Groundwater Science Relevant to the Great Lakes Water Quality Agreement: A Status Report

Groundwater science relevant to the Great Lakes Water Quality Agreement: A status report

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Reviewers of various chapters of the report included representatives of member organizations of the Great Lakes Executive Committee, members of Annex Subcommittees that report to the Great Lakes Executive Committee (notably Annexes 4 and 9), and others. These included, but were not limited to: representatives of EC, Michigan Department of Environmental Quality, and United States Environmental Protection Agency (various chapters); Janet Carter (USGS) (Chapters 1,2,6,8); Ontario Conservation Authority (Chapter 2); Agriculture and Agri-Food Canada, Ontario Ministry of Agriculture, Food and Rural Affairs (Chapters 2, 4); National Oceanic and Atmospheric Administration, Ontario Ministry of Natural Resources and Forestry, United States Army Corps of Engineers (Chapter 7).

Cover photo: Staining of rock face due to groundwater seepage along Superior shoreline: Pictured Rocks National Lakeshore near Munising, Michigan. Photo credit: Craig Blacklock, National Park Service.

This coastal wetland along Lake Huron at Dorcas Bay near Tobermory, Ontario is strongly affected by seepage of groundwater. Photo credit: Martha Allen, Parks Canada Agency.

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1. PURPOSE, SCOPE AND CONTEXT

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The Great Lakes constitute the largest volume of unfrozen freshwater in the Western Hemisphere. Their size and beauty dominate the Great Lakes drainage basin (Great Lakes Basin). These vast visible bodies of water justly draw more attention than the groundwater that lies below the land and water surfaces, even though it has been estimated that the amount of fresh groundwater in the Great Lakes Basin is approximately equal to the amount of water in Lake Huron (Coon and Sheets, 2006). Being underground and "out of sight" is one reason that recognition of the role of groundwater has been less pronounced than surface water. For many years, groundwater science in the Great Lakes Basin was focused on finding drinking water for inland communities, private supplies and irrigation. In the last several decades, however, a larger scientific effort has been devoted to understanding the role of groundwater as part of the overall water budget and ecosystems in the Great Lakes Basin.

Awareness is growing of the strong interaction between surface water and groundwater in the Great Lakes Basin, especially in areas with sandy soils and coarse-grained glacial deposits near the land surface. Much of the water in streams that flows during periods of little or no precipitation is derived from the seepage of groundwater into the surface streams, wetlands, and lakes. This seepage occurs under the surface water bodies and is spread over the length of a streambank or shoreline and goes unnoticed by the casual observer. However, groundwater scientists and ecologists have taken notice and they are quantifying these seepage rates as well as the effects of groundwater on the water quality and temperature of surface water bodies, and on aquatic habitats in these bodies.

Within the last couple of decades, a growing understanding of both the physics and chemistry of the interactions between groundwater and surface water has led to the recognition that a better understanding of how groundwater affects surface water quality is required. This recognition has implications for many of the large water quality issues that confront the Great Lakes. For example, how does the transport of nutrients, pesticides, herbicides, as well as septage from leaking sewers and septic systems that are incorporated into groundwater flowing to surface water affect the quality of water in the Great Lakes as well as the overall Great Lakes ecosystem? The need for answers to this and other groundwater-related questions have both scientists and managers determined to investigate and understand the role of groundwater in the issues confronting the health of the Great Lakes.

1.1 Purpose of this Report

When the Great Lakes Water Quality Agreement (GLWQA) was signed in 1972 by the Governments of Canada and the United States (the "Parties") (Environment Canada, 2013a), groundwater was not recognized as important to the water quality of the Lakes. At that time, groundwater and surface water were still considered as two separate systems, with almost no appreciation for their interaction. When the GLWQA was revised in 1978 (US Environmental Protection Agency (USEPA), 2012), groundwater contamination, such as that reported at legacy industrial sites such as those at Love Canal near the Niagara River, was squarely in the news. Consequently, the potential impacts of contaminated groundwater from such sites on Great Lakes water quality became a concern (Beck, 1979), and Annex 16 was added to the agreement, to address "pollution from contaminated groundwater" (Francis, 1989). However, no formal process for reporting under this annex was provided.

The GLWQA Protocol in 1987 modified Annex 16 and called for progress reports beginning in 1988 (USEPA, 1988). The Protocol in 2012 provided a new Annex 8 to address groundwater more holistically (Environment

Canada, 2013b). Annex 8 (Environment Canada, 2013b) commits the Parties to coordinate groundwater science and management actions; as a first step, to "publish a report on the relevant and available groundwater science" by February 2015 (this report); and to "identify priorities for science activities and actions for groundwater management, protection, and remediation…" The broader mandate of Annex 8 is to (1) "identify groundwater impacts on the chemical, physical and biological integrity of the Waters of the Great Lakes;" (2) "analyze contaminants, including nutrients in groundwater, derived from both point and non-point sources impacting the Waters of the Great Lakes;" (3) "assess information gaps and science needs related to groundwater to protect the quality of the Waters of the Great Lakes;" and (4) "analyze other factors, such as climate change, that individually or cumulatively affect groundwater's impact on the quality of the Waters of the Great Lakes."

A binational Annex 8 Subcommittee was formed to lead efforts to fulfill the mandate of this annex (members listed on p. i of this report). In turn, this subcommittee has recruited a task team to prepare this report (listed as authors of each chapter). This report addresses all of the above four objectives, based on a compilation of the "relevant and available groundwater science." Specifically, the second objective (to "analyze contaminants") is addressed by incorporating information obtained in ongoing monitoring and research activities conducted by the Parties, and by various other members of the Great Lakes Executive Committee.

1.2 Scope

The Annex 8 sub-committee, together with its task team, has prepared this report to focus on the current (2015) understanding of groundwater and its influence on Great Lakes water quality, and on gaps in knowledge to establish science priorities related to groundwater. The report will help meet or support the commitments within Annex 8 (Groundwater) of the 2012 GLWQA (Environment Canada, 2013a), as well as the 2014-2016 Groundwater Binational Priorities for Science and Action that were developed pursuant to Article 5 of the 2012 GLWQA (www.binational.net/2014/03/20/psa-pasa-2014). The report is also intended to complement and support the work of other Subcommittees as they address the commitments of other Annexes of the GLWQA (Environment Canada, 2013a). In this way a holistic strategy for the improvement of water quality in the Great Lakes is promoted, where all components of the water cycle are considered. As a result, the report concentrates on the influence of groundwater on Great Lakes water quality at regional scales and does not focus on groundwater as a source of drinking water (But note that approximately 8 million people in the Great Lakes Basin utilize groundwater as their source of freshwater; the wells drilled for water supply provide important information about groundwater that can be aggregated for regional assessments).

The GLWQA defines "Waters of the Great Lakes" as "the waters of Lakes Superior, Huron, Michigan, Erie and Ontario and the connecting river systems….including all open and nearshore waters" (Environment Canada, 2013b). "Tributary Waters" are defined as "surface waters that flow directly or indirectly into the Waters of the Great Lakes", and the "Great Lakes Basin Ecosystem" is defined as "the interacting components of air, land, water and living organisms, including humans, and all of the streams, rivers, lakes, and other bodies of water, including groundwater, that are in the drainage basin of the Great Lakes…." This report describes how the natural flux of groundwater to the Great Lakes and their tributaries (i.e. streams, lakes and wetlands in the Great Lakes Basin) can enhance both water quality and water quantity and provide essential habitats for the Great Lakes Basin Ecosystem. Therefore, groundwater withdrawals may affect the amount of water in streams, stream temperature, and ecosystem function. This report also describes how groundwater is a transmitter (vector) of contaminants and contributes excessive loads of nutrients to the Great Lakes, recognizing that there are both non-point sources and point sources of the various contaminants and nutrients.

The scope of this report includes cross-cutting issues that relate to other Annexes of the GLWQA. For example, it is anticipated that understanding the effects of groundwater in nearshore regions of the Great Lakes will support efforts to meet the commitment under Annex 2 of the GLWQA to develop an integrated nearshore framework in the Great Lakes by 2016. These nearshore areas provide physical, chemical and ecological links between watersheds of the Great Lakes Basin; streams, wetlands, groundwater and open waters of the lakes; and critical habitat for Great Lakes biota. Nearshore regions are also the places where human use of lake resources is most intense. The nearshore regions receive waste from industrial and municipal sources as well as nutrients, bacteria and other contaminants from urban stormwater, rural runoff and groundwater, and are places where excessive nutrients accumulate and manifest themselves in degraded water quality and nuisance algae growth. The nearshore waters are subjected to development, shoreline alterations, erosion issues and the destruction of natural features such as coastal wetlands, protected embayments and other ecosystems critical to the functioning of the lakes. Currently there are significant gaps in our understanding of the role of groundwater in the nearshore areas.

Chapters 2 through 7 of this report are related to distinct but inter-connected aspects of the nature of groundwater's relationship to water quality of the Great Lakes. Chapter 2 discusses the complexity of interactions between groundwater and surface water and describes how both direct and indirect groundwater discharge to surface water bodies are important considerations when assessing Great Lakes water quality and the health of aquatic ecosystems in the basin. In particular, it has been recognized that large quantities of groundwater enter the Great Lakes (indirectly) via discharge to tributaries that then flow into the Lakes. This chapter focuses on describing: the fundamental types of groundwater/surface water exchange processes for streams, ponds, wetlands and the Great Lakes; groundwater flow paths to surface water bodies; spatial heterogeneity in water exchanges and controlling factors; and the knowledge gaps in the understanding of these interactions.

Chapter 3 focuses on contaminants in groundwater that may reach the Great Lakes. Historically, only major cases of contamination via direct discharge from groundwater were considered. This chapter examines the current understanding of contaminants that are important to the Great Lakes water quality. The chapter describes numerous science and knowledge gaps that indicate needs for better field characterization tools, an improved understanding the importance of the transition zone (between groundwater and surface water) with respect to modifying the quality of discharging groundwater, and more research to quantify impacts of contaminated groundwater discharges on ecological receptors.

Chapter 4 describes nutrients in groundwater and is a key chapter in this report given the current status of eutrophication in parts of the Great Lakes Basin. This chapter is directly relevant to Annex 4 (Nutrients) of the GLWQA (Environment Canada, 2013b). It outlines the transport of both agricultural and non-agricultural sources of nutrients in the groundwater system. The chapter also discusses how nutrients are stored and discharged from groundwater sources.

Chapter 5 presents the effects of groundwater in Great Lakes habitats focusing on the nearshore zone, streams and wetlands in the Great Lakes Basin. This chapter describes the characteristics and groundwater dependencies that are directly relevant to Annex 7 (Habitat and Species) of the GLWQA (Environment Canada, 2013b).

Chapter 6 focuses on an area of emerging concern with respect to Great Lakes water quality; the effects of human infrastructure. Many cities mark the shoreline of the Great Lakes where both aboveground and subsurface engineered infrastructure such as buildings, paved areas, tunnels, sewers and stormwater ponds have affected both the quantity and quality of water that ultimately finds its way into the Great Lakes. Because most of these cities draw their water directly from the Great Lakes, groundwater quality has been for the most part ignored. Human activities nonetheless are intensifying and changing the flow and quality of water in the subsurface in the coastal zones. Population growth statistics indicate a significant increase by 2030 for many of these shoreline cities that is expected to result in additional water quality issues associated with urban infrastructure.

Chapter 7 highlights the current understanding of climate change on groundwater and how those changes potentially affect Great Lakes water quality. This chapter is directly relevant to Annex 9 (Climate Change Impacts) of the GLWQA (Environment Canada, 2013b). Climate change models and projections are examined to identify science needs and monitoring gaps to assist in the understanding of how our evolving climate affects this component of the Great Lakes hydrological system.

The conclusions in Chapter 8 summarize the current understanding of how groundwater affects the Great Lakes water quality. This chapter also summarizes and discusses major areas of science needs, based on priority science needs identified in the earlier chapters.

As discussed in this report, gaps remain in our understanding of groundwater in the Great Lakes Basin, and of its effect on Great Lakes water quality. The purposes of this report are to describe the state of the science, and to identify science gaps, to address the mandate of the GLWQA, particularly Annex 8 of this agreement.

This report includes over 300 references that generally fall into three main categories: (1) those that address groundwater in the Great Lakes Basin directly, (2) those that address aspects of groundwater science that are directly relevant to the focus of this report, (3) those that address other aspects of science, but are relevant to the effects of groundwater on Great Lakes water quality, because of the inter-connected nature of the Great Lakes Basin Ecosystem.

1.3 Context

Groundwater science in the Great Lakes Basin is conducted by various levels of government, by various non-government organizations, and by academic institutions and the private sector. This science supports many objectives, including management of water resources and protection of the environment. A key groundwater science activity in the Great Lakes Basin is the ongoing monitoring of groundwater, including water levels and water quality constituents. These science activities are conducted by various Federal, State and Provincial departments, and local agencies and organizations (Table 1.1).

Groundwater, being out of sight, remains an enigma to many people, including those who rely on it for their water supplies. Accordingly, one of the main goals of this report is to provide water quality managers in the Great Lakes Basin with a concise summary of relevant information about groundwater. Effective water quality policies will incorporate a state-of-the-science understanding of how groundwater is an integral and essential component of the water cycle.

Limitations

The Annex 8 subcommittee has prepared this report through the gracious efforts of a report writing task team with limited resources and short timelines for deliverables. Although these experts are some of the most knowledgeable and respected scientists in their respective areas of specialty, restrictions such as time and editorial decisions regarding audience and length of the report, prevented authors from delving into extensive detail. Additionally, considerable uncertainties in scientific knowledge and data gaps were found. Highlighting these science needs is indeed a key objective of this report.

Table 1.1 General groundwater science activities by different levels of government in the Great Lakes Basin*

Federal Departments in Canada	
Environment Canada	Groundwater as potential source of phosphorus and other nutrients to streams and nearshore areas of the Great Lakes; contaminants of emerging concern in the Great Lakes Basin (active) Estimating base-flow to streams in the Great Lakes Basin; groundwater in Great Lakes beach environments along the Great Lakes; contaminants in shallow groundwater along urban streams (recent)
Natural Resources Canada (Earth Sciences Sector)	3-dimensional geologic mapping, characterization in Southwestern Ontario, in collaboration with Ontario Geological Survey (OGS) (2014-2019) (active) Provided downhole-geophysical surveys and seismic surveys in the Simcoe region to support OGS works (recent)
Agriculture and Agri-Food Canada	No direct groundwater science component – relevant work focuses on quantity (e.g. irrigation, tile drains) and quality (e.g. leaching of nutrients and pesticides, biological contamination) of water leaving the root/soil zone
Federal Departments in the United States	
United States Geological Survey	Glacial Aquifer System Groundwater Availability Study (active) National Water-Quality Assessment Program (NAWQA) conducted two major projects in the Great Lakes Basin; Regional Aquifer Systems Analysis (RASA) Program conducted three major projects that included parts of the Great Lakes Basin; Smaller projects have been conducted in each of the Great Lakes States by USGS Water Science Certers (recent)
United States Environmental Protection Agency	Supports groundwater evaluations using programs such as the Clean Water Act, Safe Drinking Water Act, Underground Injection Control Program, Resources Conservation and Recovery Act, Source Water Protection, and Superfund
United States Department of Agriculture	United States Forest Service provides guidance for permitting use of groundwater on National Forest Service Lands; United States Department of Agriculture uses Cooperative Research and Extension Services to assist farmers with groundwater issues especially related to irrigation and contamination
Provincial Departments in Canada	
Ontario Ministry of the Environment (MOECC)	Improve understanding of relationships between groundwater and surface water, and the role of groundwater in sustaining Great Lakes water levels and tributary water flows; integrated surface and groundwater modeling in water stressed areas for source protection; enhancement of Provincial Groundwater Monitoring Network (PGMN) to include precipitation, evapotranspiration and soil moisture monitoring (active) Characterization of groundwater on a watershed basis for source protection. Determination of recharge areas and vulnerable aquifers. Groundwater modeling for determining wellhead protection areas for all municipalities using groundwater (recent)
Ontario Ministry of Natural Resources and Forestry	Enhancement of drought monitoring by working with MOECC and Ontario Ministry of Agriculture by including soil moisture at PGMN sites;some groundwater indicators for coastal wetlands under Ontario Wetland Evaluation System (active) Development and implementation of a groundwater drought indicator (recent)
Ontario Ministry of Northern Development & Mines - Ontario Geological Survey (OGS) Branch	OGS Groundwater Geoscience Initiative:ambient groundwater chemistry; 3-dimensional sediment mapping; 3-dimensional Paleozoic bedrock mapping (active) Regional Paleozoic bedrock mapping including karst mapping, sequence stratigraphy, bedrock aquifer mapping; Regional Quaternary mapping including surficial and subsurface mapping; bedrock topography; drift thickness, geophysical surveying (regional seismic reflection, ground gravity, airborne magnetics and electromagnetics, ground penetrating radar and down-hole geophysics) (recent)
State Agencies in the United States	
Departments of Natural Resources and Environmental Quality in the eight Great Lakes States	Maintain databases of well logs from domestic, irrigation, and industrial wells. Conduct site-specific studies of groundwater contamination including research on groundwater conditions. Collect groundwater withdrawal data and evaluate the effects of groundwater withdrawals as part of the Great Lakes Compact. Support county health departments with well permits.
Local governments and agencies in Canada	
Municipalities	Focus on municipal groundwater supplies, well head protection studies, monitoring of raw water, sentry well monitoring and water budget studies for sustainability of supplies, studies on water quality
Conservation Authorities	Studies of development impacts on groundwater- dependent fisheries, habitats; operational support for Provincial Groundwater Monitoring Network (ON); watershed studies to assist municipal source water protection; stream baseflow studies; developing indicators for direct groundwater discharges into Lake Ontario; guidance for seasonal in-stream flow needs and water quality for municipal water management ; water infrastructure vulnerability assessments
Local governments and agencies in the United States	
County Health Departments	Oversee permits to drill wells and conduct water-quality testing of those wells. Maintain data on wells in cooperation with State DNR or DEQ.
Municipal Governments	Communities that use groundwater for drinking water supply maintain water-level and water-quality data and conduct studies of the effects of groundwater withdrawals on aquifers.

2. GROUNDWATER/SURFACE WATER INTERACTION

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2.1 Introduction

In recent years, the role of groundwater as an integral component of the Great Lakes Basin Ecosystem has been increasingly recognized. Currently, the role of groundwater is understood to go well beyond the very limited perception of the past, where groundwater was considered relevant only in matters related to drinking water for inland communities, private water supplies, industrial supply or irrigation. Groundwater and surface water dominated systems are interconnected and should be treated as a single system and resource (Winter et al., 1998). In recent years, groundwater has been increasingly recognized as being important in the water budget of the Great Lakes as well as for its role in maintaining the chemical, physical, and biological integrity of the aquatic ecosystems of the Great Lakes Basin (Box A lists the services and values provided by groundwater/surface water exchanges). Direct and indirect discharges of groundwater to the Great Lakes are estimated to account for as much as 2.7% and 42% (respectively) of the inflows to the Great Lakes (Neff and Nicholas 2005) and for an average of 70 % of the flow of streams and rivers in the Great Lakes Basin (Neff et al., 2005). Moreover, the total volume of groundwater stored in the aquifers on the U.S. side of the Great Lakes Basin is 984 cubic miles (4100 cubic kilometers), equivalent to the volume of surface water stored in Lake Huron (Coon and Sheets, 2006) or about 25% of the volume of surface water stored in the Great Lakes, meaning that groundwater in the basin could be considered to be the equivalent of another Great Lake.

The exchange of water between groundwater and surface water systems occurs through transition zones between groundwater and surface water. These transitions zones are areas and volumes of streambeds, lakebeds, wetlands and adjacent geological materials where the characteristics change from a groundwater dominated system to a surface water dominated system and the conditions in these zones are dynamic. The flow of water through transition zones is complex and difficult to characterize. This chapter focuses on the physical processes that control the pathways of groundwater flow and the quantities of groundwater exchanging with surface water bodies. These processes are collectively referred to as groundwater/surface water exchanges. Groundwater also serves as an important transport mechanism that delivers water, nutrients, and contaminants to surface water. It is becoming more evident that the physical interaction and exchange of waters having different chemical and thermal characteristics which occurs in the transition zone is critical in determining the quality of the water discharging in to surface waters (e.g., Conant et al. 2004; Environment Agency 2009). This chapter examines issues of water flow, quantity, and to a lesser extent quality (quality issues are addressed in Chapters 3, 4, and 6), and concludes with a summary of the information gaps and science needs relative to improving our understanding of groundwater/surface water exchanges and their effects on the Great Lakes Basin.

2.2 Groundwater/Surface Water Exchanges – Types, Pathways, Variability and Complexity

The interaction between groundwater and surface water in the Great Lakes Basin occurs through numerous pathways (Figure 2.1) and, in general, groundwater flows toward and will eventually discharge into surface water bodies if not extracted. The types of exchange between groundwater and surface water are governed by the relative hydraulic head of the groundwater relative to the surface water level, and the ability of the subsurface geological materials of the system to transmit water (i.e., its hydraulic conductivity). The hydraulic conductivity of bedrock across the Great Lakes Basin ranges from very low (e.g., granite, gneiss and shale; Freeze and Cherry, 1979) to very high (e.g., sandstone and carbonate aquifers; Freeze and Cherry, 1979) (Figure 2.2). The flow of groundwater within the geological deposits and into or through the transition zone can be accelerated by fractures or karst features in bedrock units. Figure 2.3 shows the variability of the surficial (unconsolidated) deposits overlying the bedrock in the Great Lakes Basin. These deposits play a significant role in controlling the nature of groundwater/surface water exchanges and affect how much and where groundwater is recharged by precipitation. Water supply wells for municipal, domestic, industrial and agricultural needs in the Great Lakes Basin have been completed in both bedrock and surficial aquifers. Exchanges can occur between groundwater (e.g., water stored in aquifers, confining units, fractures and perched water) and a Great Lake and any other surface water body such as streams, ponds, lakes and wetlands. Examples of these exchanges include shallow and deep groundwater discharge to lakes, ponds and wetlands; base-flow contributions to streamflow; interflow (shallow subsurface flow) and bank storage in streams that occur after precipitation events; and situations where surface water recharges underlying geological deposits. From a water quantity viewpoint, groundwater is important in maintaining streamflow and inland lake levels, especially during droughts when contributions from precipitation are low and losses of water by evapotranspiration are high.

