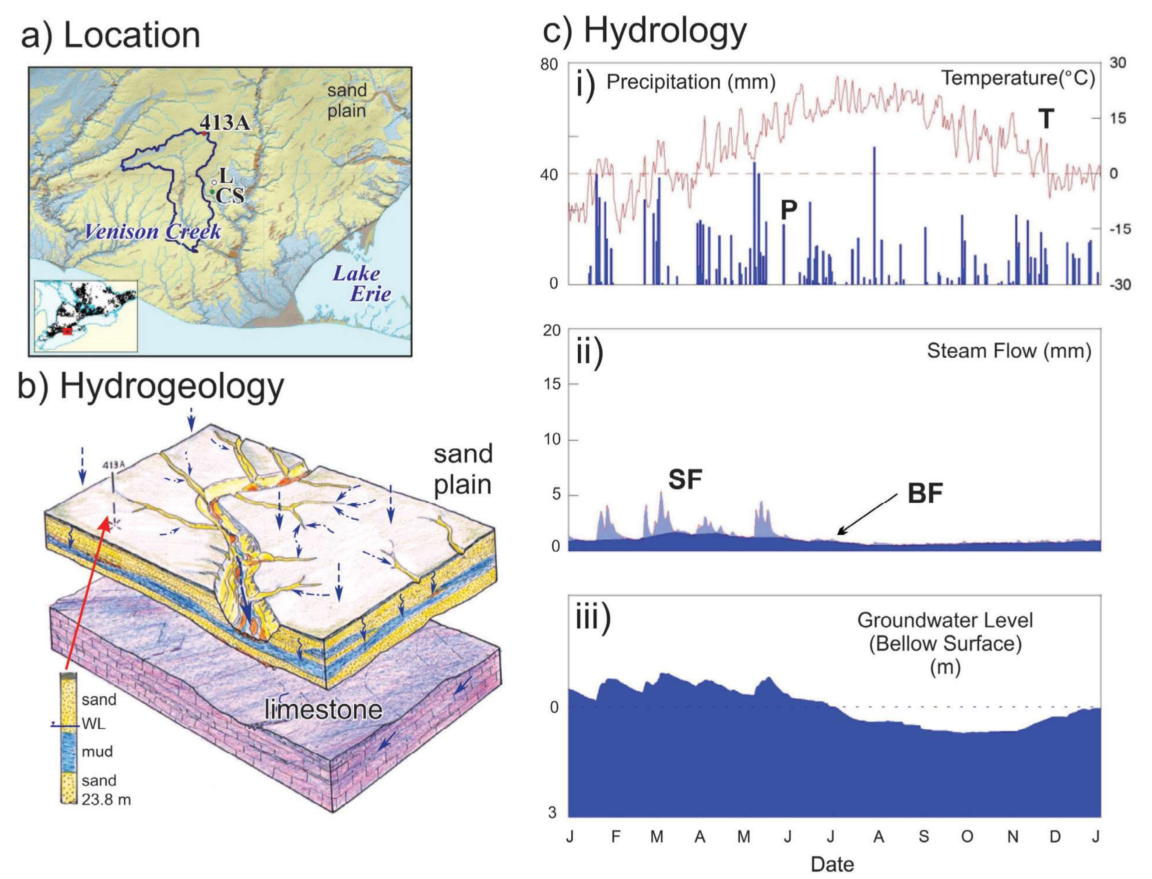


Figure 12.30 Norfolk sand plain hydrogeological setting
a) Location with sand plain geology (yellow); dark areas in inset map show sand plain coverage in southern Ontario; Lawrence Station is marked L. b) Conceptual sketch charts well-bore sediment and rock strata with local surface/ groundwater flow pattern. Arrows indicate relative flux of water movement from atmosphere to surface flow, and to groundwater flow. c) Hydrology for common year 1974 from climate station (CS) with graph scales set to aid comparison: i) precipitation (P), temperature (T); ii) streamflow (SF), baseflow (BF), separated from streamflow to Venison Creek; iii) well water levels change by ~2 m over the year, with noticeable pulses in late winter and spring

levels (Figure 12.30c) rapidly respond to precipitation and snowmelt, but the magnitude is modest, given high estimated recharge; this suggests substantial groundwater storage. The recession of groundwater levels which occurs during summer and early fall is not uniform, and varying rates may reflect recharge events during this period. The rapid response to recharge events and the even distribution of groundwater outflow from storage throughout the year appear to be representative of southern Ontario sand plain settings. Note the different hydrological behaviour of a sand plain when compared to a clay plain (see below), given similar climatic inputs.