BOX A – Services and values provided by groundwater/surface water exchanges
(particularly important in times of drought)

- Maintain base-flows in rivers and streams
- Maintain surface water levels and moderate fluctuations in water levels in lakes and ponds
- Supply water and maintain saturated conditions for certain kinds of wetlands
- Moderate surface water temperatures and provide suitable fish habitat (e.g., cold water fisheries) and fish spawning areas and proper egg incubation temperatures
- Create areas of streams, ponds, and lakes that are critical habitat for fish because they serve as thermal refuges by being cool areas during high summer temperatures and relatively warm ice-free (open water) areas during winter.
- Affect the growth and distribution of macrophytes and other vegetation in surface water
- Provide preferential habitat and conditions for benthic aquatic life and hyporheos and enhances biodiversity
- Contain the transition zones, which includes hyporheic zones, which buffer the changes in the quantity and quality of water entering surface water bodies
- Provide water purification, maintain ecosystem health, mitigate erosion and floods, provide source of nutrients

Groundwater/surface water exchanges are complex and show significant spatial and temporal variability. Spatial variability on scales ranging from centimeters to tens of kilometers has been demonstrated in numerous studies. At a regional or basin scale, groundwater flow and discharge to surface water (e.g., stream base-flow) are primarily controlled by variations in topography, stream slopes, and underlying geology (Neff et al. 2005; Winter 1999). Estimates of base-flow contribution to stream discharge range between 9 to 98% (Neff et al, 2005). Their general areal distribution is shown on Figure 2.4. At the scale of a single stream reach, groundwater discharge is observed to vary along the reach as a function of the sediment composition, streambed topography, meandering patterns, presence of fine grained organic matter, and stream stage relative to the groundwater table and these factors can either enhance or inhibit the discharge (e.g., Larkin and Sharp, 1992; Boulton et al., 1998; Conant, 2004; Smith 2005; Environment Agency, 2009; Cardenas 2008). Streams are observed to have gaining, losing, flow-through, and parallel flow (i.e., zero-exchange) sections which can exist in complex patterns (Figure 2.5) and also vary in time (Woessner, 2000). At this scale and down to scales of centimeters, water in flowing streams can also have complex patterns of exchange with groundwater as shown in Figure 2.6.

Stream water can penetrate into the sediments, move laterally through streambed sediments, potentially mix with groundwater, and then re-enter the stream farther downstream. The area where this type of flow occurs is called the hyporheic zone and is part of the transition zone that exists in and adjacent to the streambed (see Figure 2.6). The hyporheic zone is highly variable and heterogeneous and is a unique hydrological, biological, and geochemical zone that has the potential to attenuate groundwater contaminants and naturally occurring chemicals that enter it (Chapter 3).

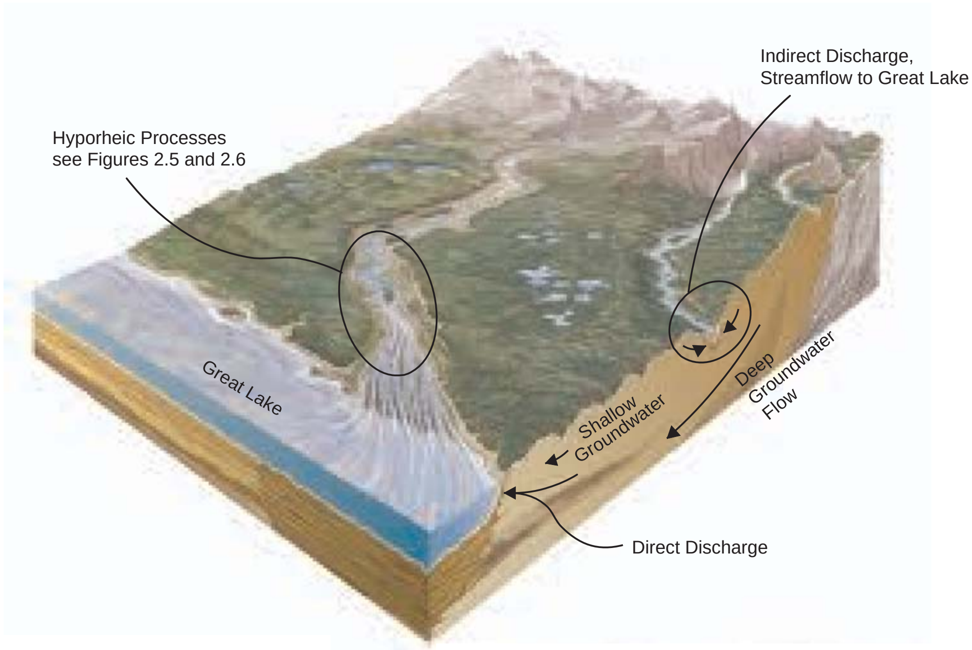

Figure 2.1. Schematic diagram showing a variety of different groundwater/surface water exchanges present in the Great Lakes Basin.

Figure 2.2. Map of upper bedrock units including aquifers in the Great Lakes Basin (from Grannemann et al. 2000).

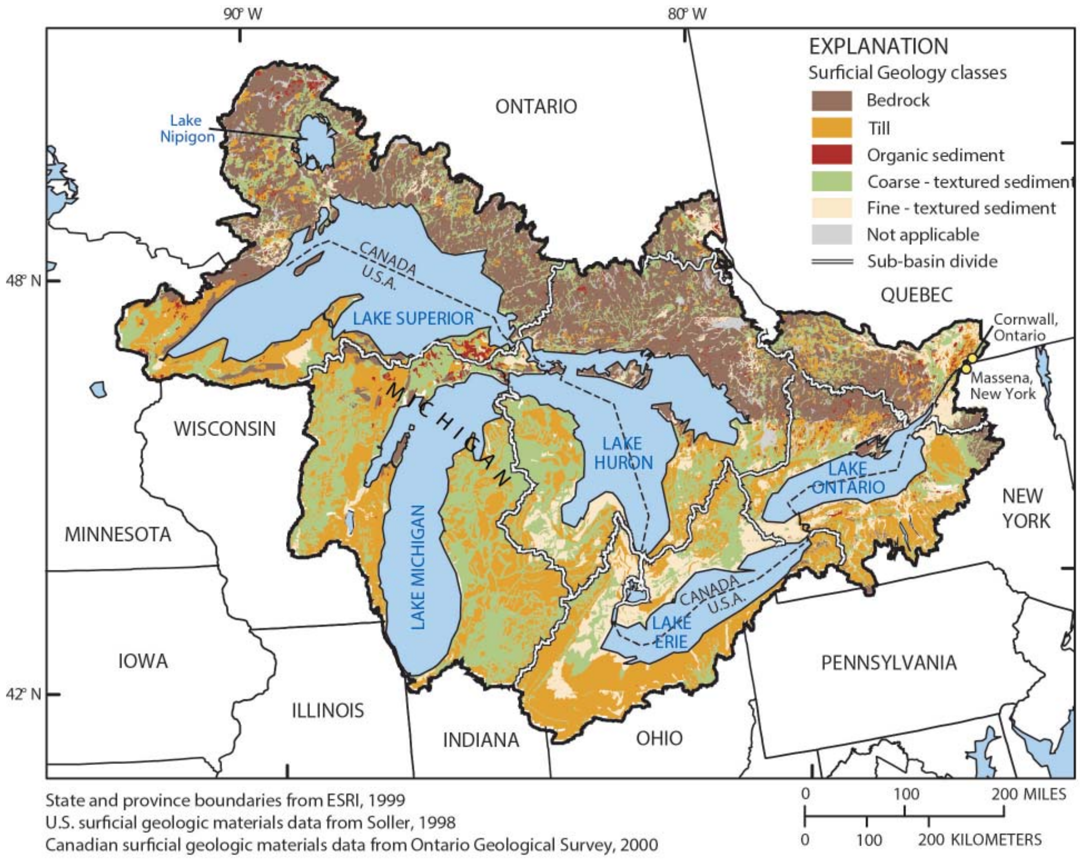

Figure 2.3. Map of the surficial geology in the Great Lakes Basin (from Neff et al., 2006).

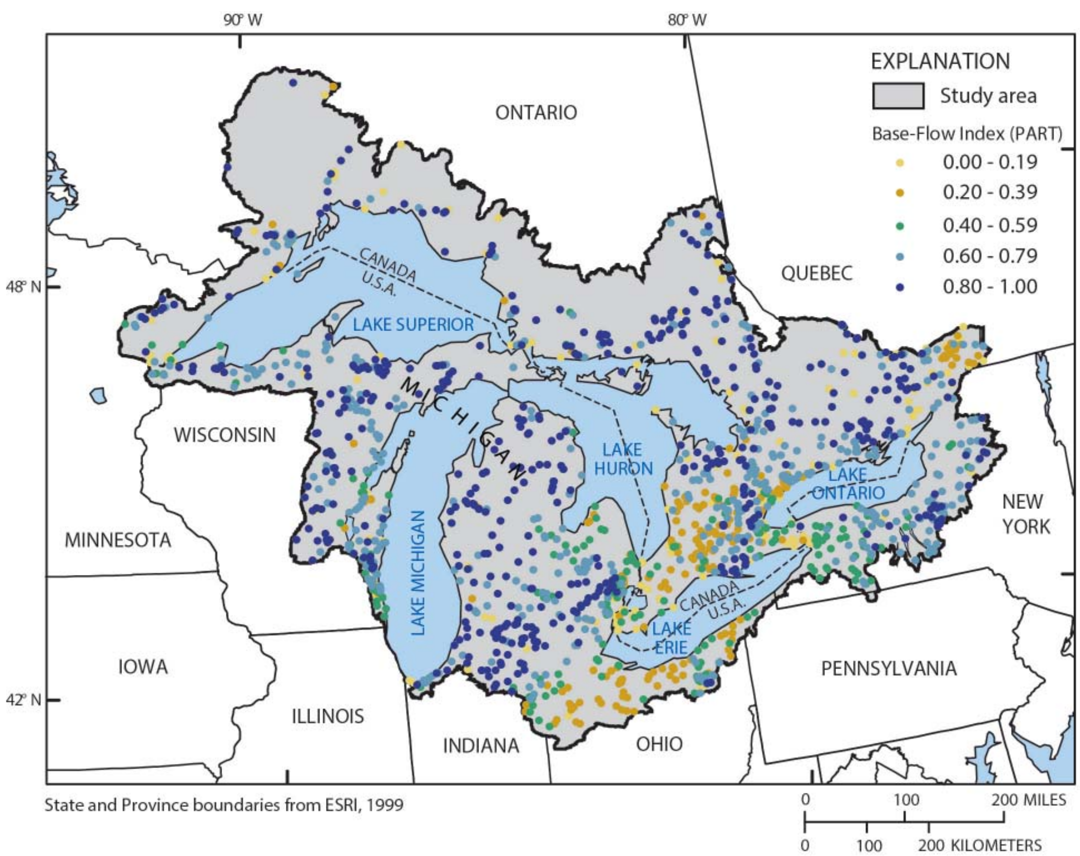

Figure 2.4. Map showing percentage of base-flow contributing to annual stream and river flows in the Great Lakes Basin (from Neff et al., 2005). A Base-Flow Index value of 1.00 means 100% of the streamflow is frombase-flow, most of which is typically derived from groundwater discharge.

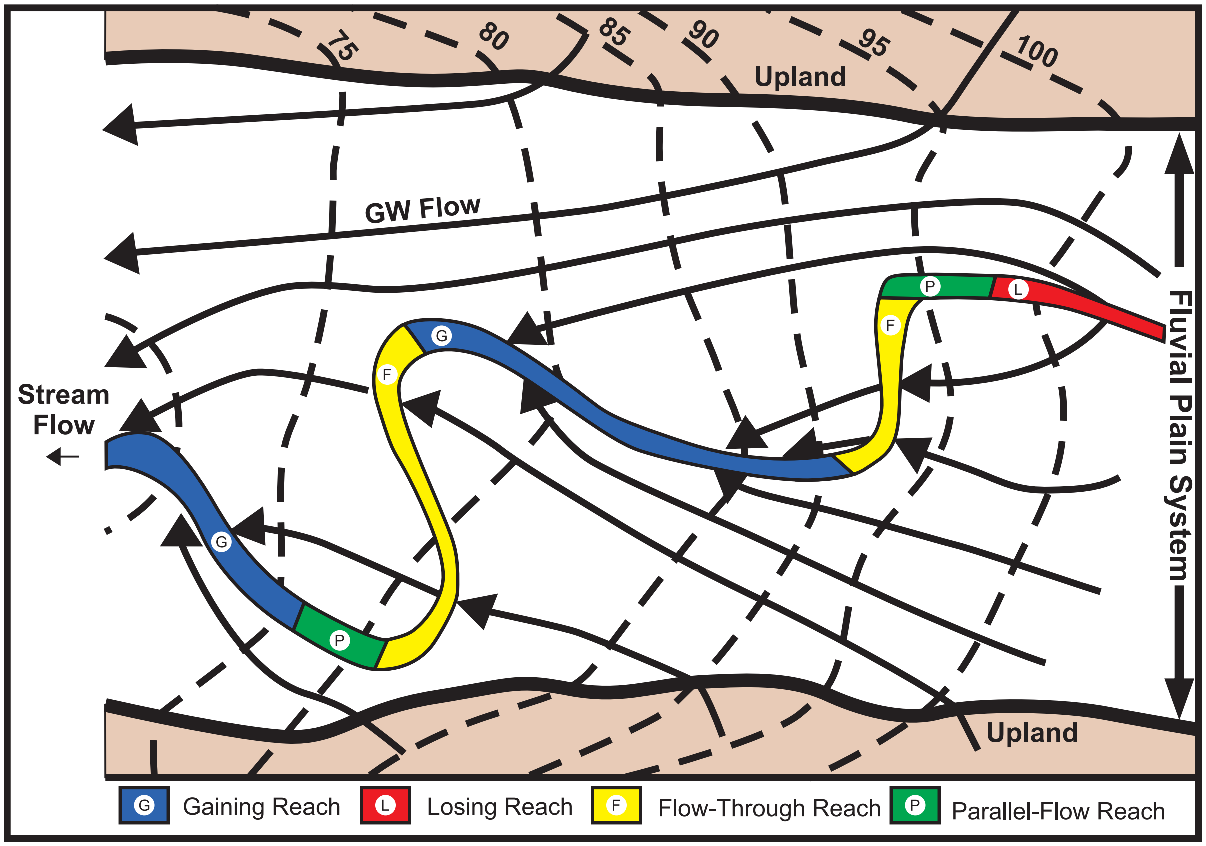

Figure 2.5. Plan-view schematic map showing gaining, losing, flow through and parallel flow (i.e., zero exchange) sections along a stream. Dashed lines show elevations of the water table and arrows show flowpaths and directions of groundwater flow (modified from Woessner 2000).

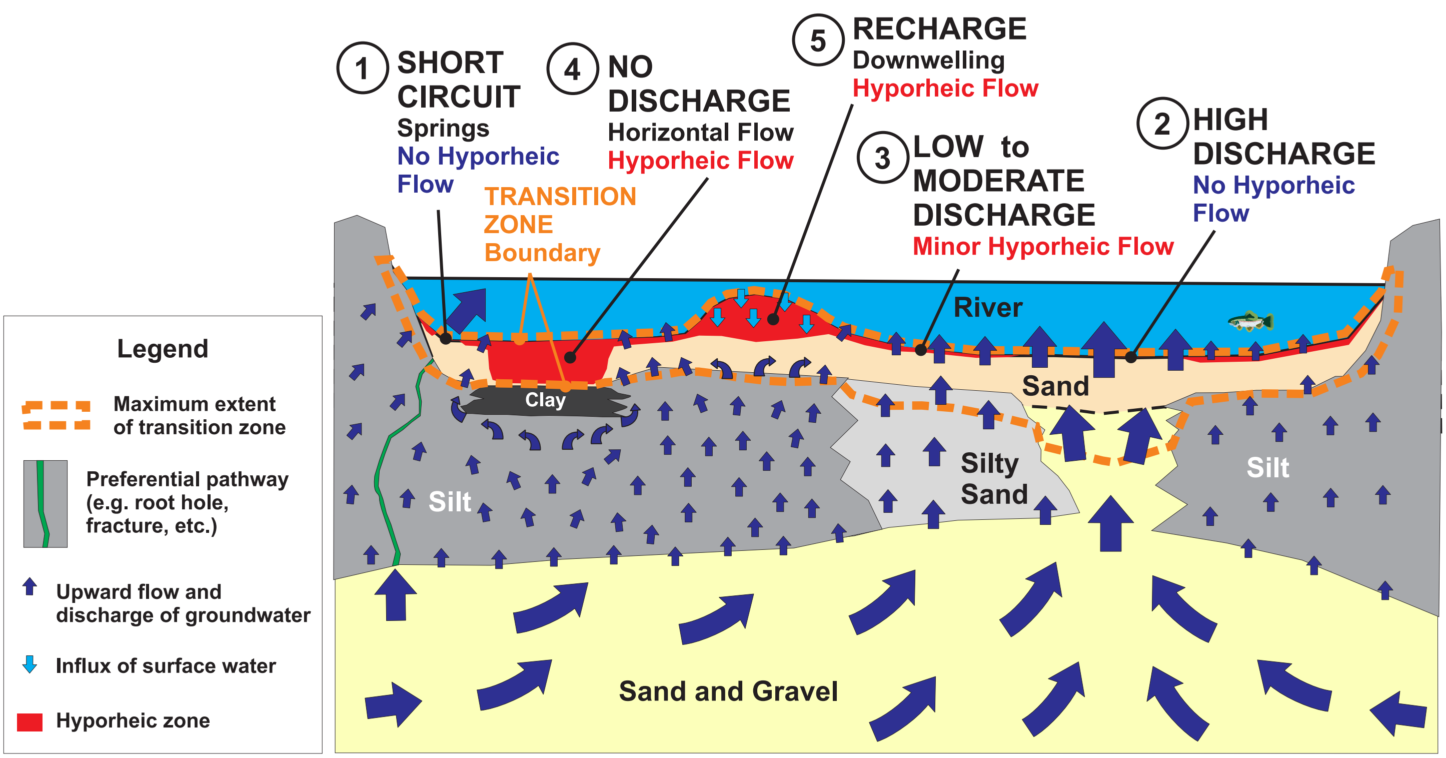

Figure 2.6. Schematic cross-section of a riverbed showing the extent and variability of groundwater/surface water exchanges including hyporheic flow and extent of the transition zone (modified from Conant 2014).

Although such small scale flowpaths and exchanges may not be considered important from a purely water quantity or water budget perspective (i.e., overall gain or loss of streamflow), processes in the hyporheic zone and other transition zones can be critical in determining the quality of water entering the stream and for creating habitats suitable for certain types of aquatic life. Lakes, ponds and wetlands can also have gaining, losing, and zero exchange areas, but are often flow through systems where groundwater discharges up into one part of the pond and surface water leaves the pond in another area to recharge the underlying groundwater (Winter, 1999). Hyporheic zones do not occur in lakebeds or wetlands (due to generally low flow rates); however, complex exchanges can occur beneath lakes and wetlands and within their transition zones. One type of groundwater/surface water exchange that occurs along shorelines in lakes happens in the swash zone as a result of wave run-up onshore, particularly during storm surges or seiches. Water coming on shore as wave run-up can infiltrate into the beach and result in water mounding beneath the swash zone and then flow back to the lake while also mixing with some underlying groundwater (Crowe and Meek, 2009).

Groundwater/surface water exchanges can vary temporally in response to both long and short duration changes. The most prominent long-term variations occur as a result of seasonal changes in precipitation and evapotranspiration that affect groundwater and surface water levels, although various studies indicate that inter-annual variability and variability associated with longer climatic cycles also occur (Coulibaly and Burn, 2005; Dolan and Chapra, 2012). The exchanges can also vary on shorter time frames. For example, immediately after a storm event, streamflows and stream stages can increase more rapidly than adjacent groundwater levels thereby greatly reducing the fraction of groundwater contributing to streamflow relative to conditions during months with low precipitation and few storm events. At peak streamflows the changes in stream stage can cause surface water to move into adjacent streambanks as bank storage (i.e., temporarily changing streams from gaining to losing), then that water can subsequently discharge back to the stream when the stage declines. These changes can result in short duration (e.g., hourly or daily) wide spread reversals in hydraulic gradients, at times converting surface water into groundwater (bank storage), and at times the reverse, when groundwater (stored in the bank) discharges to surface water. Similar types of reversals can occur along the edges of lakes where storm winds can cause short duration changes in surface water levels (i.e., wind driven pile up of water and seiches) relative to adjacent groundwater levels. These variations are important when considering the transport of contaminants or nutrients by groundwater or the role of groundwater in maintaining habitats and moderating stream temperatures.

2.3 Quantities of Direct and Indirect Groundwater Discharge to the Lakes

Groundwater can enter the Great Lakes as direct discharge and indirect discharge. The connection between groundwater and a Great Lake is considered to be direct when water flows into the Great Lakes through the lakebed and is considered indirect when groundwater is discharged into tributary waters (secondary lakes, streams, or wetlands) that then eventually flow into the Great Lakes. A few attempts have been made to quantify direct inflows into the Great Lakes using methods such as direct field measurements, calculating water balances, and numerical modeling (reviews of prior work provided in Coulibaly and Kornelsen, 2013; Conant, 2014); however, each method is subject to considerable uncertainty (e.g., Neff and Nicholas, 2005; Coon and Sheets, 2006; Reeves, 2010). The water balance estimates of direct groundwater discharges to Lake Superior, Lake Huron, Lake Ontario, and Lake Erie, range from about 0.1% to 2.7% of the total inflows (Neff and Nicholas, 2005) but rely on assumed values of shoreline groundwater discharge. Lake Michigan is the only lake for which a numerical groundwater flow model was developed at the whole drainage basin scale. This model estimated 1.1% of the total inflow for the lake was from direct discharge (Feinstein et al, 2010). By comparison, indirect discharges via tributary streams provide a greater groundwater contribution than direct discharge to the Great Lakes. Holtschlag and Nicholas (1998) estimated that indirect contributions to the Great Lake water ranged between 22% and 42% of the total input components for each lake (i.e., over lake precipitation, surface water runoff, and indirect groundwater discharge). However, there is considerable uncertainty associated with these estimates because they were extrapolated from a relatively small number of streams in the United States portion of the Great Lakes Basin.

Direct groundwater discharge to the Great Lake can occur through shallow or deep flowpaths. The shallow flowpaths correspond to shallow geological units, including both aquifer and non-aquifer deposits. These shallow flowpaths are local in scale and more likely to have been impacted by contaminants than deep flowpaths (Chapter 3). In contrast, the deep flowpaths are associated with deep geological units, including regional bedrock aquifers, which underlie relatively large areas, and might contain older water predating any impact by contaminants. However, water from deep flowpaths also might contain higher concentrations of dissolved solids or even be salty brines depending on the geological materials through which the water has flowed (e.g., Kolak et al. 1999; Hoaglund et al. 2004; Ruberg et al. 2005). Discharge to lakes of shallow groundwater tends to be focused in nearshore areas, and generally decreases in magnitude exponentially with distance from the shore (McBride and Pfannkuch, 1975; Lee 1977) although spatial heterogeneity and exceptions to this pattern has been observed in the Great Lakes by Cherkauer and Nader (1989) and Harvey et al. (1997a, 1997b). In general, deep groundwater fluxes are anticipated to be small compared to fluxes of shallow flowpath groundwater. Consequently, the assessment of the effect of groundwater in nearshore areas is of greater importance as part of the effort to restore and protect these critical zones. Groundwater/surface water exchanges in nearshore areas are controlled by the geological materials constituting the shallow aquifer, the nature of the sediments on the lake bottom and by processes such as wave action, wind driven water level effects and evapotranspiration effects. For example, groundwater will preferentially discharge through unconsolidated glaciofluvial sand and gravel aquifers rather than through the underlying low hydraulic conductivity bedrock or adjacent clayey unconsolidated materials. At a smaller scale, sand lenses can also create preferential flowpaths. Similarly, coarser sediment deposits on the lakebed in the nearshore area will promote groundwater/surface water exchanges compared to finer grained silt and clay sediments that are normally found in in the deeper parts of the lakes.