BOX 12-4 ESSEX CLAY PLAIN/INTERFACE AQUIFER CASE STUDY

A 58.5 m deep well (164A) samples an interface aquifer with limestone overlain by a sand bed beneath an extensive, ~20 m thick clay plain (Figure 12.31). Streamflow along the nearby Ruscom River responds rapidly to precipitation and snowmelt that runs off the clay surface, resulting in large peak streamflows during the early part of the year. Crop cover in this agricultural area may intercept or reduce peak streamflows during the growing season (Figure 12.31c). These factors, combined with low baseflow (BFI=0.16), indicate limited groundwater recharge and discharge. Groundwater levels

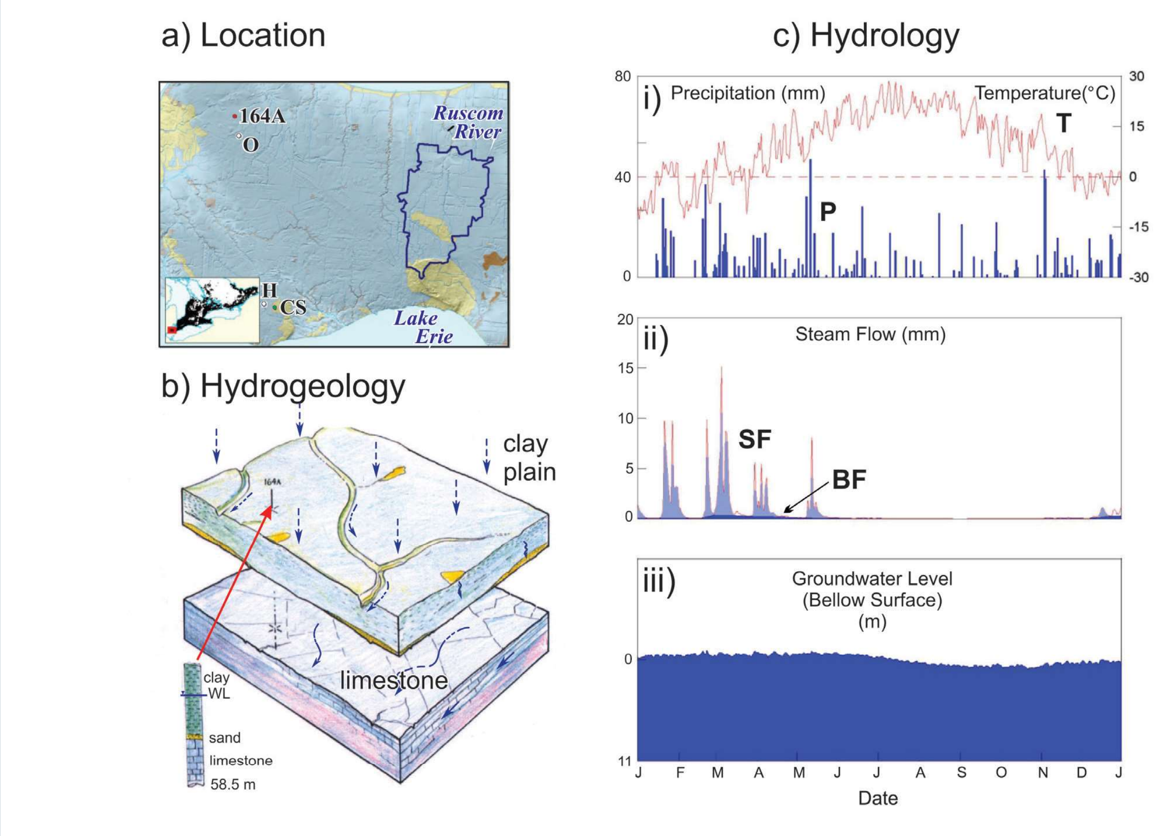


Figure 12.31 Essex clay plain hydrogeological setting.
a) Location and clay plain geology; dark areas on inset map show clay in southern Ontario; Harrow town is marked H. b) Conceptual sketch charts well bore sediment and bedrock with local surface/groundwater flow pattern. Arrows indicate relative ease of water movement from atmosphere to surface flow, and to groundwater flow. c) Hydrology for 1974 from climate station (CS), with graph scales set to aid comparison: i) precipitation (P) and temperature (T); ii) streamflow (SF), baseflow (BF) separated from streamflow; iii) well level varies very gradually <0.2 m over the year.