2.4 Groundwater Discharge in Great Lakes Basin – Relation to Water Quality

The flow and transport of quantities of groundwater to surface water will inherently have an effect on surface water quality. The transported water may be relatively pristine and likely improve surface water quality, or it may be contaminated (e.g., road salt, nutrients, industrial compounds, dissolved metals, petroleum hydrocarbons, and pharmaceuticals and other emerging contaminants) and adversely affect the surface water quality (see Chapters 3, 4 and 6 for a detailed discussion of contaminated groundwater discharges). In some cases the concentration of the discharging groundwater is the main concern; in other cases the total mass loading of substances from groundwater is the problem. In each case, it is necessary to know the quantity and flowpaths of the discharging water to evaluate the effects on the receiving body of water. In particular, characterizing groundwater/surface water interactions and how water passes through the transition zones is the key to understanding how to protect and manage aquatic ecosystems.

In terms of water quality, groundwater plays key roles in moderating surface water temperatures to provide suitable habitats (Chapter 5), in moderating pH in surface waters, or providing nutrients that affect the growth and distribution of macrophytes and other aquatic vegetation (Chapter 5). Finally differential discharge patterns can provide preferential habitat and conditions necessary for benthic and hyporheic aquatic life and enhances biodiversity. The role that groundwater plays in shaping the quantity, quality, and type of habitats in the Great Lakes Basin is discussed in detail in Chapter 5.

2.5 Human Effects on Groundwater/Surface Water Exchanges in the Great Lakes Basin

Human activities can affect the groundwater/surface water system in several ways including:

- groundwater pumping that intercepts/diverts groundwater flow from reaching surface water;
- groundwater withdrawals that induce infiltration and capture of water directly from surface water bodies (see following paragraph);
- urbanization and land use changes that alter groundwater recharge rates and runoff into surface water bodies (see Chapter 6), which could include development urban or other large or extensive infrastructures such as dams, reservoirs, storm water retention ponds, tile drains, and sewer lines;
- Point source and non-point source contamination of groundwater that eventually discharges to surface water where aquatic life and human exposures will occur (see Chapters 3 and 4).

In addition to these human activities, climate change can alter the occurrence, frequency and amount of precipitation; amount of recharge to groundwater; and intensity of surface water runoff (see Chapter 7).

Pumping of groundwater is an issue because it can reduce the amount of groundwater that would otherwise discharge to surface water and thereby adversely affect ecological habitats in surface water bodies. Pumping can significantly draw down groundwater levels, reverse the direction of flow between surface water and groundwater, induce infiltration of surface water into the groundwater, and change the locations of groundwater divides. This reversal of flow can change areas of streams, lakes, or wetlands from gaining areas to losing areas (Winter et al. 1998; Granneman et al. 2000, Reeves, 2010). Overall reductions in the flux of groundwater to surface water bodies will potentially cause these bodies to have lower water levels (or even dry up), and potentially reduce the positive role of groundwater in surface water quality (e.g., lessen beneficial thermal effects of discharging groundwater on habitats). Induced infiltration will alter the geochemical environment in the streambed, which may result in adverse effects on the quality of surface water captured by the pumping wells, which then may become unsuitable for drinking without additional treatment.

As discussed in Chapters 6 and 7, urbanization and climate change both have the potential to affect recharge rates from precipitation which can then affect surface water and habitats. Impervious surfaces in urban areas and very intense rainfalls from more frequent extreme events caused by climate change will increase surface water runoff into drainage ditches and surface water bodies and cause detrimental effects such as flash floods with high volume and velocity flows that increase erosion and damage habitats. Leaking sewers and water systems may add water to the shallow groundwater system (Chapter 6).

Both the quantity and quality of groundwater play roles in maintaining healthy surface water systems. With respect to ecosystems, one could argue that quantity is more important than quality because a reduction in quantity can result in complete loss of habitat. Without groundwater discharge, many streams, lakes, and wetlands could potentially dry out during the year because contributions of water from other sources such as direct precipitation, overland flow, interflow, and return flow, are too short lived or of insufficient quantities to offset losses from evapotranspiration, outflows, and human withdrawals. Without suitable habitat, the quality of the water is no longer relevant because life can no longer be sustained in these areas without water. However, if the groundwater discharging to surface water is contaminated or of poor quality, it can result in toxic effects, anoxic conditions, eutrophication and algal blooms that also will make it unsuitable for aquatic life and human use (see Chapter 3, 4 and 5). Ultimately, both groundwater quantity and quality must be properly managed to ensure healthy aquatic ecosystems in the Great Lakes Basin.

2.6 Priority Science Needs

There are many challenges to understanding the role of groundwater/surface water interaction in the Great Lakes Basin, and the groundwater effects on the chemical, physical and biological integrity of the waters of the Great Lakes. These effects are functions not only of the quantity of groundwater flow, but the concentration of substances in that water, the total mass loading of a substance via groundwater, the nature of the receiving water body (i.e., stream, river, pond, lake, or wetland), and the presence of ecological and human receptors.

Much is still not known with respect to the role of groundwater – surface water exchanges in determining the health of the surface waters of the Great Lakes Basin. Some of these unknowns are related to understanding fundamental processes controlling these exchanges whereas others are more related to characterizing the systems in sufficient detail to determine exactly what is happening and where. Assessing the effect of groundwater on the chemical, physical and biological integrity of the Great Lakes Basin is further complicated by the wide variety of different types of surface water bodies in the Great Lakes Basin and the possible interactions that can occur in each one. All these issues and challenges related to groundwater/surface water exchanges can be grouped into the following five priority science needs. Additional details in terms of related science needs and information gaps are provided in Table 2.1.

i) Tools are needed to appropriately characterize spatial heterogeneity and temporal variability in groundwater/surface water exchanges.

Technologies and methodologies currently do not exist to collect the data necessary on the fine scales needed to characterize the spatial and temporal variability that is known to exist over large areas. There is also a need for methods to evaluate, scale-up, and model these local scale variations in these exchanges to predict more regional scale effects in the Great Lakes Basin.

ii) Accurate quantification of groundwater discharges to surface water is needed.

The estimates of direct groundwater discharge to each of the Great Lakes are poorly known and have considerable uncertainty. More accurate water balances and field measurements are needed to determine groundwater contributions for the Great Lakes, lakes and ponds, and wetlands in order to assess relative importance of groundwater sources to each.

iii) The identification of significant groundwater flowpaths to surface water and delineation of groundwater discharge zones are needed.

Until groundwater flowpaths and discharge zones can be properly mapped, one will not be able to accurately characterize exposures and evaluate the effect of contaminated water or nutrients on aquatic life (particularly for exposures within the transition zone).

iv) Critical relationships between alterations in groundwater discharge and the negative effects on aquatic ecosystem health need to be determined.

Studies indicate that the transition zone is a valuable part the ecosystem and groundwater discharges are known to provide thermal refuges and spawning habitat for various kinds of fish and aquatic life. However, it is not known to what extent groundwater discharges can be altered or reduced by pumping or natural factors before adversely affecting the biota in the transition zone and overlying surface water.

v.) Characterization and understanding of the role of transition zone processes on the quality of surface water are needed.

The transition zone is a dynamic and active biogeochemical zone that has the ability alter the quality of the groundwater passing through this zone (i.e., attenuate some contaminants and nutrients).
Therefore, it will be very difficult determine the effect of groundwater quality on surface water because the groundwater quality can be significantly altered just prior to discharging into the surface water body.

Most of the science needs and knowledge gaps pertaining to groundwater/surface water exchanges are related to resolving the small scale complexities and heterogeneities that are known to be important and then scaling them up to characterize the potential or actual effects on the wide variety of different surface water bodies in the Great Lakes Basin. Having a good understanding of the wide variety of different types of exchanges is necessary for making informed and science based management decisions with respect to groundwater in the Great Lakes Basin.

Table 2.1 Priority science needs related to groundwater/surface water interaction.

Priority science needs	Related needs and information gaps
2A. Appropriately characterize spatial heterogeneity and temporal variability in groundwater/surface water exchanges	• Need to incorporate local heterogeneity, local groundwater flow and transition zone dynamics in models at a basin scale. • Need to determine under what circumstances small scale hydrological and biogeochemical processes in the transition zone need to be incorporated into larger scale watershed models to accurately predict effects. • Need to develop better reconnaissance methods to rapidly and inexpensively detect groundwater discharges to surface water, particularly for areas of contaminated groundwater. • Field data are insufficient to populate groundwater –surface water flow models to obtain accurate estimates of water and contaminant fluxes on the scale of variability known to exist in the basins.
2B. Accurately quantify groundwater discharges to surface water	• Understand the effects of human development, land-use, and land-cover change on the quantity and quality of groundwater that discharges to the Great Lakes. • Develop techniques to easily and directly measure and quantify deep groundwater discharges to the Great Lakes and to assess the relative importance of long residence time groundwater. • Improve techniques to accurately measure individual components of the water balance (e.g., evapotranspiration overland flow, interflow) to reduce uncertainty in estimates of direct groundwater discharge to surface waters of the Great Lakes. • The total amount of direct groundwater discharge to each Great Lake is not known (modeling of Lake Michigan has provided some estimates). • Many tributaries of the Great Lakes are ungauged and not monitored; thus, quantity and quality of base-flows of streams and rivers are not known which limits ability to accurately estimate groundwater base-flows, contaminant loadings, and indirect groundwater discharge to the Great Lakes.
2C. Identify significant groundwater flowpaths to surface water and delineate groundwater discharge zones	• Need to re-evaluate current conceptual models regarding flowpaths and hydrological processes at the Great Lake Basin scale and their ability to accurately assess effects of non-point source and point source groundwater contamination impacts. • Comprehensive and consistent mapping and delineation of groundwater flow systems that directly discharge groundwater to the Great Lakes needs to be performed. • Detailed and high resolution field studies that quantify and delineate near shore groundwater discharge to the Great Lakes are lacking. • Additional and comprehensive investigation and monitoring of groundwater discharge zones and flowpaths are necessary to identify areas of high and preferential groundwater discharge to surface water bodies (streams, rivers, lakes and wetlands). • For most groundwater flow systems, the relative importance of shallow and deep flow systems in contributing discharge to surface water bodies is unknown. In general, shallow groundwater will likely be more contaminated than deep groundwater.
2D. Determine critical relationships between groundwater discharge and aquatic ecosystem health	• Improve understanding of minimum and threshold amounts of groundwater flow required to sustain and support local ecosystems in different surface water environments. • Improve understanding of contaminant fate and transport processes in groundwater and the transition zone, and assess the ecological effects of groundwater discharges. • Information is lacking regarding where habitats are in relation to groundwater discharge and contaminated groundwater discharge and regarding what are the critical times with respect to aquatic life exposures. • Mapping and correlation analysis of ecosystem and aquatic life distributions relative to groundwater discharge/recharge zones is needed.
2E. Characterize and understand the role of transition zone processes on the quality of surface water	• Develop evaluation techniques that can separate the effects of groundwater discharges on surface water from the effects of dilution and mixing with surface water contaminated by other sources. • Understand the role of hyporheic transient storage with respect to attenuating groundwater contaminants migrating downstream from their discharge points in rivers and streams. Determine to what extent transition zones will attenuate groundwater contaminant plumes prior to discharging into surface water.

3. GROUNDWATER AND CONTAMINANTS IN THE GREAT LAKES BASIN

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3.1 Introduction

The focus of this chapter is on the direct transport of contaminants (substances released to the environment by human activities, see glossary) in groundwater to wetlands, streams, rivers, and lakes of the Great Lakes Basin, according to the pathways outlined in Chapter 2 (Figure 2.1). This topic was the impetus for the addition of Annex 16 to the GLWQA in 1978. The risk posed by groundwater contaminants to the associated ecosystems of these surface waters depends on: i) the extent and distribution of contaminant sources, ii) the fate and ease of transport of the contaminants (and their degradation products) as they pass into and through the subsurface and to aquatic ecosystem receptors, and iii) the toxicity or harmfulness of the contaminants (including degradation products), or other deleterious changes (e.g., oxygen depletion with contaminant biodegradation) to the ecosystem conditions caused by the groundwater contaminants. Water quality and ecosystems of the Great Lakes themselves may be affected both by direct discharge through lakebeds and through transfer of contaminants via groundwater discharges to tributaries and connecting water bodies (Chapter 2).

Groundwater/surface water exchanges can also have positive effects on the quality of surface waters in the Great Lakes Basin. For instance, uncontaminated groundwater inputs can reduce the concentrations of contaminated surface water through dilution. In such cases, groundwater discharge zones may be considered as areas of contaminant refuges for aquatic life. In addition, contaminated surface water that enters streambeds and lakebeds (i.e., in hyporheic zones and groundwater recharge zones) and then later returns to the same or a nearby surface water body may have reduced contaminant loads due to attenuation in the subsurface.

The full extent and effect of contaminated groundwater discharges on surface water bodies in the Great Lakes Basin is not known. It is known that many sources of groundwater contamination exist in the basin and that groundwater is a significant and often major source of water for surface water bodies, and one with significant ecological importance. Examples of some types of groundwater contaminants discharging to Great Lakes waters have been published, but very few of these studies have determined the effects on biota residing in the transition zone or the receiving water. Most of these studies focus on contamination at a single site or area (< 1 km scale), and scaling up of these results to estimate effects on the Great Lakes Basin is not currently feasible. In Michigan alone, there are more than 15,000 documented cases of groundwater contamination that could, potentially, affect the quality of water in the Great Lakes. Control of this contamination is recognized as important but is included in Federal, State, and local programs and not directly part of the GLWQA.

There is a need for developing a better scientific understanding of the processes controlling the fate of contaminants, especially emerging contaminants, and their effects on aquatic organisms and their habitats, with respect to groundwater/surface water interactions and the transition zone. This understanding can then inform management decisions and can be incorporated into the prediction of total loadings and determining the ecological significance of groundwater contaminants with respect to the Great Lakes, when using broader-scale models tied to field knowledge of contaminant sources and inputs to surface waters. Much of this work requires integrated teams of ecotoxicologists and groundwater scientists, ideally working at targeted field research sites using a long-term, holistic, comprehensive, measurement-intensive approach.

3.2 Background Information on Groundwater Contamination Effects on Surface Waters

3.2.1 Types and Sources of Groundwater Contaminants

Groundwater can become contaminated with a wide variety of chemicals and other substances; eight of the most common and important groups are outlined in Table 3.1. These include nutrients, salts (e.g., road salt), metals, petroleum hydrocarbons and fuel additives, chlorinated solvents and additives, radionuclides, pharmaceuticals and other emerging contaminants, pesticides, and microorganisms (including pathogens). Common characteristics for many groundwater contaminants are: i) widespread use or presence in the environment, ii) high solubility in water, and iii) tendency not to sorb strongly to mineral or organic substrates (i.e., generally hydrophilic compounds), so they travel relatively easily through soils and geologic formations. Sources of groundwater contamination can be categorized according to the causation, spatial extent, and duration of the release(s) to the environment (Table 3.2). Many of these contaminants also enter surface water through other pathways, such as atmospheric deposition, urban / agricultural runoff, wastewater treatment plant discharge, and industrial outflows, which may lead to difficulties in identifying groundwater contaminant inputs. In contrast, contaminants that commonly contaminate lakebed or riverbed sediments (e.g., PCBs, PAHs, and some metals) tend to be highly hydrophobic; thus, they also tend to bioaccumulate and biomagnify. The physicochemical properties that make these contaminants sorb to the sediments also retard and limit their movement in groundwater, but nonetheless they can still discharge to surface water.

In some areas, such as the urban environment, many different types of sources may contaminate the local groundwater, leading to complex mixtures (see Chapter 6 for further discussion). Typically, little or no information is publically or readily available regarding the mass of contaminants released to groundwater at a given site, or in a specific urban area.

Finally, it is important to note that there are naturally occurring chemicals (e.g., salt, mercury, arsenic, radon, methane) in groundwater that, at elevated concentrations, may be toxic and/or may have adverse effects on either human or ecosystem health. Various human activities (e.g., mining, dewatering, oil and gas extraction, contaminated site remediation) may act to increase these natural concentrations or transfer these chemicals along with the groundwater to adjacent areas (or to shallower depths) having naturally lower concentrations. For example, this is an important issue associated with hydraulic fracturing for extraction of unconventional gas, which is either occurring or proposed in several regions of the Great Lakes Basin.

3.2.2 Groundwater Contaminant Discharge to Surface Waters

The transport of contaminants in groundwater from their source to a surface water body is controlled by flow conditions and attenuation processes within the groundwater system (including the transition zone, Chapter 2). Groundwater-derived contaminants that make it to surface water are diluted, typically more rapidly in streams and rivers than in wetlands and lakes (except with strong wave action). Groundwater contaminants that are sorbed onto sediments can be mobilized through erosional processes, thus transported further within the receiving water body or to connecting waters. The groundwater transport and attenuation conditions are specific to the site and contaminant(s).

Shallow groundwater is more likely to be impacted by contaminants, whereas deep groundwater may be so old that it predates industrial and agricultural activities that could have polluted it. Not all groundwater discharges to surface water bodies; thus, some groundwater contaminants may be captured by pumping wells or drainage features (e.g., tile drains, which subsequently discharge to surface water), or may be taken up by transpiring vegetation.

Patterns of discharge can be complex because of temporal and spatial differences in hydraulic conditions (see Chapter 2). In lakes, wave run-up on shores and large-scale, short-duration changes in water levels caused by storm surges and seiches can affect flow in the lakebed. Rivers and streams experience hyporheic flow and storm runoff-induced bank storage effects, and wetlands can experience similar storm-related events and longer duration water level variations. Therefore, contaminant plumes that reach the transition zone at surface water bodies experience complicated flowpaths, which results in a variety of discharge patterns that can change over time.

Contaminant attenuation mechanisms include (see Table 3.1): sorption onto solid surfaces, mineral precipitation, radiogenic decay, microbial degradation, volatilization, and plant uptake (Schwartz and Zhang, 2003). Some of these processes may be enhanced in the transition zone. For example, dissolved metals in anoxic and reducing groundwater (e.g., iron, manganese, and arsenic) from mine tailings tend to oxidize, precipitate, and accumulate when introduced to oxygenated sediments at or below the sediment interface (Benner et al., 1995; Nagorski and Moore, 1999). Likewise, for many hydrophobic compounds, the higher organic content in the fresh sediments of streams and lakes may promote higher degrees of sorption than older materials encountered along the groundwater flowpath. Organic-rich sediments also support high densities of microorganisms, which could promote degradation of organic contaminants or the stripping of volatile contaminants, which preferentially transfer into biologically-produced gases (e.g., bubbles of methane) and may be trapped in place or transported to the surface water by ebullition of the gas. Contaminants may also be taken up by riparian or aquatic plants, or by aquatic organisms.

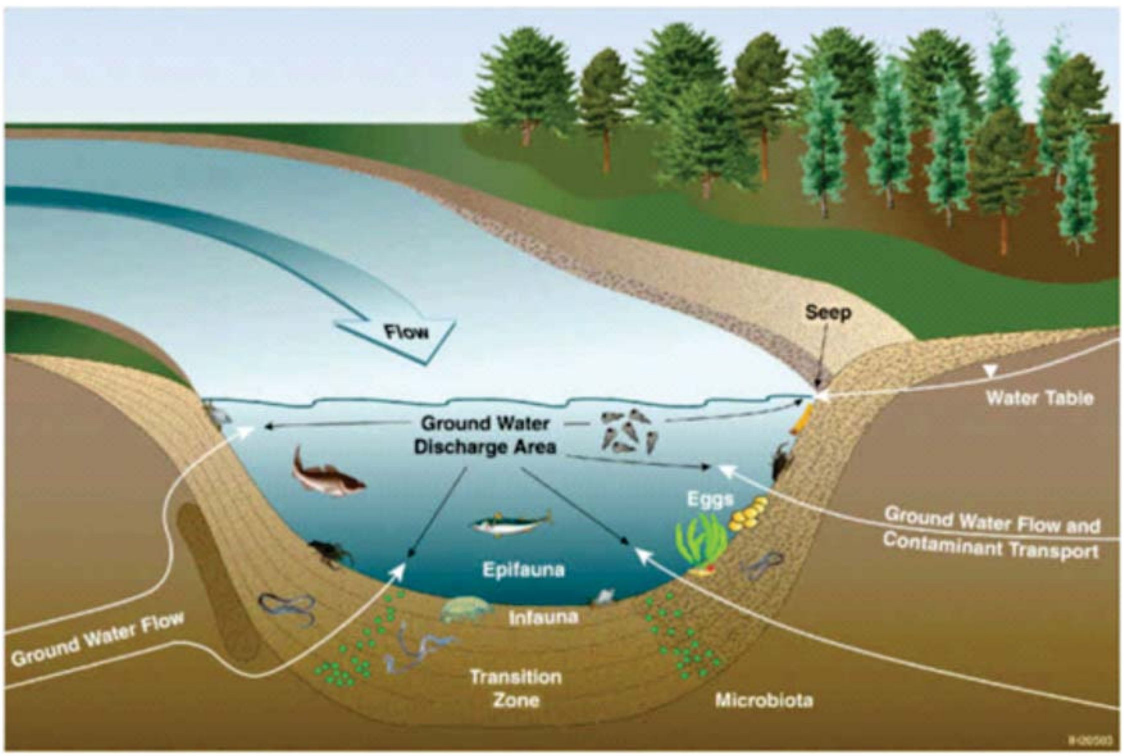

Figure 3.1. A conceptual site model diagram of the transition zone and groundwater discharge areas of a stream, which shows schematically the distribution of aquatic organisms (from USEPA, 2008).

3.2.3 Receptor Exposures and Potential Effects

Transition zones (including benthic zones) and groundwater discharge areas (Figure 3.1) provide habitats for a large variety of benthic and interstitial organisms (e.g., periphyton, shell fish, benthic invertebrates, vertebrates, plants, and endangered species), serve as thermal refuge for aquatic life, and provide beneficial locations for fish spawning. If the groundwater in such areas is contaminated, the aquatic organisms are potentially susceptible to both short-term and long-term negative effects. Their exposure to toxic contaminants may occur directly from the pore water or affected surface water, or from contact with or ingestion of affected sediment, detritus, or benthic organisms. Organisms in the transition zone may be exposed to harmful daughter products produced by contaminant biodegradation in this zone. Discharging plumes of contaminated groundwater often have low dissolved oxygen levels, which may also adversely affect aquatic ecosystems.

Table 3.1. Types of common groundwater contaminants and relevant information (not fully comprehensive) for managing and evaluating their risk to the environment.

Contaminant type	Key Sources	Ecological concerns	Attenuation processes
Nutrients (N – nitrate, ammonium; P – inorganic / organic)	Agricultural and lawn fertilizers (organic and inorganic); Sewage and septic systems; Livestock wastes (e.g., manure); Landfills, Graveyards; Forestry spoils; Mining (explosives); Urban runoff; (also naturally from vegetation decomposition or geologic materials)	Contributions to eutrophication (especially P); N compounds pose some toxicity risks	Nitrate – plant uptake, denitrification under anaerobic conditions, rarely sorption Ammonium – nitrification under aerobic conditions, sorption, volatilization Phosphorus – sorption, plant uptake, mineral precipitation
Salts (chloride) (road salt is predominantly NaCl or other chloride salts)	Road salt application and storage; Snow storage locations; Urban runoff; Landfills; Graveyards; Sewage and septic systems; Mining wastes; Oil and gas development (produced waters); (also naturally from geologic materials)	Toxicity (chloride) mainly; possible effect on processes dependent on water density (e.g., lake turnover)	Chloride – is a conservative solute (not normally attenuated)
Metals, metalloids (often mining-related)	Mining wastes, Industrial activities and wastes (e.g., smelting, metallurgy, steel mills, tannery, pulp & paper, dye mills); Landfill & Incineration & Hazardous wastes; Sewage and septic wastes; Pesticides; Fuel additives; Paints; Wood preservatives; Urban runoff; also naturally from geologic materials	Can be toxic to aquatic life at very low concentrations; toxicity often dependent on form (organic, inorganic) and valence state	Metals – sorption, plant uptake, mineral precipitation (are not destroyed by biological or chemical reactions)
Petroleum Hydrocarbons and Fuel Additives (benzene, toluene, ethylbenzene, and xylenes - BTEX; polycyclic aromatic hydrocarbons - PAHs) (Light Non-Aqueous Phase Liquids – LNAPLs float near water table)	Oil and gas development - crude oil, bitumen, and gas condensate (wellhead or mine site, pipelines, refineries, disposal wells); Fuel transfer stations and storage facilities (leaking underground storage tanks); Auto repair shops; Creosote (rail ties); Landfills; Manufacturing - lubricating oils; Construction (coal tar, greases, asphalt)	Aquatic toxicity; Oil phase coating wildlife (respiration, mobility issues); Volatilization to soil or indoor air; Flammable and explosion risk (including for biodegradation products); Oxygen uptake via biodegradation	Sorption (especially PAHs), Microbial biodegradation (lighter, components like BTEX; preferentially under aerobic conditions)
Chlorinated Solvents and Additives (Dense Non-Aqueous Phase Liquids – DNAPLs sink below water table)	Industrial manufacturing facilities (spills, leaking tanks and pipes, improper disposal) – aircraft & automobile production, metal fabrication, paint, electronics & electrical fabrication, tool & die, transformer & capacitor production; Hazardous and municipal waste, Printing shops, Automotive repair, Pesticides, Dry cleaners	Aquatic toxicity (many do not have guideline values for long-term exposures; some can bio-accumulate); Volatilization to soil or indoor air	Polychlorinated biphenyls (PCBs) – strong sorption; Halogenated aliphatic compounds (e.g., TCE - trichloroethene,) – sorption, volatilization, and biodegradation (generally preferentially under anaerobic conditions)
Radionuclides	Produced water from oil and gas wells; Mining waste and waters; Nuclear waste; At trace levels in some fertilizers	Chemical and (mainly) radiological toxicity	Radioactive decay and sorption are highly compound specific; some compounds (e.g., ^{222}Rn) are volatile
Pharmaceuticals and other emerging domestic chemicals (see Table 3.4 for list of compounds)	Septic and sewage waste; Landfills; Manure storage and spreading	Toxicity (much still unknown)	Sorption and biodegradation are highly compound specific
Pesticides	Manufacturing plants; Agricultural and urban application; Golf courses; Watercourse / airborne application (e.g., mosquito suppression); Landfills and hazardous waste	Toxicity (especially for similar groups to pest target); Habitat alteration	Sorption, volatilization, biodegradation highly compound specific
Pathogens (bacteria, viruses, etc.)	Septic and sewage waste; Manure storage and spreading	Disease	Sorption and filtration through geologic media; inactivation (die-off)

Table 3.2. Categorization of anthropogenic sources of groundwater contamination.

Causation	i) Accidental releases – spills, leaks, seepage from holding structures) ii) Intentional applications or releases – fertilizer & pesticide application, road salting, septic systems, illegal dumping
Spatial extent	i) Point sources – releases as localized events like a leaking underground storage tank, a septic system discharge, or a leaking landfill ii) Non-point sources – broad area sources, like agricultural applications or atmospheric deposition; linearly distributed sources such as road salt applications, leaking canals, and pipeline or sewer leakage
Duration	i) Single releases – spill, ruptured tank or pipeline ii) Recurring or continuous releases – septic system or leaking landfill

Organisms that reside in groundwater discharge zones will typically be exposed to relatively high concentrations of contaminants before the groundwater is diluted with surface water. In contrast, those dwelling in hyporheic zones of streams or in wave swash zones of lakes will benefit from some degree of subsurface dilution by influxing surface water. Within the surface water body, contaminant concentrations may range from those of the discharging groundwater (typically just above the sediment in stagnant waters) to near-background levels of the surface water body itself.

The unique nature of the biota and possible exposure scenarios in the transition zone prompted the USEPA to issue guidance for evaluating groundwater/surface water transition zones in ecological risk assessments (USEPA, 2008). Canada has also recently developed a guidance document for federal contaminated sites on this topic (Environment Canada, 2014). Both promote application of existing water quality guidelines (freshwater ecosystems) to situations involving groundwater contaminants, including transition zone organisms. However, these guidelines do not include consideration of all common groundwater contaminants (e.g., vinyl chloride) or possible synergistic effects of exposure to multiple contaminants simultaneously.

Finally, human uses of surface waters may be impaired if the groundwater-derived contaminants make water supplies non-potable or fish hazardous for human consumption (via contaminant bioaccumulation), or if they contribute to algal blooms that make these waters unsuitable for recreation. The potential economic cost associated with such adverse effects can be substantial. These costs may result from the loss of water supplies and/or the need for expensive treatment, remedial actions, or replacement of the supply, or from damages to fisheries and tourism.

3.2.4 Characterizing Groundwater Contaminant Discharge

The potential for groundwater contaminants to reach a surface water body can be estimated from tracking where groundwater plumes flow to the surface water bodies, using groundwater data and conceptual or numerical models. However, to determine actual discharge locations in the transition zone or water body requires direct field measurements (see Rosenberry and LaBaugh, 2008, for detailed discussion), given the uncertainties in attenuation processes and the potential for groundwater flow to by-pass some surface waters (e.g., Savoie et al., 1999 documented a plume that travels under one pond to discharge to another one further down-gradient). The most common method to assess groundwater contaminant discharge is to measure increases in contaminant concentrations (or related groundwater tracers) within the surface water. However, this is often unsuccessful because concentrations frequently are reduced substantially by dilution not far from the discharge area or by other attenuation processes. In cases where contamination can enter the surface water by several different routes, it is necessary to sample the water discharging from streambeds, lakebeds, and wetland deposits to definitively determine if groundwater is contributing to the surface water contamination. Groundwater can be sampled directly from the transition zone using piezometers or mini-profilers (Conant, 2004; Roy and Bickerton, 2010) or passive vapour diffusion samplers (Church et al., 2002), which, combined with measures of groundwater discharge (see Rosenberry and LaBaugh (2008) for methods to measure discharge), can be used to assess the contaminant loading to the surface water body. Discharging groundwater can also be sampled directly with a seepage meter or assessed at the sediment interface with contaminant-specific probes (e.g., chloride probe). Indirect measurements include using geophysical methods for high-conductivity plume detection or observations of an unusual presence or absence of flora or fauna (Roy et al., 2009).

3.2.5 Groundwater Processes Improving Surface Water Quality

Groundwater, if relatively uncontaminated, may improve the water quality of contaminated surface waters, possibly providing areas of contaminant refuges in groundwater discharge zones in an otherwise contaminated surface water body. This may be analogous to groundwater influences on thermal refuges (see Chapter 5 for further details). For example, the stretch of the Grand River between Cambridge and Branford, Ontario has been termed "the recovery reach" because incoming groundwater dilutes the surface water that is contaminated with sewage treatment plant effluents. Likewise, contaminants in surface waters may enter the shallow sediments or aquifer system and become attenuated (as described above) prior to discharging to the same or another surface water body. Indeed, the hyporheic zone has been termed the "river's liver" (Fisher et al. (2005). Finally, Ledford and Lautz (2014) showed that stream water flow into and out of riparian zone sediments (e.g., bank storage) reduced temporal variation (i.e., lowered peak values) in urban stream chloride concentrations, which were linked with road salt runoff.

Groundwater flow direction can also influence toxicity of contaminants in transition zone sediments. For example, Greenberg et al. (2002) concluded that down-welling reduced the bioavailability of chlorobenzenes in the surficial sediments by mobilizing the freely dissolved and colloid-bound fractions down and away from benthic organisms, thereby reducing the in- situ exposure of the organisms.

3.3 What Information Exists and What are the Information Gaps for the Great Lakes Basin?

3.3.1 Identifying Contaminant Sources

As outlined in Table 3.1, there are many potential groundwater contaminant sources in the Great Lakes Basin, including natural sources, inputs related to agricultural practices and urban activities, and those from major industries (e.g., mining, oil and gas, manufacturing). This list of contaminants is similar to the lists others have created and discussed in detail (Environment Canada, 2001; Great Lakes Science Advisory Board to the IJC, 2010). As described in Chapter 2, combined direct and indirect groundwater flow into the Great Lakes is very significant and, consequently, contaminants in the groundwater have the potential to affect the Lakes.

Incidents of groundwater contamination are quite common and well known, with information residing in many government databases (Table 3.3) and the published scientific literature. Additionally, ambient groundwater quality monitoring programs may contain data that could indicate areas of potential groundwater contamination (also Table 3.3). However, none of these data sources can be readily searched in a manner that would identify or display locations of actual or potential contaminated groundwater discharge into surface waters of the Great Lakes Basin. Some of the most promising sources are the Source Water Protection Plans being developed for each watershed in Ontario as required by the Ontario Clean Water Act, 2006 (Ontario Regulation 287/07) (Ministry of the Environment (MOE), 2006). Some studies have collated information for particular areas – for example, a report by MacRitchie et al. (1994) on groundwater quality in Ontario indicated that there are a large number of chemical, petrochemical, steel producing, and other industries located along the Great Lakes connecting channels and summarized their potential to be sources or potential sources of groundwater contamination. According to the Upper Great Lake Connecting Channels Study (Nonpoint Source Workgroup, 1988a,b,c,d), 214 sites were identified on the U.S. side of the lakes (in Michigan) and 110 sites were identified on the Canadian side of the channels. However, the vast majority of site-specific information that exists regarding contaminated groundwater discharges to surface water is contained in consultant reports submitted to site owners and/or regulatory agencies. These reports are typically confidential and not publically accessible in database searches of the USEPA or MOECC web sites.

Table 3.3. Examples of databases with information on the locations of contaminated groundwater in the Great Lakes basin. (not an exhaustive list, especially for the State governments).

Government(s)	Databases
Government of Canada (federal)	**Federal Contaminated Sites Inventory** (maintained by the Treasury Board of Canada Secretariat) http://www.tbs-sct.gc.ca/fcsi-rscf/home-accueil-eng.aspx
Government of Ontario (provincial)	**Environmental Site Registry** (maintained by the Ontario Ministry of the Environment) http://www.ene.gov.on.ca/environment/en/subject/brownfields/STDPROD_075742.html **MOE Spills Action Centre** (maintained by the Ontario Ministry of the Environment) http://www.ene.gov.on.ca/environment/en/about/emergency_planning/STDPROD_080741 **Ontario Landfill Inventory** (maintained by the Ontario Ministry of the Environment) http://www.ene.gov.on.ca/environment/en/monitoring_and_reporting/limo/landfills/index.htm **Source Water Protection** (administered by the Ontario Ministry of the Environment and Conservation Ontario) http://www.ene.gov.on.ca/environment/en/subject/protection/
Government of the U.S.A.	**USEPA: Superfund Sites Where You Live, Region 5 (Minnesota, Wisconsin, Illinois, Indiana, Michigan, and Ohio)** http://www.epa.gov/R5Super/ **USGS National Water Quality Assessment Program (NAWQA):**http://water.usgs.gov/nawqa/ Three study units are within the Great Lakes basin: Lake Erie-St. Clair basin (Indiana, Michigan, New York, Ohio, and Pennsylvania), the Upper Illinois River basin (Illinois, Indiana, and Wisconsin), and the Western Lake Michigan drainages (Wisconsin and Michigan). **U.S. National Ground Water Monitoring Network** http://cida.usgs.gov/ngwmn/ This is a compilation of selected groundwater monitoring wells from Federal, State, and local groundwater monitoring networks across the nation. It is maintained by U.S.G.S.
State Governments – New York, Minnesota, Wisconsin, Illinois, Indiana, Michigan, and Ohio, Pennsylvania (similar databases likely for other states to those examples provided here)	**Michigan Dept. of Environmental Quality**: **Site Investigation and Cleanup page**: http://www.michigan.gov/deq/0,4561,7-135-3311_4109_9846---,00.html **Michigan Dept. of Licensing and Regulatory Affairs:** Online facility search for underground storage tanks and leaking underground storage tanks http://www.deq.state.mi.us/sid-web/UST_Search.aspx **Minnesota Pollution Control Agency:** What's in My Neighborhood – permitted facilities, clean-up sites, etc.**:** **Minnesota Pollution Control Agency:** What's in My Neighborhood – agricultural interactive mapping**:** **Ohio Ambient Ground Water Quality Monitoring Network** http://epa.ohio.gov/ddagw/ambientmap.aspx

It is likely that much groundwater contamination goes undetected, especially at locations distant from municipal drinking wells and from federal (USGS) and state/provincial monitoring wells (Figure 3.2), which often are relatively deep and may be the only wells in the area that are routinely tested for a wide range of contaminants (especially emerging contaminants; Table 3.4). Groundwater quality surveys are difficult and expensive to conduct and generally suffer from poor spatial coverage, potential dilution effects by sampling long-screened wells, and limited chemical analyses (i.e., often focused on only a few types of contaminants). Some examples of groundwater quality surveys relevant to the Great Lakes Basin include Warner and Ayotte (2014), Dubrovsky et al. (2010), Groschen et al. (2004), Myers et al. (2000), and Peters et al. (1998).

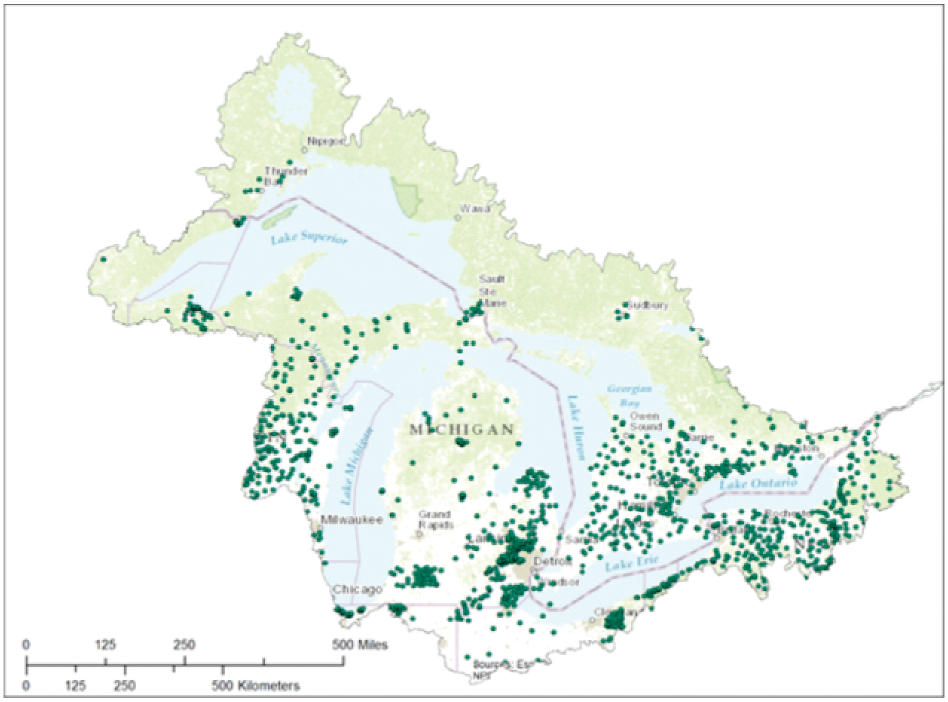

Figure 3.2. Locations of monitoring wells in the Great Lakes Basin with publicly available water quality analyses conducted between 1994 and 2015. Sources: USGS National Water Information System (1759 wells); Ontario Ministry of Environment and Climate Change, Provincial Groundwater Monitoring Network (358 wells).

3.3.2 Studies Documenting Contaminated Groundwater Discharges into Surface Water

There are few relevant documents provided in the scientific literature for contaminated groundwater discharge to surface water bodies of the Great Lakes Basin. A summary of these is provided in Table 3.5. Note that additional studies of nutrients are discussed in Chapter 4. Many of the published studies involve localized contamination (e.g., a single point source contaminant plume) and focus on fate and transport processes, including in the transition zone. For example, studies are available of chlorinated solvent plumes of contaminated groundwater discharging to streams (Ontario; Conant et al., 2004) and lakes (Michigan; Lendvay et al., 1998a, 1998b) of the Great Lakes Basin. Several of these studies reported measurable concentrations in the receiving water. Others, such as Bain et al. (2000), who examined the reactive transport of acidic drainage in groundwater near Sudbury Ontario from the Nickel Rim Mine to a lake, note discharge to a surface water body but focus mainly on groundwater processes.

Non-point contaminant sources, such as agricultural application of nutrients (see Chapter 4 for a detailed discussion) and road salt, are also important and the subject of several studies. Chloride attributed to the application of road salt has been found in streams at levels above acute and chronic toxicity levels, including at times (e.g., summer) when groundwater would be the dominant contributor of water (Corsi et al., 2010). A review of previous studies contained in Howard and Maier (2007) found several examples where groundwater and springs in the Toronto, Ontario area have 100s to 1000s of mg/L of chloride and as high as 14,000 mg/L at one location near a highway. Road salt inputs with groundwater to streams have also been noted for the Frenchman's Bay watershed near Pickering, Ontario (Meriano, et al., 2009; Eyles and Meriano, 2010) and at sites in northern municipalities of the U.S. (e.g., Milwaukee, Wisconsin) (Corsi et al., 2010). Such indirect groundwater inputs via discharge to streams flowing to the Great Lakes ultimately contribute to the increasing chloride concentrations and mass loading that have been observed in each of the Great Lakes (Chapra et al., 2009).

Almost all the activities and potential sources of contamination listed in Table 3.1 can occur in urban environments. These can lead to numerous point source and non-point source releases of contaminants, which together comprise the non-point source urban contaminants. Studies of urban-sourced contaminants discharging to the shoreline of Lake Simcoe, Ontario (Roy and Malenica, 2013) and numerous streams in Ontario (Roy and

Table 3.4. Types of emerging contaminants (i.e. chemicals of emerging concern; new or increased detections due to improved analytical capabilities), according to a study in the United Kingdom by Stuart et al. (2012). Excludes pesticides, which are included as a separate contaminant group in Table 3.1.

Type of compounds	Example chemicals
Pharmaceuticals	anti bacterials – triclosan; veterinary and human antibiotics - ciprofloxacin, erythromycin, lincomycin, sulfamethoxazole, tetracycline; prescription drugs - codeine, salbutamol, carbamazepine; non-prescription drugs - acetaminophen (paracetamol), ibuprofen, salicylic acid; x-ray contrast media - iopromide, iopamidol; chemotherapy drugs - 5-fluorourcil, ifosfamide or cyclophosphamide; and illicit drugs - cocaine and amphetamines
Life-style compounds	nicotine and its metabolite cotinine; and artificial sweeteners like acesulfame, saccharine, cyclamate and sucralose
Personal care products	bacteriocide and antifungal agents - triclosan and parabens; fragrances such as polycyclic musks tonalide and galaxolide; insect repellants - DEET (N,N-diethyl-meta-toluamide)
Industrial additives and by-products	(fuel oxygenates - MTBE; plasticisers/resins bisphenols; adipates and phthalates; solvent stabilizers - 1,4-dioxane; benzotriazole derivatives in pharmaceuticals
Food additives	foam stabilizers - triethyl citrate; butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) used to prevent fat spoilage; and others - camphor, 1,8-cineole (eucalyptol), citral, citronellal, cis-3-hexenol, heliotropin, hexanoic acid, menthol, phenylethyl alcohol, triacetin, and terpineol
Water treatment by-products	trihalomethanes and haloacetic acids; nitrosodimethylamine (NDMA); bromo- and iodo-THMs and brominated MX ((3-chloro- 4-dichloromethyl)-5-hydroxy-2(5H)-furanone); polyacrylamide and epichlorohydrin
Flame/fire retardants	Polybrominated diphenyl ethers and tris-(2-chloroethyl) phosphate (TRCP)
Surfactants	perfluorinated sulfonates and carboxylic acids including perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA); alkyl phenol ethoxylates (APEs) and octyl- and nonyl-phenol (OP and NP) used to make APEs
Hormones and sterols	androgen and oestrogen sex hormones – androstenedione, testosterone, oestrone, oestriol, 17α- and 17β-oestradiol, and progesterone; synthetic oestrogens used as contraceptives (17α-ethinyl oestradiol and diethylstilbestrol
Ionic liquids	salts with low melting points to replace industrial volatile compounds - nitrocyclic rings (pyridinium, pyrrolidinium, morpholinium moieties) and quaternary ammonium salts]

Bickerton, 2012) revealed contaminant levels in the transition zone higher than aquatic life guidelines for chloride (road salt), nutrients, petroleum hydrocarbons, chlorinated solvents, and metals. Other compounds (including some emerging contaminants) were also detected at lower levels, including 1,4-dioxane, MTBE, perchlorate, glyphosate, 2,4-D, and several artificial sweeteners (e.g., acesulfame and saccharin). The findings suggest this sort of effect may be common for surface waters adjacent to urban centers. A modeling study by Howard and Livingstone (2000) inventoried possible urban groundwater contaminant release locations in the Toronto area, assumed concentrations and contaminant loading at those locations (e.g., landfills, snow dumps, septic systems, underground storage tanks, agricultural areas, and roads (road salt)), and simulated concentration and arrival times at streams and Lake Ontario. The study concluded the urban contamination would seriously threaten the quality of urban streams and shallow near-shore areas of Lake Ontario over the next 100 years and continue to be a problem thereafter.

Table 3.5. Studies published in the peer-reviewed scientific literature reporting on field observations of groundwater contaminant discharge to surface waters of the Great Lakes basin (excludes studies on Great Lakes Areas of Concern, which are listed in Table 3.6).