do not respond to precipitation and snowmelting events, and there is minimal yearly variation of levels. A small recession in water levels during July and August is followed by a gradual increase during November and December. Figure 12.31c). This may be due to seasonal groundwater withdrawals, such as irrigation, followed by redistribution of groundwater within the aquifer. Short-term (~1–2 day) variations in groundwater levels are closely related to changes in atmospheric pressure, and are indicative of confined conditions (e.g., thick clay cover) within the aquifer. Limited shallow groundwater flow and confined conditions at depth typify this aquifer and likely other low-permeability clay-plain settings in southern Ontario. In clay plain interface settings, groundwater in deep clay can be many thousands of years old, and solute transport may be largely by diffusion rather than by flowing groundwater; hence, clay is able to protect groundwater from surface contamination.

BOX 12-5 NAPANEE LIMESTONE PLAIN AQUIFER CASE STUDY

A 31.7 m deep well (478A) samples shallow unconfined fresh water in a limestone bedrock plain near Napanee (Figure 12.32). Streamflow in Wilton Creek rapidly responds to precipitation and snowmelt running off the limestone surface. Thin discontinuous till in the watershed does not modify the pronounced

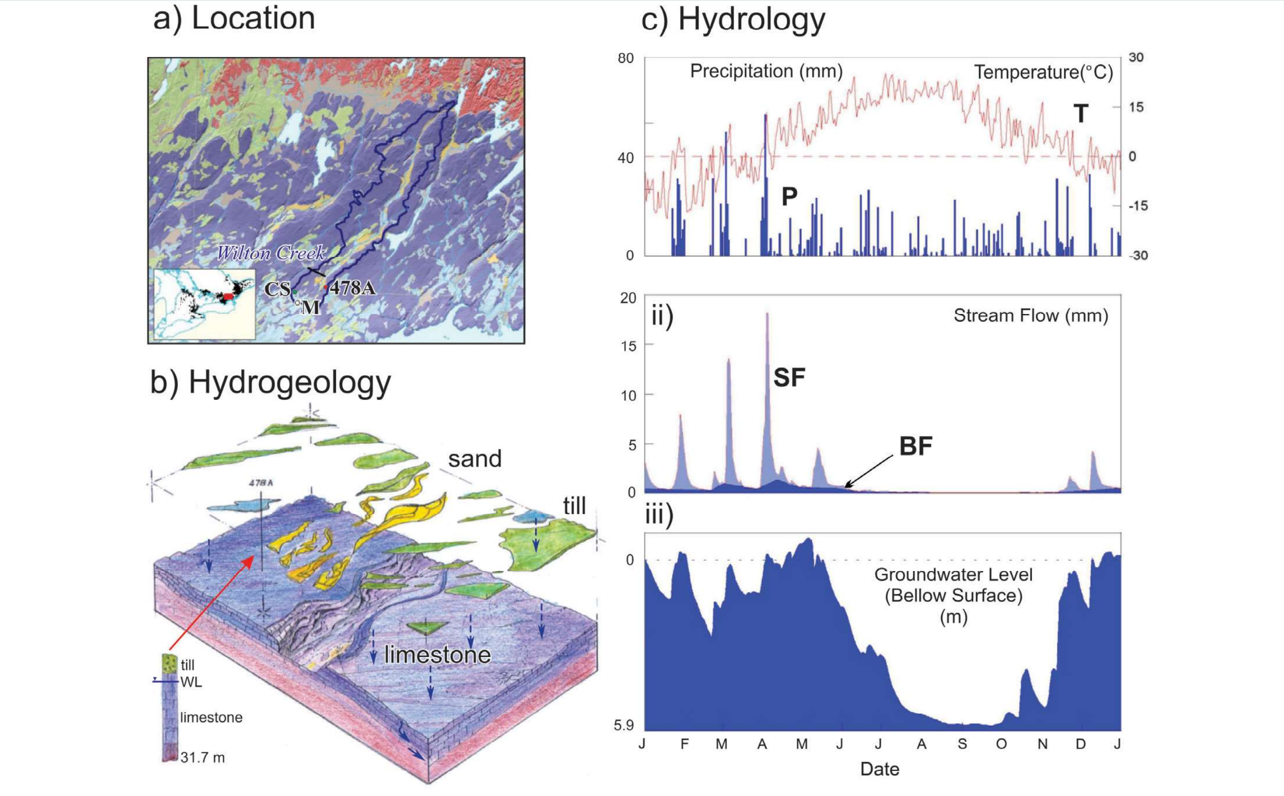


Figure 12.32 Napanee limestone plain hydrogeological setting.
a) Location with limestone terrain geology (purple); dark areas on inset map show exposed bedrock; town of Morven marked M. b) Conceptual sketch charts well bore sediment and rock with local surface/groundwater flow pattern. Arrows indicate relative ease of water movement from the atmosphere to surface flow, and to groundwater flow. c) Hydrology for common year 1974 from climate station (CS), with graph scales set to aid comparison: i) precipitation (P), temperature (T); ii) streamflow (SF), separated from baseflow (BF) separated from streamflow for Wilton Creek; iii) well water level: the large (~6 m) seasonal water level change may relate to karst storage and discharge trends.

high flow to Wilton Creek. Groundwater levels also respond rapidly to precipitation and snowmelt events (Figure 12.32c). A protracted period of low streamflow occurs during summer and early fall. Groundwater levels decline dramatically (~6 m) beginning in mid-May and continuing until mid-October. The relatively constant levels that occurred during this period may indicate that groundwater is slowly yet steadily discharging to surface water. The limestone terrain appears to have variable to low capacity to store groundwater; that is, high water levels may be connected to more storage (karst chambers) which readily discharge; whereas at low levels, stored water only occurs in fractures that provide very modest discharge to streams during low flow periods. Groundwater capacity and function in this terrain is thus influenced by karst enlargement of fractures and cavities. The resultant variations in the stream hydrograph, particularly the very low summer baseflow, may lead to a source of stress to in-stream water quality and the aquatic ecosystem. Note that bedrock groundwater levels are very different than those in clay and sand plains described earlier.

BOX 12-6 FLUORIDE IN GROUNDWATER OF SOUTHERN ONTARIO

Monitoring results from the Provincial Groundwater Monitoring Network and Drinking Water Surveillance Program show that fluoride is commonly found in Ontario groundwater, usually at concentrations below the Ontario Drinking Water Quality Standard (ODWQS) of 1.5 mg/L. However, the majority of exceedances of any of the ODWQS parameters have been for fluoride and these exceedances have primarily occurred in southern Ontario (MacRitchie et al., 2007).

Fluoride occurs naturally in groundwater and is important to bone and tooth development. Typically 0.8–1.5 mg/L natural fluoride in drinking water supports healthy tooth and bone growth. In Ontario, where water samples with higher fluoride levels, 1.5–2.4 mg/L, are found, local boards of health are required to raise public and professional awareness to control fluoride exposure. Concentrations at these levels in drinking water can cause health issues ranging from pitting and alteration of teeth to debilitating fluorosis or bone conditions. Currently, levels of > 2.4 mg/L must be reported to local medical officers to assess potential risks for human intake.