Contaminants	Study	Receiving water(s) / area
Nitrate	Cey et al., 1999; Hill and Lymburner,1998; Devito et al., 1999	Various Ontario streams
Phosphate	Carlyle and Hill, 2001, Macrae et al., 2011; Roy and Bickerton, 2014	Various Ontario streams
Chloride	Howard and Beck, 1993; Howard and Haynes, 1993; Williams et al., 1999; Meriano et al., 2009; Eyles and Meriano, 2010; Howard and Maier, 2007	Springs in the Toronto, ON, area
	Meriano, et al., 2009; and Eyles and Meriano, 2010	Frenchman's Bay watershed near Pickering, ON
Chlorinated solvents	Conant et al. (2004), Roy and Bickerton, 2010	Pine River, Angus, ON
	Lendvay et al., 1998a, 1998b	Lake Michigan
Acid mine drainage (metals, acidity)	Bain et al. (2000)	Nickel Rim Mine near Sudbury, ON
Urban pollutants (chloride, nutrients, petroleum and chlorinated organics, pesticides, metals, glyphosate, artificial sweeteners)	Roy and Bickerton, 2012	Five Ontario streams
	Roy and Malenica, 2013	Lake Simcoe shoreline, Barrie, ON
Septic system (nutrients, salts, perchlorate, artificial sweeteners)	Robertson et al., 2011; Van Stempvoort et al., 2011; Robertson et al., 2014	Long Point, ON, adjacent to Lake Erie; also streams in Burlington, ON for perchlorate
Landfill leachate	Dickman and Rygiel 1998	Creek in St. Catherines, ON
	Atekwana and Krishnamurthy, 2004	Davis Creek, Kalamazoo, MI
Artificial sweeteners	Van Stempvoort et al., 2011	Various Ontario streams
Uranium mine drainage (acidity, metals)	Dubrovsky et al., 1984; Blowes and Gillham, 1988	Buckles Creek and drainage channel at mine site, near Elliot Lake, ON

Table 3.6. Great Lakes Areas of Concern (AOCs ; Figure 3.3) with studies reporting direct discharges of contaminated groundwater to surface waters.

Area of Concern	Associated Studies
Port Hope Harbour	Bobba and Joshi, 1988; and Bobba, 2007
Hamilton Harbour	Harvey et al., 1997a, 1997b, and 2000
Toronto and Region	Howard and Livingstone, 2000; Eyles and Meriano, 2010; Howard and Maier, 2007
St Clair River	Sklash et al., 1986; Cherkauer and Taylor, 1990; Gillespie and Dumouchelle,1989; Intera Technologies Ltd., 1992
Detroit River	Cherkauer and Taylor, 1990; Gillespie and Dumouchelle,1989; Intera Technologies Ltd., 1992
Niagara River	Maslia and Johnston, 1984; Gradient Corporation and Geo-Trans Corporation, 1988
St. Marys River	Gillespie and Dumouchelle, 1989; Beak Consultants Limited, 1992
Buffalo River	Taylor, 1994
Menominee River	Baker Engineering, Inc., 1988
Sheboygan River	Blasland, Bouck and Lee, Inc, 1995
Grand Calumet River	Fenelon and Watson, 1993; Greeman, 1995

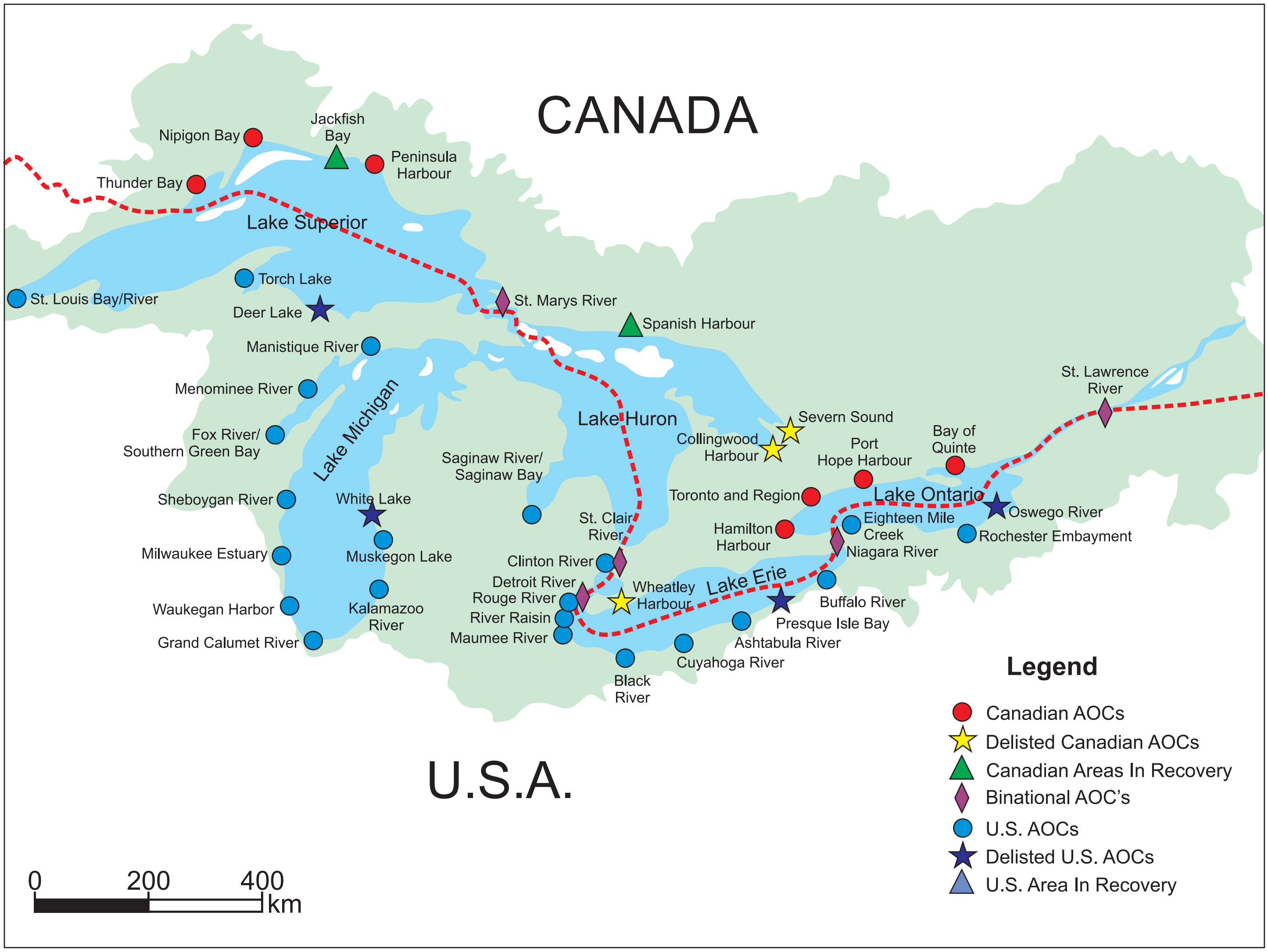

Figure 3.3. Map showing Areas of Concern (AOCs) for the Great Lakes (from Environment Canada and the Ontario Ministry of the Environment, 2011).

Many of the most common contaminants or sources have not received much, if any, attention in the peer-reviewed literature to date with respect to discharges to Great Lakes surface waters. For example, no studies of hydrocarbon contaminant plumes discharging to surface water bodies of the Great Lakes were found, but it is suspected numerous consultant reports contain relevant data that are not publically available, such as for a 600 m (2000 ft) wide benzene plume discharging to Lake Michigan (Conant, 2010, 2012; and Conant et al., 2012a, 2012b) that resulted in surface water concentrations higher than drinking water and aquatic life standards.

Direct discharges of groundwater and contaminated groundwater to the lakes have been reported for several of the AOC sites (Table 3.6), despite the fact that surface water discharges or sources of contaminants (e.g., sewage treatment plant effluent, pulp mill effluent, and urban and agricultural runoff) have generally been identified as the primary sources of contaminants. It's not clear that groundwater sources of contamination have been adequately assessed at many of these sites, and instead the focus is often on contaminated sediment with little attention to the role of groundwater. However, in a 1989 report, contaminant loading via groundwater (315 kg/day) was thought to be roughly equal to the loading from all point sources combined (307 kg/day) at the Niagara River binational AOC in western New York (Hodge, 1989). As a result, cleaning up the Niagara River (and Lake Ontario) is expected to be difficult, owing in part to technical limitations, the large amount of chemical waste, and complex hydrogeological conditions at the four major Superfund sites in the area, as well as the high levels of contamination in groundwater below operating industrial facilities. Eliminating point source surface water discharges is relatively simple in comparison to addressing loading via groundwater (Hodge, 1989).

Broader scale assessments (e.g., km-scale and above, whole river or lake) have not been attempted. Thus, it is not known where the worst discharges of contaminated groundwater to surface water are occurring in the Great Lakes Basin or to what extent (and again where) contamination is accumulating in lakebed or riverbed sediments as a result of groundwater discharging into the sediments from below. In addition, it is not known how discharges of contaminated groundwater to surface water will change over time. There is some evidence to suggest that the worst may be yet to come for non-point source contaminants such as road salt and nitrate applications, given the long residence times of groundwater flow systems. Thus, groundwater contaminated by applications decades ago may only be reaching some surface waters now.

In contrast, there has likely been a reduction in contamination of groundwater by petroleum hydrocarbons as a positive result of the improved regulation of underground storage tanks. For example, since 1985, U.S. federal and state programs have significantly reduced the risk of new releases by implementing release-prevention and leak-detection requirements and establishing improved design, installation, and operational technical standards. Additionally, programs have overseen the cleanup of nearly 351,000 leaking tank sites (Ground Water Protection Council, 2007).

3.3.3 Estimating the Effect of Groundwater Contaminants on Receptors

The most common method for evaluating groundwater contaminant effects on surface water ecosystems involves comparing transition zone concentrations to aquatic water quality guidelines (e.g., Conant et al., 2004; Lorah et al., 2005; Roy and Bickerton, 2012; Roy and Malenica, 2013). There are only a few studies from the Great Lakes Basin that have directly linked groundwater contaminants to impaired aquatic ecosystems. In one, Williams et al. (1999) sampled water and biota at salt-affected groundwater springs and found concentration-dependent patterns of salt tolerant and non-salt tolerant macroinvertebrates at the springs. Dickman and Rygiel (1998) noted marked changes in stream biota for a groundwater-fed stream flowing below a landfill from 1976 (pre-landfill) to 1991, with pollution-sensitive invertebrates such as scuds, mayflies and caddisflies replaced by pollution-tolerant snails, sludge worms, nematodes and blood worms. However, actual measurements of discharging groundwater quantity and quality were not made.

The literature lacks studies regarding how much the surface water or transition zone can be affected by contaminated groundwater discharges before there are detectable adverse effects on this habitat. Likewise, information is lacking regarding potential correlations between common groundwater contaminant discharge areas and any effects on sensitive aquatic habitats.

3.4 Priority Science Needs to Fill Information Gaps

The overall effect of contaminated groundwater on surface water in the Great Lakes Basin is currently unknown because of gaps in scientific knowledge and insufficient information with respect to groundwater contamination in the basin. Some of the priority science needs relate to fundamental groundwater flow processes (see science needs outlined in Chapter 2 regarding improved understanding of the hydrogeology of transition zones and better quantification of groundwater contributions to wetlands, streams, and lakes of the Great Lakes Basin) and further mapping of groundwater flows in shallow and deep aquifers in the Great Lakes Basin. Whereas, other priority needs relate to the relationships between groundwater contributions and maintaining ecological habitats (see science needs in Chapter 5). Resolving those science needs are necessary to inform our understanding of groundwater contaminant effects on Great Lakes waters. Specific science needs that are critical to fully understanding and assessing the effects of contaminated groundwater are listed below. All of these should give special consideration to addressing the winter season, and exposures during critical life cycle stages for aquatic organisms, which have received little research attention.

i) Methods for detection and assessment of contaminated groundwater discharges

The complex flows and heterogeneous nature of attenuation processes in groundwater can lead to variations in contaminant concentrations over a wide range of scales (cm to km). Rapid, inexpensive and better field-based sampling, sensing, and measuring methods and tools are required to more fully assess the effects of contaminated groundwater discharges on surface water and the key processes affecting it over these spatial scales and over time. Until groundwater contaminant discharges can be properly delineated and quantified, we will be unable to determine exposures with certainty or to prioritize remedial actions. Likewise, models to simulate geochemical processes and to estimate contaminant fluxes at larger scales will not be able to be confidently calibrated or validated without this kind of data.

ii) Assessing the remediation potential of the transition zone

Although the potential of the transition zone to attenuate contamination in groundwater has been demonstrated, a considerable amount of work remains to be done to understand these attenuation processes sufficiently to evaluate their true effectiveness for the wide variety of contaminants. This work is especially necessary for the plethora of emerging contaminants (Table 3.4), because it has implications for determining exposures for aquatic life and for remediation strategies. This work is required at sites covering the full range of geological and groundwater/surface water exchange conditions in the Great Lakes Basin.

iii) Sensitivity of transition zone organisms – re-assess and expand coverage of guidelines?

There is a need for toxicity information (field and lab) to: i) develop appropriate water quality criteria for the wide variety of groundwater contaminants that are still lacking guidelines or standards, including emerging contaminants (Table 3.4), and ii) to assess the applicability of current aquatic life guidelines (USEPA, 2015; CCME, 2015) to organisms exposed to contaminated groundwater within the transition zone (as directed by USEPA (2008) and Environment Canada (2012). Guidance is also lacking regarding how to evaluate possible synergistic effects of multiple contaminants in the transition zone.

iv) Actual ecological effects of groundwater contaminants

Very few studies have examined the ecological effects of discharging groundwater contaminants (singly or as mixtures) on aquatic organisms, either within the transition zone or in the receiving water. Part of the reason for this may be a lack of appropriate testing methods. Thus, new in- situ toxicity tests that target ecotoxicological effects of contaminated groundwater, especially in the transition zone, are needed. These new tests must be capable of assessing variable effects over fine spatial scales and long temporal scales. These tools should then be applied in integrated ecotoxicological and hydrological studies to determine aquatic organism responses to contaminants under field conditions, leading to evaluations of the subsequent repercussions to the larger ecosystem. The findings of these studies will also help in assessing the ecological costs and benefits of using the transition zone for in- situ plume remediation.

v) Regional-scale contaminant loading to Great Lakes waters

To assess the potential broader-scale effects of groundwater contaminants on surface waters in the Great Lakes Basin, understanding of site-scale effects (e.g., mass loadings, ecological effects, etc.) of various contaminant sources must be related to regional scale contaminant source databases (e.g., GIS-based). Ideally, predictions of water quality effects would be made using site data and sophisticated hydrological models that account for the physical flow and contaminant transport and fate processes, appropriately scaled-up to provide accurate estimates. However, detailed information is lacking for the predominant groundwater flow systems that discharge to surface water in many areas of the Great Lakes Basin. Until such information becomes available, regional scale contaminant source databases (e.g., GIS-based methods) and black-box-type models, such as the Lake Capacity Model for septic system inputs to Canadian-shield lakes likely will continue to be used, but the results should be viewed with caution due to their inherent limitations.

Table 3.7 Priority science needs related to groundwater and contaminants.

Priority Science Needs	Related needs and information gaps
3A. Methods for detection and assessment of contaminated groundwater discharges	• Better and more economical field-based sampling, sensing, and measuring methods and tools • Improve assessment of contaminant variation across small and large spatial and temporal scales • Calibrate and validate computer models to simulate geochemical processes and to estimate contaminant fluxes
3B. Assessing the remediation potential of the transition zone	• Develop an understanding of the attenuation (remediation) mechanisms for wide variety of groundwater contaminants, especially emerging contaminants, in the transition zone • Understand how site geological and groundwater/surface water exchange conditions affect these attenuation mechanisms
3C. Sensitivity of transition zone organisms to contaminants	• Develop appropriate water quality criteria for the wide variety of groundwater contaminants that are still lacking guidelines or standards, including emerging contaminants • Assess the applicability of current aquatic life guidelines (USEPA, 2015 CCME, 2015) to organisms exposed to contaminated groundwater within the transition zone • Information to answer how to evaluate possible synergistic effects of multiple contaminants in the transition zone
3D. Actual ecological effects of groundwater contaminants	• Develop new in-situ toxicity tests that measure ecotoxicological effects of contaminated groundwater, especially in the transition zone • Integrate ecotoxicological and hydrological studies to determine aquatic organism responses to contaminants under groundwater/surface –water exchange conditions • Investigate the repercussions for the larger ecosystem of organisms impairment or behavioural changes caused by discharging groundwater contaminants • Assess the ecological costs and benefits of using the transition zone for in-situ plume remediation
3E. Regional-scale contaminant loading to Great Lakes waters	• Determine methods to upscale and relate site-scale effects of discharging groundwater contaminants to the regional scale (particularly the effect of the transition zone) • Obtain detailed information for the predominant groundwater flow systems that discharge to surface water in many areas of the Great Lakes Basin • Develop detailed and coordinated regional scale groundwater contaminant source databases (e.g., GIS-based) in the Great Lakes Basin • Develop sophisticated models capable of linking these 2 sets of information, which account for up-scaled groundwater flow and contaminant transport and fate processes, for the wide range of contaminants and groundwater/surface water exchange processes

4. GROUNDWATER AND NUTRIENTS

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4.1 Introduction

Nutrients are currently one of the most important contaminants in the Great Lakes Basin and subsequently warrant their own Annex in the GLWQA (Annex 4). The pervasiveness of nutrient contamination is in part due to the numerous point sources (e.g., wastewater effluents) and the large spatial extent of non-point sources (e.g., agriculture). Although essential for life, in excessive concentrations of nutrients can degrade water quality by stimulating excessive macrophyte and algal growth (eutrophication), and in some cases the subsequent destruction of fish and wildlife habitats and loss of species diversity (National Wildlife Federation (NWF), 2011; Phosphorous Reduction Task Force (PRTF), 2012). Furthermore, eutrophication negatively affects human water uses such as recreational activities, tourism, fisheries, and drinking water supply (e.g., International Joint Commission (IJC), 2011). As phosphorus (P) typically limits primary production in freshwater ecosystems, excessive P loading is implicated as the main contributing factor to eutrophication in the Great Lakes (PRTF, 2012). Under certain conditions, excessive nitrogen (N) can also promote algal growth, including toxic blue green algae blooms (Moon and Carrick, 2007; NWF, 2011). In addition to P and N, silica and iron have also been shown to stimulate algal growth in the Great Lakes (Moon and Carrick, 2007; North et al., 2007).

While efforts to reduce nutrient loading to the Great Lakes were successful in reversing the rapid deterioration of water quality experienced in the 1960s, they have not been sufficient. Over the past decade, eutrophication and the occurrences of algal blooms continue to increase in the Great Lakes (PRTF, 2012). Management of nutrient loading to the Great Lakes has focused primarily on controlling inputs from point sources (e.g., wastewater treatment plants), banning P detergents, and implementing agricultural best management practices.

While groundwater is often identified as a potential non-point nutrient source (e.g., Barton et al., 2013), its role remains poorly understood, in part because of the difficulty in quantifying groundwater nutrient loading to surface waters (Burnett et al., 2003). Groundwater discharges to surface waters in the Great Lakes Basin either by indirect discharge into tributaries or direct discharge into the Great Lakes (Grannemann et al., 2000). The factors affecting these two discharge pathways and their respective contributions to nutrient loading to the Great Lakes are distinct (Section 4.4). Evaluating groundwater as a nutrient source to the Great Lakes and their tributaries requires knowledge of the (i) sources of nutrients in groundwater, (ii) groundwater flowpaths and the associated nutrient transport, and (iii) geochemical processes that regulate the fate of groundwater nutrients.

4.2 Nutrients in Groundwater

4.2.1 Nitrogen

Nitrogen is present in groundwater in different forms: soluble organic N, NH_4^+ (ammonium), NO_3^- (nitrate), NO_2^- (nitrite), and N associated with sediment as exchangeable NH_4^+ or organic N. Cycling of N is extremely dynamic with complex processes, mostly microbially-mediated (Figure 4.1). The mobility of N in groundwater depends on its specific form. A comprehensive review of the N cycle is beyond the scope of this report and is provided by Rivett et al. (2008) and Burgin and Hamilton (2007). Here we discuss some key aspects that pertain to groundwater nutrients.

NO_3^- is very soluble and mobile in groundwater and is subsequently one of the most ubiquitous groundwater contaminants. Denitrification, the reduction of NO_3^- to N_2O (nitrous oxide gas) and N_2 (nitrogen gas) is the dominant process for NO_3^- attenuation in the subsurface. Other alternative pathways by which NO_3^- can be transformed include: (i) dissimilatory NO_3^- reduction to ammonium (DNRA), (ii) assimilation of NO_3^- into microbial biomass; and, (iii) NO_3^- removal via vegetation uptake (Rivett et al., 2008).

Denitrification occurs under anaerobic conditions when suitable electron donors (typically organic carbon, reduced iron and/or reduced sulfur) are available. These conditions often exist near the interface between groundwater and surface waters, for example, in riparian zones (Gold et al., 2001; Mayer et al., 2007; Puckett, 2004; Puckett and Hughes, 2005; Vidon and Hill, 2004) and hyporheic zones (Harvey et al., 2013; Ranalli and Macalady, 2010). Subsequently, these zones can have a disproportionate effect on regulating fluxes of N from groundwater to surface waters (see Section 4.4).

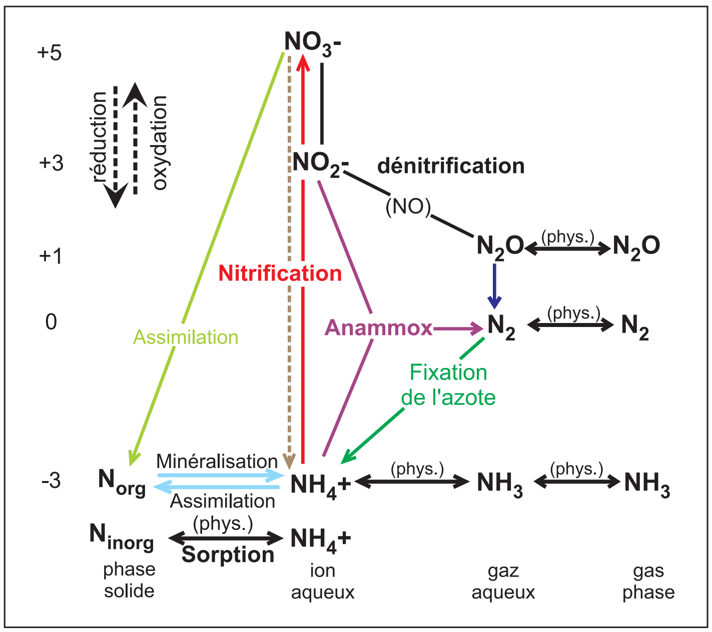

Figure 4.1. Some key biogeochemical and physicochemical (phys.) reactions of the nitrogen cycle in terrestrial and aquatic environments. Compounds are organized according to their phase and the oxidation state of the nitrogen atom. Figure from Böhlke et al. (2006); used with permission.

NH_4^+ is much less mobile than NO_3^- in groundwater as it readily adsorbs to sediment. In oxic environments, NH_4^+ can be converted to NO_2^- and NO_3^- via nitrification and, in anaerobic environments NH_4^+ can combine with NO_2^- to produce N_2 gas via anaerobic ammonium oxidation (anammox) (Rivett et al., 2008). Although under certain hydrogeological and geochemical conditions NH_4^+ can be delivered to surface waters via groundwater, NH_4^+ is often delivered via sediment erosion and surface runoff (Balderacchi et al., 2013).

4.2.2 Phosphorus

Phosphorus exists in the environment as inorganic and organic P, as either particulate or soluble forms. Inorganic soluble P (e.g., orthophosphate (PO_4^{3-})), is the most important form of P as it is the form used by aquatic biota. Soluble PO_4^{3-} can react with cations (e.g., iron, aluminum, calcium and manganese) to form stable minerals, adsorb to sediment, or be taken up by plants and converted to organic P. Organic P can be returned to a system as PO_4^{3-} by animal wastes and the decomposition of plant materials. P tends to accumulate in sediment, presenting major challenges for water quality management efforts. “Legacy” P that has accumulated in landscapes may act as a source of P to water bodies for a long time, even after changes in land use and management practices are implemented (Jarvie et al., 2013).

Due to its tendency to accumulate in sediment, there is a long-held belief that PO_4^{3-} is not very mobile in groundwater, and that surface runoff and sediment erosion dominate P loading to surface waters (e.g., Owens and Shipitalo, 2006; Sharpley et al., 1993). However, increasing evidence suggests that, under certain hydrogeological and geochemical conditions, PO_4^{3-} can be mobile in groundwater. An assessment of P concentrations in national groundwater quality monitoring data from Republic of Ireland, Northern Ireland, Scotland and England and Wales indicated that the majority of samples had P concentrations above important ecologically relevant thresholds (Holman et al., 2008). Roy and Malenica (2013) also provide a list of studies that have reported high dissolved PO_4^{3-} in groundwater in both rural and urban settings. PO_4^{3-} tends to be more mobile in aquifers with high pH water, high organic content, low metal oxide content and anoxic conditions (Carlyle and Hill, 2001; Domagalski and Johnson, 2011; Domagalski and Johnson, 2012). PO_4^{3-} mobility can also be high when sediments have become saturated with P.

4.3 Nutrients in Groundwater in the Great Lakes Basin

Groundwater quality in the Great Lakes Basin is generally good but nutrient concentrations, particularly NO_3^-; are often elevated in urban and agricultural areas (Dubrovsky et al., 2010; IJC Great Lakes Science Advisory Board (GLSAB), 2010). Groundwater nutrient concentrations vary widely due to land use practices, landscape characteristics and local hydrogeological and geochemical conditions. Groundwater quality is routinely monitored at wells throughout the Great Lakes Basin, especially at the local level where groundwater is a source of drinking water. The U.S. Environmental Protection Agency (EPA) drinking water standard (Maximum Contaminant Level) and the Ontario Drinking Water Quality Standard for NO_3^- are 10 mg/L (as N) (Ontario Ministry of the Environment, 2008; U.S. EPA, 2002). The Canadian Guideline For The Protection Of Aquatic Life is even lower (2.95 mg NO_3--N/L).

Regional groundwater quality networks such as the USGS NAWQA Program have been established and these networks improve the availability and accessibility of historical groundwater quality data (IJC GLSAB, 2010). Groundwater quality data routinely collected at the local level however is not included in these regional networks and databases. While no reports compiling and assessing groundwater quality in the Great Lakes Basin, including historical trends, were found (U.S. and/or Canadian), the USGS NAWQA Program reported that NO_3^- concentrations exceeded background levels in 64% of shallow aquifers sampled in agricultural and urban areas across the U.S. (Dubrovsky et al., 2010). Further, a survey of farm drinking wells sampled through Ontario showed 14% of wells had NO_3^--N concentrations above the 10 mg/L drinking water quality limit (Goss et al., 1998).

The USGS NAWQA Program found that concentrations of other nutrients, including P and other forms of N, were generally not elevated in most areas (Dubrovsky et al., 2010). However, most groundwater wells are not located in riparian zones, where geochemical reactions generally decrease NO_3^- and increase PO_4^{3-} concentrations in groundwater prior to its discharge to surface waters. Therefore groundwater assessments such as the USGS NAWQA Program likely do not provide a complete picture of the impact groundwater has with respect to transporting PO_4^{3-} to surface waters (Holman et al., 2008; Roy and Bickerton, 2014).

4.4 Sources of Nutrients in Groundwater

4.4.1 Agricultural Sources

The application and storage of fertilizer and animal manures can be a source of groundwater nutrient pollution where these agricultural land use activities are practiced (Almasri, 2007; Nolan et al., 1997; Withers and Lord, 2002). With about 35% of land in the Great Lakes Basin being farmed, agriculture is a significant potential source of nutrients to aquifers, particularly in the southern and eastern portions of the basin where agriculture is an important land use activity (McIsaac, 2012).

Although the intensity of agriculture in the Great Lakes Basin continues to increase, P fertilizer application rates have slightly decreased in recent years due to the implementation of legislation requiring nutrient management plans. N fertilizer application rates however have "remained constant or increased at a relatively slow rate" (McIsaac, 2012). Lefebvre et al. (2005) reported that NO_3^- leaching to groundwater increased by about 24% between 1981 and 2001, due mainly to increasing fertilizer application and livestock numbers. There are some federal–provincial programs in place to promote best management practices that are designed to reduce groundwater NO_3- contamination, however their adoption by agricultural producers needs to be improved (The Council of Canadian Academies (CCA), 2009).

Subsurface artificial drainage systems, including tile-drains, are often used in agricultural areas throughout the Great Lakes Basin. These systems provide a direct conduit to surface waters and as a result may rapidly deliver leached nutrients to surface waters (Dinnes et al., 2002; Hansen et al., 2002; van Es et al., 2004). Dinnes et al. (2002) provides a good overview of the impact of tile drains in transporting transport nutrients from soil to surface waters in Midwestern U.S. agricultural environments.

Intensive livestock operations are of particular concern for nutrient groundwater pollution due to the large amount of manure produced and the potential for its improper storage and land application. The resulting accumulation of nutrients in the soil can lead to excessive N and P concentrations in groundwater and have long lasting effects (Sharpley et al., 2013).

4.4.2 Non-Agricultural Sources

Many non-agricultural sources also contribute to nutrient groundwater pollution. In some cases, NO_3^- concentrations in groundwater have been found to be higher in urban areas than in surrounding agricultural areas (Nolan et al., 1997; Wakida and Lerner, 2005).

Septic systems. An estimated 20% of septic systems cause excessive nutrient leaching into groundwater due to poor design, poor maintenance and inappropriate site conditions (CCA, 2009; IJC, 2011). Many waterfront residences along the shores of the Great Lakes are located where the conditions are not suitable for the use of septic systems (IJC, 2011). Also, many small seasonal cottages are being replaced by large year-round homes that continue to use septic systems despite considerable increases in water use. The IJC GLSAB (2010) has summarized the extent of septage application and related policies, septic system installations, failure rates, regulations and management initiatives in the Great Lakes Basin.

Leaky infrastructure. In urbanized areas, leaky underground sewer lines are a concern for groundwater quality (see also Sections 6.1.1 and 6.1.2). The IJC GLSAB (2010) estimates that 30% conveyance loss is common, that thousands of line breaks occur every year in the Great Lakes Basin due to aging infrastructure, that 85% of U.S. water infrastructure will have reached the end of its life by 2020, and that about 45% of the sewer lines in the U.S. will be in poor or worse condition then. Nutrient loading to groundwater from leaky sewers in the basin is not well quantified and merits study.

Landfills and industry. The effect of municipal and industrial landfills on groundwater quality in the Great Lakes Basin has been widely reported (Coakley, 1989). Leachate from municipal landfills typically has a high content of N, predominantly NH_4^+, with concentrations between 50 - 2200 mg/L observed (Christensen et al., 2001; Kjeldsen et al., 2002). While protective regulations are now in place throughout the basin, landfills, particularly closed unlined landfills, may be long-term sources of nutrients to aquifers (Eyles and Boyce, 1992). Many landfills are located along the shores and tributaries of the Great Lakes, thus increasing the likelihood of leachate impacting surface waters.

Current and historical industrial activities can also be sources of nutrients to groundwater. N and P compounds are used in many industrial processes (e.g., textile, plastic and metal treatments, steel production, household and pharmaceutical production) (Wakida and Lerner, 2005). Elevated nutrient concentrations in groundwater are also associated with poor leachate disposal at coal gasification facilities, including discharges with NH_4^+ concentrations between 50 - 1000 mg/L (Wakida and Lerner, 2005).

Atmospheric deposition. In less developed areas of the Great Lakes Basin, atmospheric deposition may be the largest non-point source of N to groundwater (Dubrovsky et al., 2010). Atmospheric deposition includes inputs from rain and snow (known as wet deposition), and gaseous and particulate transport from the air to terrestrial and aquatic landscape surfaces (known as dry deposition). The highest N deposition rates in the U.S. (>2 tonnes per square mile) are estimated to occur in a band from the upper Midwest through the Northeast states (Dubrovsky et al., 2010). Although atmospheric deposition of P is often considered insignificant compared with N deposition, recent studies suggest that atmospheric deposition may be an important source of P to groundwater, particularly near areas with considerable land disturbances such as agricultural activities (Anderson and Downing, 2006).

Non-agricultural fertilizers. Fertilizer use in gardens, lawns, domestic horticulture, parks and golf courses contributes nutrients to groundwater. The total quantity of urban fertilizer use is small compared with agricultural areas, but studies have shown that more nutrients leach to groundwater from fertilizer use on a per area basis in urban areas than in agricultural areas (Balderacchi et al., 2013; Wakida and Lerner, 2005). Increasingly, shoreline residents along the Great Lakes replace native vegetation (e.g., beach grasses) with turf grass (Crowe and Meek, 2009), potentially increasing fertilizer use and nutrient loading to the lakes.

4.5 Discharge of Nutrients from Groundwater to Surface Waters

Nutrient loading to surface water from groundwater is affected by water percolation through the unsaturated zone, groundwater flowpaths and nutrient biogeochemistry (i.e. from recharge to discharge). Groundwater flows into the Great Lakes either directly, near the shoreline or lake bottoms, or indirectly, into tributaries that then discharge into the lakes (see Section 2.3). The amount of groundwater flowing in shallow glacial deposits in the Great Lakes Basin is generally much larger than that flowing in deeper regional bedrock aquifers (Reilly et al., 2008). The shallow glacial deposits are also more vulnerable to contamination from anthropogenic activities and associated with shorter transport pathways and residences times for nutrients in the aquifer. Regional aquifers recharge and discharge over larger areas and have longer flowpaths, thereby providing more time for geochemical reactions to take place. As with local aquifers, regional aquifers can also be affected by land use and may have legacy nutrient storage. The balance of the quality and quantity of the local and regional aquifers is an important component of Great Lakes water quality.

4.5.1 Indirect Groundwater Discharge

Groundwater discharge to tributaries can have beneficial or adverse effects on water quality in tributaries. While inputs of high quality groundwater can dilute poor quality surface water, in some cases poor quality groundwater can deteriorate surface water quality and thus aquatic ecosystems (Domagalski and Johnson, 2012; Puckett and Hughes, 2005; Sandford and Pope, 2013). Tributary water quality is especially affected by groundwater inputs during low flow periods when base-flow is sustained mainly through groundwater discharge (Environment Canada (EC) and U.S. EPA, 2009; Stamm et al., 2013).

The contribution of groundwater nutrient loading to water quality in the tributaries of the Great Lakes Basin is not well understood. Due to its high mobility in groundwater, a significant portion of NO_3^- in tributaries may be derived from groundwater, particularly in areas where NO_3^- is elevated in shallow aquifers (e.g., Dubrovsky et al., 2010; Pärna et al., 2012; Ranalli and Macalady, 2010). For instance, in the Chesapeake Bay watershed it is estimated that groundwater contributes 48% of the total annual N load to streams (Bachman et al., 1998). P loading from groundwater may also be significant, particularly in settings with coarse-grained soils and shallow confining layers, soils that are artificially drained, or where there is preferential flow through fractures and macropores (Domagalski and Johnson, 2011; Domagalski and Johnson, 2012; Holman et al., 2008; Roy and Bickerton, 2014). There is increasing recognition that the ecological health of a freshwater tributary may be controlled by continuous P inputs, such as groundwater discharge, that dominate during periods when the biological demand is greatest, (e.g., low flow periods during summer) (Holman et al., 2008; Stamm et al., 2013). Therefore, although event-based P loading (i.e. surface runoff) may dominate annual loads in some watersheds, continuous loading of groundwater P may be more important for overall tributary health (Holman et al., 2008; Stamm et al., 2013).

Evaluating groundwater nutrient loading to tributaries is extremely challenging. Firstly, indirect groundwater discharge is difficult to quantify due to high temporal and spatial variability. Furthermore, the discharge of nutrients is controlled not only by the groundwater discharge rates, but also by the specific nutrient sources (Section 4.3), and the complex biogeochemical reactions and hydrological processes occurring during nutrient transport. Additionally, nutrient loading from groundwater is often highly regulated by intense biogeochemical and/or hydrological activity occurring in localized areas (hot spots) or periods in time (hot moments) in landscapes such as riparian and hyporheic zones (McClain et al., 2003; Vidon et al., 2010).

Riparian zones. Riparian zones are at the interface between the land and tributary where groundwater interacts intensively with vegetation and soil (Figure 4.2). These zones are biogeochemical hotspots that are important for the retention, attenuation and production of nutrients, and often act as buffers by removing nutrients in groundwater prior to their discharge to surface waters (Mayer et al., 2005; Vidon et al., 2010). Reviews are available that detail the importance of riparian zones in regulating groundwater nutrient loading to surface waters, including the use of riparian zones as nutrient management tools (Gold et al., 2001; Mayer et al., 2005; Ranalli and Macalady, 2010; Vidon et al., 2010).

Nitrate is often attenuated in riparian zones by denitrification, and uptake by vegetation and microorganisms (Ranalli and Macalady, 2010). The extent of attenuation is complex and depends on the geomorphology, subsurface hydrology (soil saturation, groundwater paths, hydrogeological heterogeneities), subsurface biogeochemistry (redox conditions), temperature, and human alterations (e.g., drainage networks) (Ranalli and Macalady, 2010; Vidon et al., 2010; Vidon and Hill, 2004). A study by Hill (1996) that examined twenty riparian zones in Ontario found NO3- removal from groundwater prior to discharge to adjacent surface waters ranged from 65 - 100%.

Loading of groundwater P to tributaries may also be affected by riparian zones whereby P can be attenuated by sediment retention processes (e.g., adsorption, precipitation) and biotic uptake (Hoffmann et al., 2009). These attenuation processes generally only lead to temporary P storage; stored P can later be released and exported to streams under different hydrological or geochemical conditions (Carlyle and Hill, 2001; Hoffmann et al., 2009; Roy and Bickerton, 2014). In a study of groundwater P fluxes through a riparian zone in an agricultural area in southern Ontario, Carlyle and Hill (2001) demonstrated that at any given time, both external P inputs and internal P stores contribute to P loading to streams via groundwater.

Hyporheic zones. The hyporheic zone (see Figure 2.4) also regulates nutrient fluxes in watersheds (Ranalli and Macalady, 2010). Reactions occurring in this zone can significantly modify the chemistry of discharging groundwater and recirculating surface water (Gu et al., 2008). Significant research has focused on evaluating reactions occurring in the hyporheic zone that can both produce (via organic matter mineralization and nitrification) and consume (via denitrification) N derived from surface waters and groundwater (Briggs et al., 2014; Kasahara and Hill, 2007; Vidon et al., 2010). Hyporheic zones can also regulate P by providing temporary storage of P during base-flow conditions (Thompson and McFarland, 2010). Similar to riparian zones, the functioning of hyporheic zones is extremely complex and strongly influenced by spatial heterogeneities, hyporheic flowpath residence times, and hydrological events such as streambank flooding (Gu et al., 2008; Harvey et al., 2013).

4.5.2 Direct Groundwater Discharge

Direct discharge of groundwater to the Great Lakes can occur either near the shore with discharge from permeable aquifers (Crowe and Meek, 2009; Grannemann et al., 2000) or at discrete offshore points (e.g., sinkholes, Ruberg et al., 2005). Although direct groundwater discharge is only estimated to be a small component in the Great Lakes water balances (see Section 2.3), it may play a disproportionately important role in delivering nutrients to the lakes (CCA, 2009; Grannemann et al., 2000). In particular, nutrient loading via direct groundwater discharge may be considerable where shallow aquifers in shoreline areas have high nutrient concentrations (Johannes, 1980).
No conceptual frameworks are available that can be applied as screening tools to evaluate the potential for direct groundwater discharge along a shoreline, and moreover to evaluate if groundwater may be an important pathway

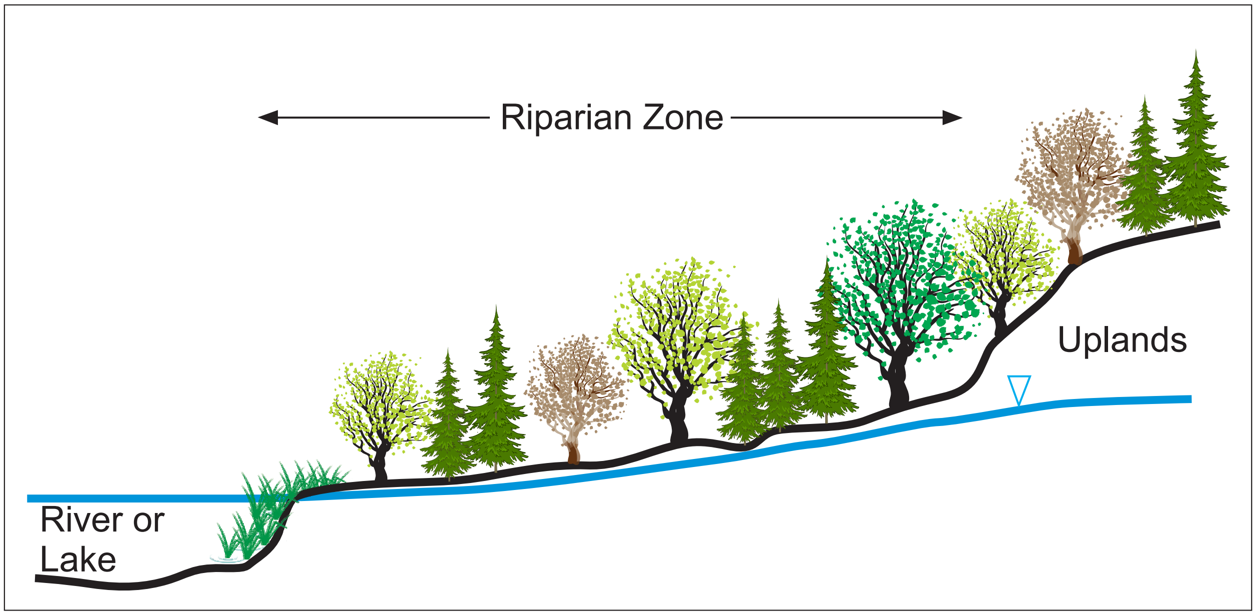

Figure 4.2. Example of the relative position of a riparian zone in the landscape.

in delivering nutrients to nearshore waters. In some jurisdictions it is acknowledged that nutrient concentrations (particularly NO_3^-) are elevated in shallow aquifers, however it is unclear if there is a link between groundwater nutrient pollution and deteriorating nearshore water quality. Howard and Livingstone (2000) illustrated via computer modeling that sources including landfills, septic systems and fertilizers may deliver high quantities of nutrients into Lake Ontario over a long time period (>100 years).

Similar to hyporheic and riparian zones, a zone of high biogeochemical reactivity may exist near a groundwater-lake interface that ultimately regulates the flux and speciation of groundwater nutrients discharging to the lake (Charette and Sholkovitz, 2006; Robinson et al., 2007). While the factors controlling groundwater flows, and nutrient transformation have been relatively well studied near the groundwater/surface water interface in oceans (Anwar et al., 2014; Kroeger and Charette, 2008) and tributary settings (Briggs et al., 2014; Harvey et al., 2013), little is known regarding the reaction zone that exists at the interface of large inland waters, such as the Great Lakes (Crowe and Meek, 2009; Haack et al., 2005; Lee et al., 2014).

4.6 Knowledge Gaps and Research Needs

Although increasing amounts of evidence demonstrate that groundwater is significant for the water quality and health of the Great Lakes and its tributaries, the effects of groundwater on nutrient enrichment of surface waters remains unclear. As a result, the groundwater contribution is poorly managed and often ignored. Priority needs to be given to generating the fundamental science required to understand groundwater as a source of nutrients to surface waters in the Great Lakes Basin and generating science-based tools that can be applied by program managers and policy makers. Major knowledge gaps and priorities are outlined below.

i) Linkage between land-use, land management and groundwater nutrient loading

While numerous reports and scientific studies indicate the linkage between land-use practices and groundwater nutrient pollution, the role of these activities in delivering nutrients to surface water via the groundwater pathway is often not well understood. The transport and transformation of nutrients in groundwater, particularly close to the groundwater-lake interface, are extremely complex and nutrients may be attenuated or produced in the subsurface close to the point of discharge (e.g., riparian and hyporheic zones). Furthermore, the delivery of nutrients to surface waters via the groundwater pathway is highly time-dependent due to slow groundwater travel times and retardation of nutrients, particularly P, by sediment interactions (Ray et al., 2012; Sanford and Pope, 2014). This time lag between when land-use changes or nutrient management strategies are implemented and when changes are expected in the surface water quality needs to be considered when evaluating the impact of these scenarios on water quality. This lag effect, including the long-term effects of "legacy" nutrient accumulation in landscapes, is not well understood, although it needs to be incorporated into management decisions and water quality assessments.

The potential effect that the various nutrient sources may have on groundwater quality needs to be prioritized so that research effort can focus on investigating sources that are either associated with the highest level of uncertainty and/or may contribute significantly to nutrient loading to the surface waters. Research effort also needs to be devoted to evaluating the effectiveness of nutrient best management practices in different landscapes throughout the Great Lakes Basin for reducing nutrient exports to surface waters. Stakeholder investment in managing groundwater resources in agricultural and urban settings where nutrients are a major issue is imperative.

Local stakeholders (landowners, local jurisdictions) often do not have the tools and practical knowledge to effectively reduce groundwater nutrient loading to nearshore waters and tributaries. Priority needs to be given not only to generating the fundamental science required to better understand groundwater nutrient sources, transport pathways and loading to surface waters but also to ensuring that the science generated is relevant and can be applied by program managers and policy makers.

ii) Role of hot phenomena in regulating groundwater nutrient fluxes to surface waters

The importance of biogeochemical and hydrological hot spots and hot moments in regulating nutrient loading from groundwater to surface water in tributary settings is now well recognized (e.g., Vidon et al., 2010). This presents a new set of challenges in that new measurement techniques are needed that are capable of capturing the associated high temporal and spatial variability. Temporal, trending and seasonal groundwater quality data collection is rare and therefore the seasonality of groundwater recharge and discharge is not well understood.