Man-made sources of fluoride in groundwater

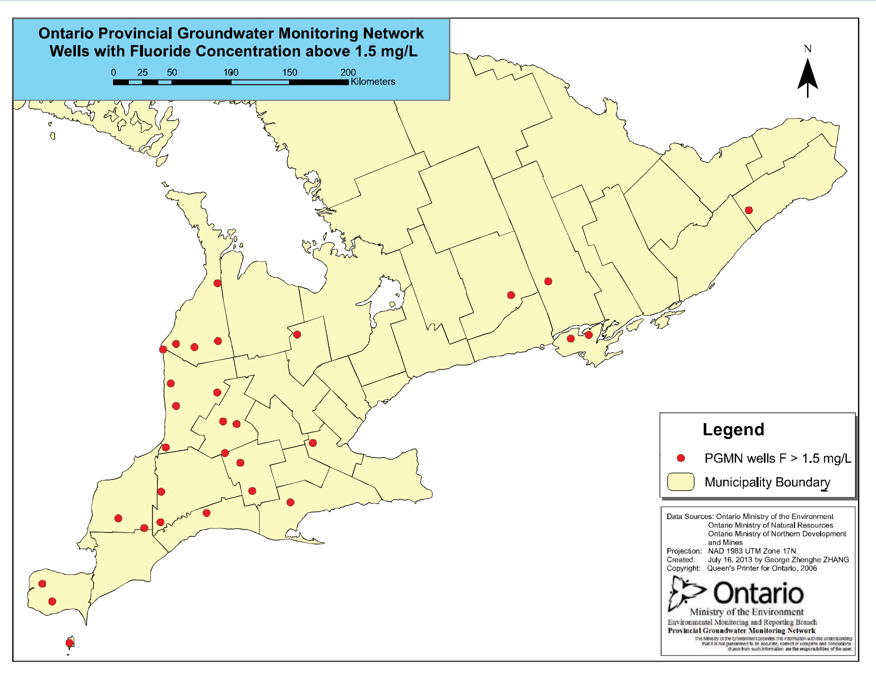


Figure 12.33 Location of PGMN wells with confirmed concentrations above the 1.5 mg/L standard.

appear to be related to manufacture of phosphate fertilizers, which currently does not occur in Ontario. Natural fluoride occurrence in groundwater results from geological, chemical and physical characteristics of aquifers such as conductive, porous and acidic soil, as well as rock and groundwater temperature and geochemistry. Natural sources of fluoride include dissolution of fluoride-bearing minerals such as fluorite, long residence time of groundwater in deep aquifers, fluoride-rich pore water in clay, and weathering of mica, a mineral that can rapidly leach fluoride.

Southern Ontario sources of fluoride appear to be fluorite, a mineral deposited when warm fluids migrated into fractures and reefs associated with carbonate rock. Clay minerals may also be a fluoride source.

BOX 12-7 THE ECOLOGICAL SIGNIFICANCE OF GROUNDWATER IN SOUTHERN ONTARIO

Surface aquatic habitats such as springs, streams, wetlands and many lakes depend on groundwater. The volume of groundwater discharge, or the elevation of the water table, can play an important role in maintaining surface water depth, or the “living space” used by aquatic organisms. Groundwater can sustain the moisture regime within wetland soils and along stream banks, where healthy vegetation contributes to stream-bank stability. It can sustain moist food production and spawning areas in streams. Groundwater is the source of baseflow in streams that sustain connections along the channel, and it allows fish to access refuge areas during low-flow periods. As an example, low-flow conditions in Grindstone Creek, near Hamilton (Figure 12.1), resulted in the loss of fish habitat and restricted migration to suitable aquatic conditions.

Also of importance to ecosystems are the timing, frequency and duration of groundwater conditions. For example, amphibians depend upon the timing and duration of ponding in wetlands during their breeding season.

Groundwater discharge plays an important role in moderating thermal regimes within streams, and this is particularly important for sustaining southern Ontario’s cold-water fisheries (Figure 12.34). On a smaller scale, groundwater discharge can create cooler refuges which help a variety of

Figure 12.34 Brook trout spawn over a groundwater upwelling in the Credit River. Brook trout are dependent on the uniform temperature of groundwater discharge to keep water temperature cooler during the summer and warmer during the winter, and, to provide suitable habitat for their nests and eggs. (Photograph by Jack Imhof, National Biologist, Trout Unlimited Canada)

aquatic organisms survive extreme summer conditions and provide warmer refuges for overwintering. A change in the chemical composition of groundwater, which is different than that of surface water, can result in significant shifts in vegetation communities.

There is a strong link between surface water–groundwater ecology in southern Ontario. Several uncertainties are associated with prediction of the water table within abundant wetlands or with estimating groundwater flux within a brook-trout spawning habitat, so as to evaluate fairly whether impacts might be tolerable by the ecosystem. Quantifying groundwater–surface water links is a key area to target groundwater ecological research.

BOX 12-8 GRAND RIVER WATERSHED WATER BUDGET

A water budget can be defined as a means to assess and account for the movement of water through the hydrologic cycle. By quantifying each component of the cycle, including key processes, pathways and uses, one gains an understanding of watershed trends and stresses to groundwater and surface water.

A typical simple watershed water budget can be summarized as follows (using measurements/ estimates in mm/year converted to volume estimates, based on local climatic norms over 20–30 years). On average, precipitation (number 1 in the following table) minus losses due to evaporation-transpiration (2) leaves a water surplus, or water excess, of ~ 442 mm/year. This surplus/excess is accounted for in two ways: by surface runoff (3), and by subsurface infiltration or recharge (4).

Approximately 58% of the water flowing through the Grand River watershed does so as surface water runoff (3). The remaining 42%, recharge, flows through the groundwater system (5, 6 and 7) at a rate of 180 mm/year. The majority of groundwater flow (~82%) eventually re-surfaces within the watershed as flow to surface water features (5, e.g. base flow discharge to streams or ponds), while a small portion (6), discharges to areas outside of the watershed. Groundwater pumping (7) accounts for ~10% of recharge or flow through the groundwater system.

Groundwater storage

Information about groundwater storage is needed to complement a watershed-wide water budget. Without accounting for groundwater storage, we could interpret the above water budget to mean that if there is a low rainfall year, there will be little flow left for baseflow or for water supply pumping. Groundwater storage in the Grand River watershed is very large (>100 billion m^3) in proportion to the renewable water resources (3.3 billion m^3) or annual groundwater pumping (~0.3 billion m^3). This estimate of potable water storage found in the

GRAND RIVER WATERSHED WATER BUDGET COMPONENT	VALUE M^3/S	MM/YEAR
1. Precipitation (P)	200	933
2. Evaporationtranspiration (ET)	105	491
(Surplus, P–ET)	(95)	(442)
3. Runoff (~58% of surplus)	56	262
4. Recharge (~42% of surplus)	39	180
5. Net groundwater discharge to surface water features (~82% of recharge)	33	148
6. Net flow of groundwater from watershed (8%)	2	14
7. Groundwater pumping (10%)	4	18

top ~100 metres below ground indicates that with current groundwater recharge rates (~2 billion m^3 / year), it would take >150 years to replace the storage of potable groundwater in the Grand River watershed.

This example of a water budget is a simple approach to estimate the water resources of a watershed. One can refine these estimates with detailed studies of surface soils and subsurface sediment and rocks. This detailed approach is often used at landfill sites to determine any potential landfill leachate effects on groundwater, and to develop protection measures for municipal water-well fields.