While studies of hot phenomena (spots, moments) associated with groundwater-riverine (hyporheic zone, riparian zones) and also groundwater-ocean (subterranean estuary) interactions are active areas of research, there is little understanding of how these phenomena regulate the flux of groundwater nutrients directly into the Great Lakes. This knowledge gap needs to be addressed to improve prediction of nutrient loading to nearshore waters along different types of shoreline so that the contribution of direct groundwater discharge can be effectively managed.

iii) Upscaling local scientific understanding to regional scale assessment

Although numerous small-scale studies have been conducted in the Great Lakes Basin that provide valuable understanding of nutrient groundwater inputs, upscaling site specific findings for application at stream-reach, watershed and basin scales represents a major challenge. There is an urgent need to develop the techniques for upscaling detailed scientific knowledge so that the relative contribution of groundwater to nutrient loading to surface waters can be evaluated at larger scales. Identifying the landscape controls on groundwater nutrient fluxes in representative physiographic and climate settings and developing a system of classifying landscapes in the Great Lakes Basin may be a first step in developing tools to identify watersheds where groundwater nutrient fluxes impact surface water quality. Identifying priority watersheds in the basin will also enable resources and research efforts to be allocated to areas where groundwater is likely to have the greatest ecological impact on surface waters.

iv) Availability and systematic assessment of groundwater quality data

Although regional scale groundwater quality monitoring networks have been established in the U.S. and Ontario, there is a large abundance of groundwater quality data collected locally that is not widely available or easily accessible. Monitoring well data collected by local jurisdictions may provide important insights into the occurrence and distribution of nutrients in aquifers in the Great Lakes Basin, and linkages with land use activities (EC and U.S. EPA, 2009; IJC, 2011). However, existing monitoring networks were generally not designed to address nutrient issues specifically, often sampling groundwater from deeper aquifers rather than the more vulnerable shallow aquifers. Therefore existing monitoring networks may need to be augmented to assess temporal and longer term trends of nutrients in groundwater.

In addition to compiling new and historical groundwater quality data so it is available and accessible, there is a need for regular systematic assessment of nutrient groundwater quality trends in the Great Lakes Basin (both U.S. and Ontario). A summary that provides a comprehensive picture of chemical pollutants, including nutrients, across the basin, and evaluates data with regards to the hydrogeological conditions and land-use practices, is required.

While a concerted effort goes into geological and hydrogeological mapping in both the U.S. and Canada by federal, state and provincial governments, mapping data, particularly at the stream-reach or watershed scale is often not widely available and accessible. Co-ordinated mapping efforts are needed to help determine the local and regional impacts of groundwater flow on surface water bodies, including identifying groundwater recharge and discharge areas, the extent of offshore aquifers and associated discharge zones, and the delineation of riparian zones. Mapping of shallow unconfined aquifers is the most urgent for nutrient management efforts as these aquifers are the most susceptible to nutrient pollution, and generally interact most intensively with surface waters.

Table 4.1 Priority science needs related to groundwater and nutrients.

Priority Science Needs	Related needs and information gaps
4A. Linking land management and groundwater nutrient loading	• Acknowledgement that groundwater nutrient loading is linked to land management • Evaluation of best management practices for reducing groundwater nutrient export to surface waters • Understanding the temporal lag between the implementation of best management practices and improvements in groundwater and surface water qu ality
4B. Role of hot phenomena with respect to groundwater nutrient fluxes	• Groundwater sampling to evaluate the spatial and temporal variability associated with hot phenomena • Research on the importance of hot phenomena with respect to direct groundwater nutrient discharge to the Great Lakes
4C. Upscaling of site specific knowledge	• Development of tools for scaling up local groundwater knowledge for application at watershed and basin scales • Identify the landscape controls on groundwater nutrient fluxes • Identify priority watersheds in which to focus research efforts
4D. Basin-wide assessment of groundwater	• Compile historical groundwater quality data • Augment monitoring networks to assess groundwater nutrient trends • Regular systematic assessment of groundwater nutrient trends in Great Lakes Basin • Increase availability of hydrogeological mapping products

5. GROUNDWATER AND AQUATIC HABITATS IN THE GREAT LAKES

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5.1 Introduction

This chapter discusses the mechanisms by which groundwater influxes shape nearshore, tributary and wetland ecosystems in the Great Lakes Basin. It complements Chapter 2, 3 and 4, which focus on groundwater and surface water hydrology, contaminant and nutrient dynamics. Understanding groundwater-habitat interactions will contribute directly towards meeting commitments that are specified in Annex 2 and 7 of the GLWQA. Annex 2 outlines commitments to develop an integrated Nearshore Framework to be implemented collaboratively through the lakewide management process for each Great Lake. Activities under Annex 7 of the Protocol makes specific revisions to contribute to the achievement of the general and specific objectives of are intended to help conserving, protecting, maintaining, restoreing and enhanceing the resilience of native species and their habitat, and to supporting essential ecosystem services.

Groundwater influences the water budgets and availability of suitable habitat for organisms within the Great Lakes, coastal wetlands, and the inland lakes, streams and wetlands within the Great Lakes Basin. It is recognized as an important factor maintaining ecosystem function in many streams and wetlands (Grannemann et al. 2000; Fig. 5.1). Groundwater fluxes into and out of aquatic ecosystems can shape the hydrological, thermal and chemical characteristics of those systems and consequently, the quantity, quality and types of habitats available to biota.

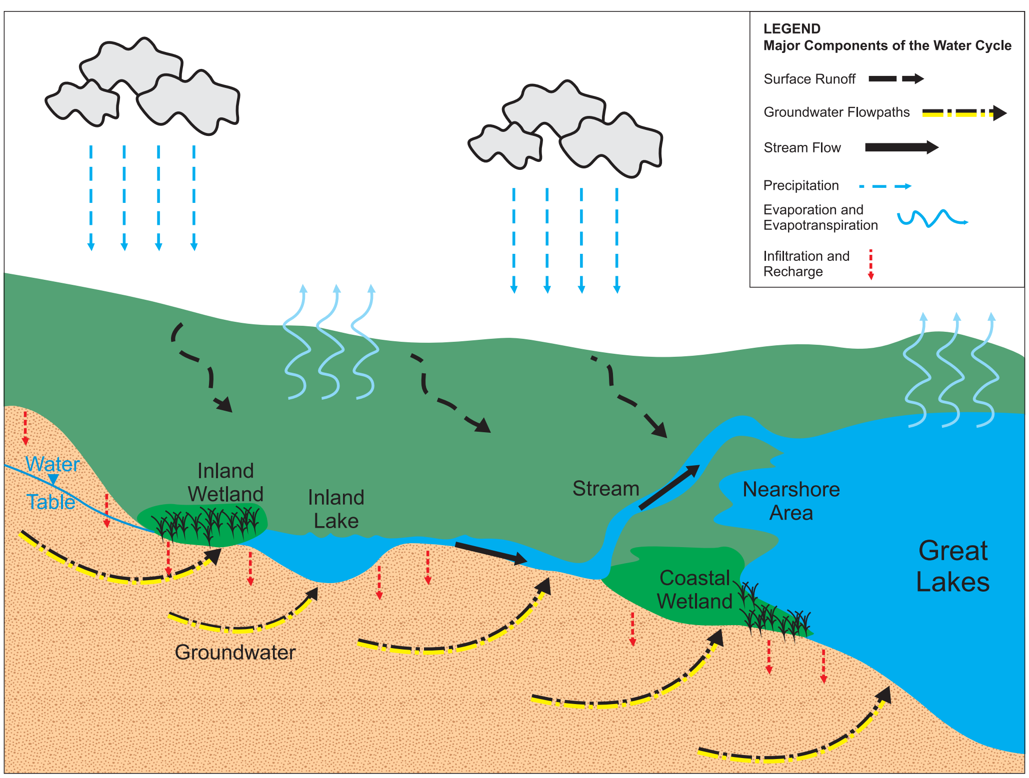

Figure 5.1. Schematic of groundwater flow through wetland stream and lake ecosystems. Modified from Li (2015).

In the Great Lakes region, groundwater is, in essence, a large, subsurface reservoir (~4,920 km3 in volume; Great Lakes Science Advisory Board to the IJC, 2010) from which water slowly discharges to surface environments (aquatic and terrestrial) (Chapter 2). The quantity and timing of these releases affect the hydrology of tributaries and wetlands, and to a lesser extent, the Great Lakes, by supplying a reliable minimum inflow between precipitation and snow melt events (Grannemann et al. 2000; Winter 2007).

Temperature is one of the most important drivers in temperate aquatic ecosystems. Species are physiologically adapted to thermal niches, and the availability of suitable thermal habitat influences their growth, survival, timing of reproductive events and distribution (Caissie, 2006). Groundwater temperatures within 100 m of the surface are typically 1 - 2°C greater than the mean annual air temperature (Freeze and Cherry, 1979). Groundwater temperatures typically range from 5°C to 13°C in the Great Lakes Basin (unpublished data: United States Geological Survey, Ontario Ministry of the Environment and Climate Change). Surface water temperature varies more seasonally and diurnally than groundwater temperature, therefore, influxes of groundwater can attenuate diurnal and seasonal changes in surface water temperature, leading to cooler temperatures in summer and warmer temperatures in winter.

The chemical composition of groundwater affects water quality in aquatic habitats, and can be influenced by both the surrounding geology, the length of time the water has spent in the ground and human activities in the watershed e.g., point-source pollution (Winter et al. 1998) (Chapters 2-4). Most of the direct groundwater discharges to the Great Lakes originate from local flow (shallow) systems, often in sand and gravel aquifers (Grannemann et al., 2000; Kornelsen and Coulibay, 2014; Chapter 2). This type of groundwater often has a chemical composition similar to that of lake water whereas groundwater from regional aquifers (deeper and longer flowpaths) bears very little resemblance to the chemical composition of lake or surface water. Discharges from these aquifers could create sharp chemical gradients in pore water near the lakebeds (Haack et al. 2005) and at point discharges, as has been documented for a sinkhole in Lake Huron (Biddanda et al. 2006).

5.2 Influence of Groundwater in Great Lakes Habitats

Groundwater provides a link between the Great Lakes and their watershed and therefore has significant influence on aquatic habitats in the Great Lakes region. Here we address aquatic habitat in Great Lakes nearshore areas, tributaries to the Great Lakes, and Great Lakes Basin wetlands. Groundwater affects aquatic habitat in these areas by influencing their hydrological, thermal, and chemical characteristics (Table 5.1).

5.2.1 Nearshore Areas

Nearshore areas of the Great Lakes provide essential habitat for biota and link the terrestrial watershed and open water. They are the focal areas for water quantity, water quality and natural resource issues in the Great Lakes because they are the regions of lakes that are most affected by human stressors such as polluted runoff, regulated water-level fluctuations and shoreline hardening (Haack et al. 2005; IJC 2009). Groundwater influxes into nearshore areas impact their hydrology, water temperature, clarity and chemistry, and thus the availability of suitable habitat for resident species (Haack et al. 2005).

In general, direct groundwater discharge to the Great Lakes is highest in nearshore areas and decays offshore (Kornelsen and Coulibaly 2014). Heterogeneities in discharge are formed by differences in hydraulic gradients and the hydraulic properties of nearshore rocks, unconsolidated materials and/or lake bottom materials. Lake bottoms and shores with glacial till, sandy or silty-sand materials tend to have higher groundwater discharge rates than clay and silt materials (Grannemann and Weaver 1998; Neff et al. 2005). Shoreline configuration, onshore heads and topography, and lake bathymetry also influence groundwater discharge (Grannemann and Weaver 1998). The spatial and temporal variability in groundwater discharge created by these factors and other coastal hydrological processes - water-level fluctuations (storm surges, seiches, seasonal water level changes), long shore and offshore currents and run-off (Haack et al. 2005) influence the quantity, quality and types of habitats available to biota.

5.2.1.1 Hydrological characteristics. As indicated above, most groundwater discharge enters the lakes through tributaries, with only a small portion entering the lakes directly. For example, it is estimated that groundwater discharge to streams entering Lake Michigan is about 906 m3/s versus direct groundwater discharge of about 76.5 m3/s (Grannemann et al. 2000). While direct groundwater inputs may be more stable temporally than other more weather-dependent components of the Great Lakes' water budgets, their volume is small, relative to some of the other hydrological fluxes (i.e. tributary inputs, evaporation). It is expected that the stabilizing effect of direct groundwater discharge on Great Lakes' water levels is proportional to the discharge volume and therefore, also relatively small.

5.2.1.2 Thermal characteristics. Direct groundwater inputs to nearshore areas have the potential to affect near-shore thermal habitat. The influence of thermal regimes (of which groundwater temperature is a component) on habitat, species distributions, growth and community composition have been well-documented for different taxa: macrophytes (Rosenberry et al. 2000), zooplankton (Thomasen et al. 2013), ichthyoplankton (McKenna et al. 2008), and fishes (Stewart and Bowlby 2009). As noted above, groundwater temperatures in the Great Lakes Basin generally range from 5°C to 13°C, which is typically cooler than nearshore water temperatures in summer and warmer than nearshore water temperatures in winter. However, the influence of groundwater on the overall thermal regimes of the Great Lakes is limited because of the dominance of heat exchange at the air:water interface and the thermal inertia of the large volume of lake water. The thermal effect of groundwater is likely to be greatest within the substrate and at the groundwater:surface water interface. Benthic biota are most likely to be affected by thermal heterogeneity within the Great Lakes substrates but, to the best of our knowledge, there has been no research in this area. Brook Trout (Salvelinus fontinalis) is the only Great Lakes fish species that is thought to spawn exclusively in areas of groundwater discharge (Snucins et al. 1992: Curry and Noakes 1995; Blanchfield and Ridgway 1997; Guillemette et al. 2011, Van Grinsven et al. 2012). It has been suggested that this behavior may increase survival of the embryos of this fall-spawning species, particularly when cold winters can, in the absence of groundwater, cause redds to freeze and embryos to perish (Curry and Noakes 1995; Blanchfield and Ridgway 1997; Guillemette et al. 2011). Within the Great Lakes proper, Brook Trout now occur only in a few areas of Lake Superior (Huckins et al. 2008). Most of the Lake Superior populations are adfluvial (Van Grinsven et al. 2012; Mucha and Mackereth 2008; D'Amelio et al. 2008) but presumptive spawning areas have been documented in Isle Royal embayments (Gorman et al. 2008) and there are reliable anecdotal reports of Brook Trout spawning at a few locations on the Canadian side of Lake Superior (R. Swainson, OMNR biologist, Nipigon, Ontario; pers. comm. with C. Portt).

5.2.1.3 Chemical characteristics. Chemical characteristics of groundwater inputs to nearshore waters are related to characteristics of the water-bearing sediments and rocks, the length of time water is in contact with them and any human activities in the area that may introduce contaminants (see Chapter 3). The most common bedrock aquifers in the region are carbonate rocks such as limestone and dolomite (Fig. 2.2; Chapter 2). Carbonate minerals are also common in the sediments (glacial deposits, lake and stream sediments) that overlie bedrock and can have a strong influence the chemical characteristics of the groundwater, particularly the concentrations of dissolved inorganic carbon, calcium and magnesium. Silicate minerals are also abundant in the subsurface and they exert a strong influence on groundwater chemistry when it reacts with the sediments and rocks through which it flows. Less abundant are a wide range of other minerals such as metal sulfides and gypsum. Weathering of these minerals contributes a range of solutes to groundwater including silica, sulfate, sodium, potassium, calcium, magnesium and various metals (see Chapter 2 and 3). Due to the interaction of groundwater with sediments and rocks, it is often depleted in dissolved oxygen relative to surface water, which can make condition uninhabitable for some biota at discharge sites. The chemical influence of groundwater on nearshore waters is likely strongest in the substrate and at the groundwater-nearshore water interface.

5.2.2 Tributaries

Tributaries are streams and rivers that supply water to the Great Lakes. Tributaries provide a connection between watersheds and the lakes by transporting surface water and groundwater to the lakes. In this process they also transport nutrients and pollutants and provide habitat for thousands of riparian and riverine flora and fauna. Tributaries are the principal spawning and nursery habitats for one-third of the fishes in the Great Lakes (Lane et al. 1996).

Tributaries supply significant amounts of water to the Great Lakes: 41% of water inputs for Lake Superior, 46% for Lakes Michigan and Huron, 47% for Lake Erie and 67% for Lake Ontario (Great Lakes Commission, 2003). It is estimated that 40–75% of this water is derived from groundwater inflow to the tributaries. Therefore, the total groundwater discharge entering the Great Lakes through tributaries is estimated to be 20–40% of the total inflow to the Great Lakes (Kornelsen and Coulibaly 2014). Discharge of direct groundwater into tributaries is spatially variable due to spatial variability in surficial and bedrock geology, which influence the rates at which precipitation infiltrates and is conveyed and storage capacity. Climate influences the amount of precipitation that is available for infiltration. At a given location, temporal variability in groundwater discharge is primarily due to variability in weather /climate.

5.2.2.1 Hydrological characteristics. Groundwater discharge and surface runoff (from adjacent riparian and upland areas in the catchment) combine to form streamflow that supplies water to the lakes. In this simplified description, surface runoff is a short-term component of streamflow resulting from precipitation or snowmelt events whereas groundwater discharge is a more stable component. Groundwater discharge affects the hydrology and physical structure, biogeochemistry, water quality and ecology of tributaries (Jones and Mulholland, 2000). Spring-fed headwaters are characterized by hydrological and thermal stability that can persist during drought conditions (Stubbington and Wood, 2013).

5.2.2.2 Thermal characteristics. The influence of direct groundwater discharge on stream temperature, and thus on stream communities is widely recognized (Ricker, 1934; Chu et al., 2010; Stewart et al., 2015). Groundwater directly discharging into streams can moderate both summer and winter temperatures at the discharge site and downstream. The magnitude of the thermal effect is roughly proportional to the relative volumes of surface and groundwater. Once groundwater enters a stream it becomes subject to the heat fluxes that affect stream temperature, the largest of which occur at the air:water interface. Where groundwater mixes with surface water prior to reaching the stream, for example as a consequence of hyporheic exchange, the effect on stream temperature may be diminished. In winter, groundwater seeps provide overwintering habitat free of subsurface ice, and mobile species actively seek and inhabit them (Power et al. 1999). In summer, direct groundwater discharge cools stream temperatures, and provides refuges for species exposed to temperatures approaching their thermal limits during hot weather (Power et al. 1999; Stubbington and Wood 2013). Sites with higher groundwater discharge may also support higher stream benthic invertebrate abundance, taxonomic richness and periphyton respiration (Hunt et al. 2006).

5.2.2.3 Chemical characteristics. Chemical characteristics of groundwater inputs to tributaries like those of groundwater inputs to Great Lakes nearshore areas, are related to characteristics of the water-bearing sediments and rocks and the length of time water is in contact with sediments and rocks (i.e., the residence time of groundwater, before it discharges to streams). Inputs from specific groundwater flow systems to individual streams may have a strong influence on their chemical characteristics, particularly when groundwater constitutes a large proportion of the water (up to 100% at some times in some locations). In contrast, the chemistry of water in the Great Lakes, which has a much longer residence time, is strongly affected by mixing processes and a significant portion of the water in the lakes is derived from direct precipitation. This greater influence of groundwater on the chemical characteristics of tributaries may in turn influence the aquatic flora and fauna present in tributaries.

5.2.3 Wetlands

Wetlands are among the most ecologically diverse and biologically productive systems in the Great Lakes region. Coastal wetlands act as a transitional zone between watersheds and the lakes, and they play an important role in mitigating and filtering human impacts on water resources (Grannemann et al. 2000). Wetlands in the Great Lakes improve water quality by filtering pollutants and sediment, storing and cycling nutrients and organic material from land into the aquatic food web, reducing flooding and erosion, and providing specialized spawning and nursery habitat for many Great Lakes species (Michigan Sea Grant, 2014).

Of the four commonly recognized types of wetlands (bog, fen, swamp and marsh) groundwater discharge is recognized as an important functional attribute of fens and some types of swamps (OMNR 2013, 2014). Direct groundwater contribution to Great Lakes wetlands is dependent upon the underlying geology, adjacent physiography and may be influenced by lake levels (Keough et al. 1999). Kraus and White (2009) identified rich coastal fen as the principal groundwater-dependent Great Lakes coastal wetland, noting that the surrounding uplands are typically dominated by northern white cedar (Thuja occidentalis), which is the dominant species in groundwater-influenced rich conifer swamps (Racey et al, 1996; Fig. 5.2). In rich coastal fens, groundwater provides a stable influx of water and nutrients, and may buffer the influence of lake level fluctuations on resident communities (Mortsch et al. 2006). Fens occurring in Lake Huron and Georgian Bay have been identified as having imperiled communities, and have over 40 species of provincially significant plants (Ontario Natural Heritage Information Centre 1995; Wilcox 1995). Coastal fens along the shoreline of Lake Michigan harbour 25 species of federally listed rare plants and animals (Cohen et al. 2010).

5.2.3.1 Hydrological characteristics. As indicated above, groundwater inputs are essential for fens and some types of swamps. Mortsch et al. (2008) suggested that the stability of two of the three Lake Huron coastal fens studied despite fluctuating lake levels was attributable to groundwater inputs.

5.2.3.2 Thermal characteristics. There are few studies examining the influence of groundwater on the thermal dynamics, and subsequently thermal habitat, of Great Lakes coastal fens and swamps. However, water temperature in wetlands, which is in partly determined by groundwater, mediates the biogeochemical processes governing nutrient cycling, microbial activity, and growth and reproductive activities of wetland biota. In a study of bogs, fens and swamps in the Hiawatha Upper Peninsula Forest of Michigan, Kudray and Gale (1997) found groundwater temperature differed among the three wetland types. Groundwater temperatures were the coldest in swamps, intermediate in bogs and warmest in fens. They attributed this pattern to the depth of the water table in each wetland type with fens having the shallowest and therefore warmest groundwater temperatures.

Figure 5.2. Groundwater seepage area in groundwater-influenced rich conifer swamp; orange line delineates seepage area and blue line highlights the stream. (Photo credit: C. Portt).

Table 5.1 Groundwater influences on aquatic habitats.

Habitat	Habitat influence
Tributaries and wetlands	Direct groundwater discharge can maintain flow and water supply, which affects habitat quantity year-round.
Tributaries and wetlands	At discharge sites (and downstream reaches in streams), surface water -groundwater interaction can moderate surface water temperatures, cooling temperatures in summer and warming them in winter. This can create suitable habitat for biota that cannot tolerate high temperatures, such as salmonid fishes. Direct groundwater can also provide habitat free of ice in the winter (Power et al. 1999).
Nearshore	At small-scales, direct groundwater influxes can cool nearshore water temperatures in summer and warm nearshore temperatures in the winter, but the contribution of groundwater to the overall nearshore thermal regime is likely overwhelmed by the thermal inertia and air:water interface of the Great Lakes.
Nearshore and tributaries	Groundwater discharge can provide spawning habitat for Brook Trout in tributaries. This is suspected, but has not been confirmed, in the few nearshore areas in Lake Superior where Brook Trout are known to spawn.
Nearshore, tributaries and wetlands	Groundwater influences the physical cycling and flow of nutrients and organic matter important to biota (see Chapter 3 and 4).
Nearshore and tributaries	Some microbial and invertebrate communities are adapted to conditions in the hyporheic zone (cf. Chapter 2) where biogeochemical and physical characteristics of surface and groundwaters mix to create suitable habitat.