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GROUNDWATER
RESOURCES

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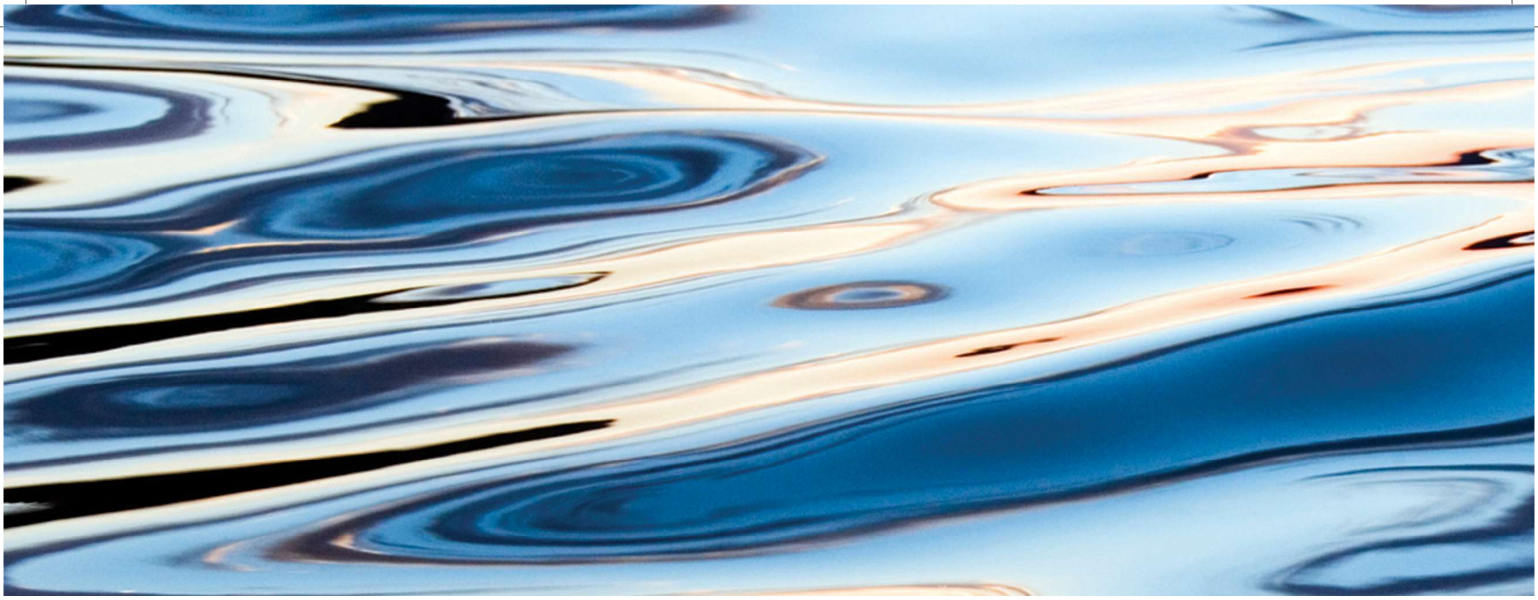
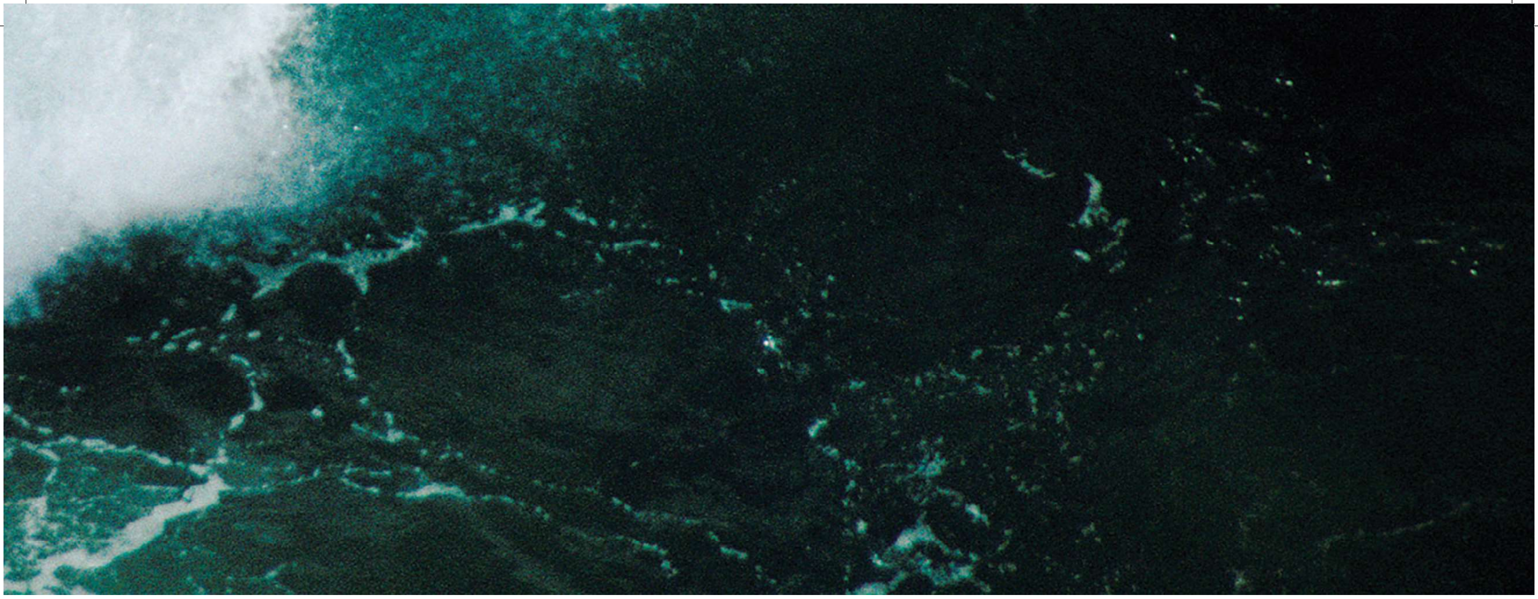


CHAPTER 3 AN APPROACH TO REGIONAL ASSESSMENTS OF GROUNDWATER

CONTENTS



CHAPTER 14 APPALACHIANS 541