5.2.3.3 Chemical characteristics. Groundwater can have a significant influence on the chemical characteristics of wetlands because of the dissolved minerals and nutrients carried by groundwater. Kudray and Gale (1997) found that pH, calcium concentration and manganese concentration differed among the three wetland types in a study of bogs, fens and swamps in the Hiawatha Upper Peninsula Forest of Michigan.

5.3. Science Needs

Science needs were identified to build upon the existing knowledge described in this chapter with a focus on approaches that could directly contribute to improved understanding of groundwater on aquatic ecosystems and groundwater management.

i) Map groundwater recharge and discharge.

Basic spatial information on groundwater movement has not been developed in many areas of the Great Lakes Basin, but is critical for understanding its effects on habitat. Where the appropriate data are available (geology, soils, topography, well logs), groundwater models such as MODFLOW can be used to simulate groundwater movement, including its discharge into habitats on the land surface. When developing these models, it is critical to select spatial and temporal resolutions that are relevant for the ecosystems in question. For example, if a model is to be used to simulate the hydrology of small, ephemeral wetlands, it will need a high spatial and temporal resolution. Groundwater monitoring can play a role in constructing and calibrating a model. The outputs of groundwater models can be used to target field habitat assessments and model the relationships between hydrology and ecosystem attributes.

ii) Integrate groundwater models with other ecosystem models, such as nearshore hydrodynamic, tributary and wetland thermal and hydrological models.

Between the discharge of groundwater and its effect on an ecosystem, other physical processes often play a role. For example, the influence of groundwater on nearshore habitat is likely to be related to bathymetry and circulation patterns. Surface water quality models such as SWAT (Arnold et al. 2012) could be improved by linking to the outputs of a groundwater model. To the extent that it is practical, models that simulate inter-related ecosystem components should be linked.

iii) Evaluate the importance of groundwater discharge on species distributions and ecosystem attributes.

As summarized above, the influence of groundwater on species distributions and communities in stream habitats is well recognized and many aspects are quite well understood. The influence of direct groundwater discharge to lakes, including the Great Lakes, in this regard has received much less attention. Investigations to assess the effect of groundwater discharge on species and communities, particularly benthic communities, would benefit our understanding of nearshore ecosystems.

iv) Evaluate the importance of spatial patterns in groundwater discharge on ecosystem attributes.

The effects of the patchy nature of groundwater discharge on ecosystem patterns and processes are not well studied. The patchiness of groundwater discharge may play a role in species dispersal, invasive species establishment and meta-population structure. For example, a series of spatially discrete groundwater discharges in a stream may provide thermal refuges for stenothermal organisms, but may not be individually recognized as important.

v) Identify ecosystems that are vulnerable to changes in groundwater discharge.

Prioritizing conservation ofgroundwater dependent ecosystems depends on being able to assess their vulnerability to environmental change. Vulnerability is a function of exposure (degree of stress), sensitivity (degree of response to stress), and adaptive capacity (potential to adjust to stress). For example, an organism living in a groundwater-fed stream is most vulnerable where feasible environmental changes are likely to reduce groundwater discharge to the stream, where the organism is stenothermal, and where it has no opportunities to escape the stress through migration to suitable habitat.

Table 5.2. Priority science needs related to aquatic habitats.

Priority Science Needs	Related needs and information gaps
5A. Map groundwater recharge and discharge	• Integration of monitoring data and modelling tools to map groundwater recharge and discharge areas throughout Great Lakes Basin
5B. Integrate groundwater models with other ecosystem models, such as nearshore hydrodynamic, tributary and wetland thermal and hydrological models	• Link groundwater recharge and discharge models w ith hydrological models to identify groundwater dependent habitats in wetlands, streams, and nearshore areas of the Great Lakes Basin.
5C. Evaluate the importance of groundwater discharge on species distributions and ecosystem attributes	• Maps of direct groundwater discharge into Great Lakes • Water budget models of direct groundwater discharge into Great Lakes • Improve understanding of the influence of direct groundwater discharge on Great Lakes species distributions and habitats
5D. Evaluate the importance of spatial patterns in groundwater discharge on ecosystem attributes	• Research linkages between spatial patterns in groundwater recharge and discharge areas and habitat patchiness, species distributions and ecosystem function
5E. Identify ecosystems that are vulnerable to changes in groundwater discharge	• Map groundwater dependent ecosystems in Great Lakes Basin • Assess their exposure and sensitivity to groundwater variation and other stressors e.g., watershed development • Prioritize conservation of these groundwater dependent ecosystems

6. EFFECTS OF URBAN DEVELOPMENT ON GROUNDWATER

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6.1 Introduction

As noted in Chapter 2, urban infrastructure impacts the quantities of groundwater exchange with surface water in the Great Lakes Basin. Furthermore, as discussed in Chapters 3 and 4, urban development in this basin has significantly impacted the quality of the groundwater. All of these impacts of urbanization on groundwater indirectly affect Great Lakes water quality. This chapter provides a closer look at the impacts of urbanization on groundwater in the Great Lakes Basin, and how these impacts may change over time.

About half the world's population lives in urban areas and this is expected to increase to 60% by 2030 (Howard, 2012). This trend is largely mirrored in the Great Lakes Basin which hosts some of North America's most populous cities including Chicago, Detroit and Toronto. Groundwater can be an important source of supply for sprawling city suburbs (Theobald, 2005) and smaller, rural towns. However, most large cities of the basin draw most of their water from the Great Lakes (Grannemann et al. 2000) meaning that urban groundwater attracts little attention until problems arise. Such problems relate either to groundwater quality or groundwater quantity (Foster, 1990) and are usually manifest in terms of water quality effects on receiving water bodies including sensitive aquatic ecosystems, or rising groundwater levels that threaten tunnels, engineering structures and electrical utilities (Howard, 2007; Pokrajac and Howard, 2011). Polluted urban springs and rising groundwater levels observed in cities throughout Europe and parts of North America demonstrate that proactive management of urban groundwater is required whether or not it is used for potable supply.

6.1.1 Quantity Issues

Until recently, it was popularly believed that urban development causes a net loss in groundwater recharge due to the widespread prevalence of asphalt and concrete that creates an impermeable seal to the land surface. Studies confirm that urbanization depletes direct recharge to groundwater, but there is considerable evidence (Custodio, 1997; Lerner, 2002) indicating that urbanization radically alters the entire urban water cycle (Figure 6.1) introducing new sources of recharge that may more than offset any losses of direct recharge. These sources include:

- infiltration from septic systems (in small communities, suburbs, also rural areas);
- leaking sewers;
- leaking pressurized water mains;
- excessive irrigation of domestic and municipal gardens;
- infiltration of run-off (naturally as indirect recharge); and
- infiltration of run-off (intentionally as a consequence of stormwater management schemes).

The contribution of these sources can be difficult to quantify. As indicated by Lerner (1990), all water supply networks leak, particularly those that are strongly pressurized. Well-maintained systems may lose only 5-10% of supply but older systems can readily lose 20% or more (Table 6.1). Sewer exfiltration rates are also very difficult to estimate (Eiswirth 2002; Hornef, 1985; Seyfried, 1984), with most published work concerned with sewer pipes constructed below the water table that receive infiltration from groundwater (Mills et al., 2014). Although, comparable flows might be expected to occur in the reverse direction when sewers are constructed in the unsaturated zone, little is known because most studies of sewer pipe exfiltration have focused on water quality rather than quantity. In a study conducted in the UK, leakage from a very old combined storm-sewer system beneath Liverpool was found to be comparable in volume to water-main leakage (University of Birmingham, 1984). In a German study, Eiswirth (2002) estimated that sewer leakage contributes around 15L /person /day to groundwater recharge. As a general rule, cities that import water but export sewage can expect to contribute around 15-25% of imported water to recharge (Lerner 1990).

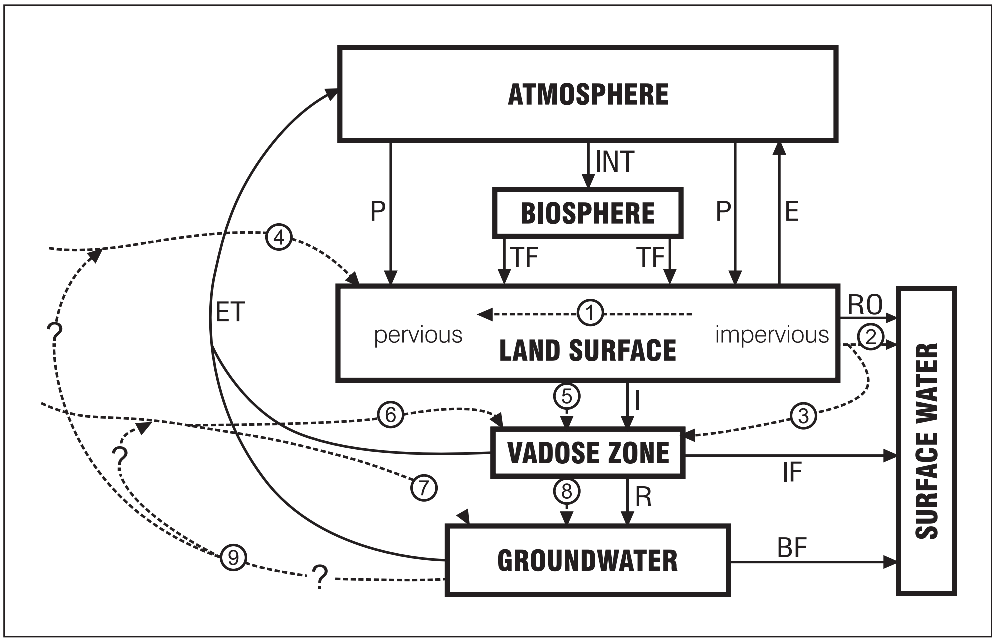

Figure 6.1. Changes to the water cycle with urbanization (Garcia-Fresca and Sharp, 2005). E Indicates evaporation; ET, evapotranspiration; P, precipitation; INT, interception; TF, throughfall; I, infiltration; R, recharge; RO, surface runoff; IF, interflow; and BF, base flow. Nine potential changes are noted: (1) increased impervious cover; (2) changes in surface runoff; (3) increased indirect recharge; (4) irrigation of lawns, parks, and gardens; (5) increased infiltration; (6 and 7) leaky water, sewer, and storm sewer systems, which may be above the water table, but below the water table only leakage would be from pressurized systems; (8) increased recharge; and (9) groundwater pumpage.

The least understood source of recharge in urban areas is stormwater that infiltrates via grass swales and stormwater management ponds. Many cities throughout the Great Lakes Basin use the subsurface as a convenient means of solving their stormwater management issues, but do so with little or no consideration of the ability of the shallow subsurface to accept this water or what water quality problems may arise. This is a serious concern as, over time, excess recharge can lead to rising groundwater levels and an upward flushing of salts and contaminants that had previously accumulated in the shallow unsaturated zone. As experienced in many parts of the world, rising groundwater levels can cause flooding of streets, cellars, sewers, septic systems, utility ducts, and transport tunnels, reduce the bearing capacity of structures, and impact amenity space by water-logging sports fields and killing trees (Heathcote and Crompton, 1997).

6.1.2 Quality Issues

Urban areas manufacture, import, store, transport, and utilize large volumes of polluting chemicals, a proportion of which inevitably contaminates urban groundwater (Howard, 1997; Squillace et al., 2002; Lerner, 2003; Kaufman et al., 2009) (Figure 6.2). The pollutant sources can generally be grouped into point sources that emanate from a discrete location, and line or distributed sources which have a much broader or "diffuse" impact (Table 6.2, cf. Chapter 3). In many urban areas, a high density of point and line pollutant sources (e.g., septic systems, leaking sewers and salted roads, respectively) effectively merge to create a distributed source. Point sources tend to cause severe degradation of groundwater quality near the point of release and can seriously damage receiving streams. However, the impact to groundwater is limited to the extent of the contaminant plume that develops. Distributed sources often represent a more serious problem as they can render the entire groundwater resource unsuitable for drinking by increasing contaminant concentrations to levels marginally above drinking water quality standards.

In cities throughout the Great Lakes Basin, urban groundwater is contaminated by the full range of urban-sourced pollutants. Ultimately, most of this water will enter the Great Lakes, usually either directly as lakeshore discharge or indirectly via drains, streams and tunnels. Many of the contaminants are a legacy of past practices, for example tens of thousands of brownfield sites within the industrialized port cities of the Great Lakes (Kaufman et al., 2009) represent a substantial contaminant load to water. Also, most closed landfills are sited in old quarries and are devoid of modern liners and leachate collection systems. That said, many current-day "best management practices" (BMPs) have very dubious benefits when the quality of urban groundwater is concerned. "Green infrastructures" use permeable pavement, bioswales, and infiltration planters to manage rainwater and aid stormwater management but often provide convenient pathways for urban pollutants including road salt, metals, oils and greases to be rapidly conveyed to shallow groundwater (Selbig et al., 2010; Chahar et al., 2012).

A chemical audit performed for a representative area of Toronto by Howard and Livingstone (1997) found that chemicals associated with road de-icing (primarily halite (NaCl)), leaking underground storage tanks (benzene, toluene, ethylbenzene, and xylene (BTEX)) and domestic landfills (a broad range of organic and inorganic chemicals) represent the most serious threats to urban groundwater. Concern for NaCl is heightened because of its high mobility in water and its potential ecological effects on groundwater dependent ecosystems. Dissolved salt can also mobilize trace elements such as cadmium, copper, lead and zinc through ion exchange, lowered pH, chloride complex formation and possible colloid dispersion (Bäckström et al., 2004). Contrary to popular belief that most salt applied to roads and highways in urban areas is flushed from the catchment each year via runoff, around 50% of salt enters the subsurface (Howard and Haynes, 1993; Perera et al., 2013) and will lead to a gradual long-term increase in the salinity of groundwater and receiving streams. Currently several Toronto rivers already exhibit chloride concentrations in base-flow above the 250 mg/L level considered chronically toxic for many freshwater species

Table 6.1. Estimates of leakage from water utility systems (modified after Hibbs and Sharp, 2012; Garcia-Fresca, 2004 and 2006).

City	Water Main Loss (percent)*
Hull, U.K.	5
Los Angeles, CA, USA	6-8
Hong Kong, China	8
San Antonio, TX, USA	8.5
Évora, Portugal	8.5
Milano, Italy	10
Austin, TX, USA	12
New Auckland, New Zealand	12.3
Toronto. Canada	14
Calgary, Canada	15
USA average	16
Sáo Paulo, Brazil	16
Dresden, Germany	18
U.K. general rates	20-25
Baltimore, MD, USA	23
Gotebeg, Sweden	26
Round Rock, TX, USA	26
Tomsk, Russia	16-30
Amman, Jordan	30
Kharkov, Ukraine	30
Sana'a, Yemen	30
St. Petersburg, Russia	~30

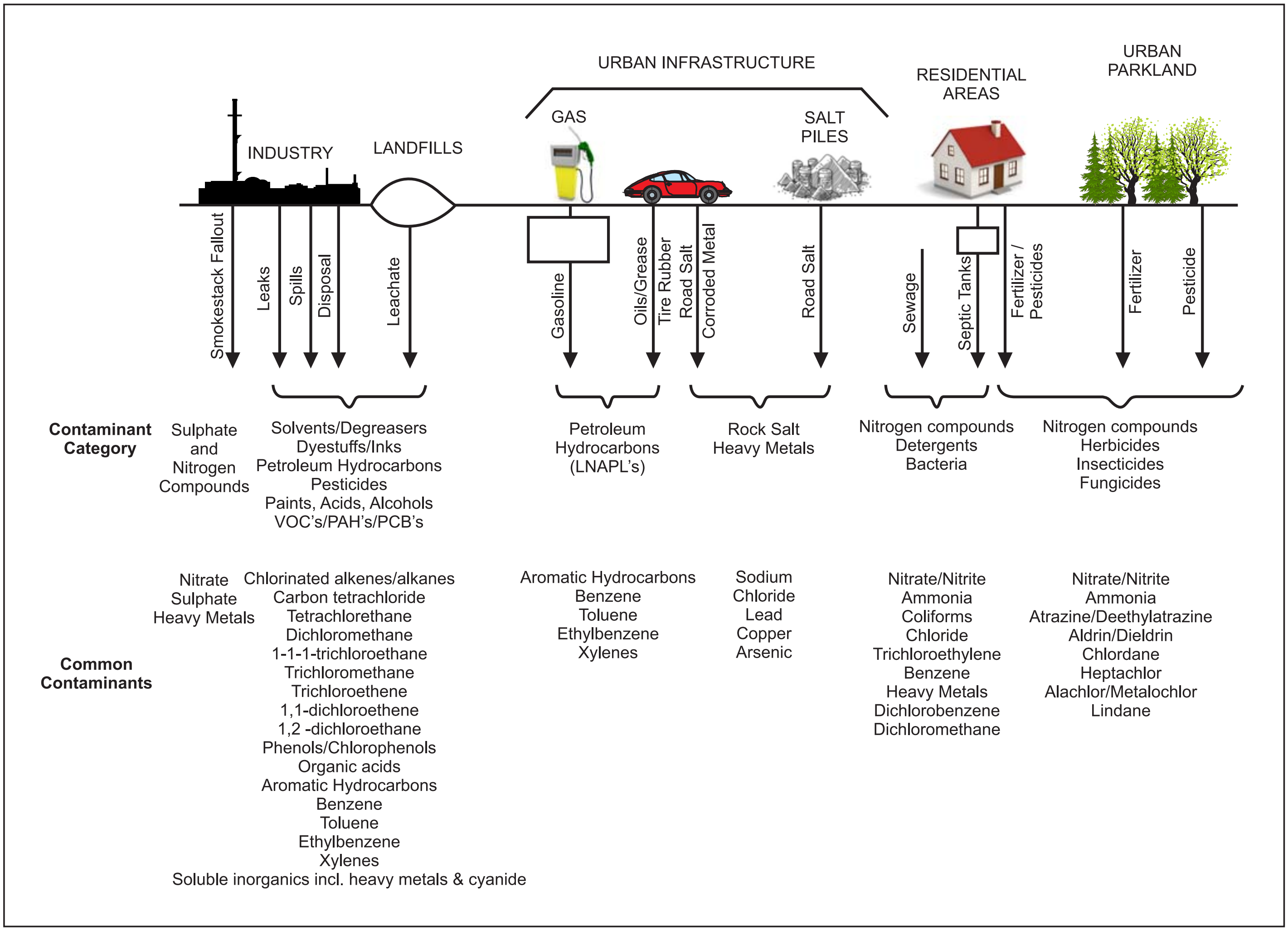

Figure 6.2 Common urban groundwater contaminants (modified after Howard, 1997).

(Jackson and Jobbágy, 2005). Environment Canada and Health Canada (2001) suggests 5% of aquatic species are seriously affected at chloride concentrations marginally above 200 mg/L (the median lethal concentration), and significant changes in the structure of some aquatic communities can occur at concentrations as low as 12 mg/L. Although road salt is also considered to be a serious issue in most urban areas of the Great Lakes Basin, septic systems are also a cause for concern, particularly in the United States. Septic systems are a key source of nitrate, bacteria and viruses, but can also cause elevated potassium, boron, chloride, dissolved organic carbon, and sulfate (Katz et al., 2011). In a study of shallow groundwater near Detroit (Thomas, 2000a), impacts on groundwater quality were found to be mostly associated with septic-system effluent (domestic sewage, household solvents, water softener backwash) and infiltration of stormwater runoff from paved surfaces (road salt, fuel residues). Contaminated groundwater is believed to be a primary source of high fecal coliform in urban streams including the Rouge River in Michigan (Murray et al., 2001).

In terms of the Great Lakes Basin, the primary challenge is to make reliable predictions of how, and over what time frame, contaminants that have accumulated beneath urban areas will be released to the Great Lakes. Although much has been learned from a scientific standpoint about urban hydrology and the nature and behavior of urban groundwater contaminants, many complicating factors will need to be addressed. The first of these relates to the fact that "urban karst" (i.e. cracks in the impermeable pavement, and permeable zones associated with fill material and the presence of underground pipe networks, such as drain tiles, utility pipes and stormwater tunnels) together with green infrastructure, strongly affects urban recharge and is a dominating factor on shallow groundwater/contaminant flow. Characterizing the "urban karst" and understanding its relationship to the natural hydrogeology is a difficult challenge.

The second complicating factor relates to the pumping regime and the following facts:

- High volume pumping (for water supply or dewatering) can lower water levels, induce movement of stored contaminants, and cause groundwater from different parts of urban aquifers to mix (Eberts et al., 2005; Eberts et al., 2013; Warner and Ayotte, 2014). Mixing of groundwater can have the unintended consequence of changing redox conditions and mobilizing contaminants that had previously precipitated or been adsorbed.
- Pumping can also radically change groundwater flow direction, in some cases inducing contaminated groundwater (e.g., wastewater from leaking sewer lines) to enter supply (see Hunt et al., 2010).

Reliable predictions of effects to the Great Lakes can be made only if the groundwater flow systems underlying urban areas are properly evaluated, contaminant sources are fully assessed and quantified, and appropriate monitoring is undertaken. In the interests of protecting the Great Lakes, it is essential that urban groundwaters of the Great Lakes Basin are both monitored and managed whether or not they are used for supply.

6.2 Urban Groundwater and the Great Lakes Basin

6.2.1 The Great Lakes Basin within the US

Most large population centers in the Great Lakes Basin lie within the United States (Table 6.3) and about 70% of the basin's US population live in cities. These include two of the ten most populated cities in the entire country (Chicago and Detroit). Although parts of Chicago lie outside the basin from a surface water perspective, the ground and surface water catchments are not coincident meaning that groundwater originating beyond the surface water divide may still affect Lake Michigan. The situation is further complicated by a series of drainage diversions dating back to 1848 that have converted 673 square miles of the original Lake Michigan watershed into part of the Illinois River-Mississippi River drainage basin (Illinois Department of Natural Resources, 2015). By using the original Lake Michigan basin boundary rather than the present "man-made" one which demarks a drainage area only 11 percent of its former size, the population of the Lake Michigan basin is increased by nearly 3 million persons.

Table 6.2. Point, line and distributed sources of contamination in urban areas (from Howard, 2002).

Point Sources	Line and Distributed Sources
Industrial and municipal waste sites (landfills) Industrial discharges, leaks and spills Leaks from underground storage tanks containing solvents, brines, gasoline and heating fuels Snow dumps Spillages during road and rail transport of chemicals Stockpiles of raw materials and industrial wastes	Effluent from latrines and cesspits Leaking sewers and septic systems Oil and chemical pipelines Lawn, garden and parkland fertilizers and pesticides Road de-icing chemicals Oil and grease from motorized vehicles Wet and dry deposition from smoke stacks Fill material containing construction waste

According to Theobald (2005), the urbanized landscape in the United States has grown from less than 9,000 square miles in 1940 to almost 40,000 square miles in 2010. This has increased demand for potable water while introducing contaminant sources that pose a significant threat to potable water quality. All the states bordering the Great Lakes have aquifers yielding adequate water supplies, and many rural towns rely exclusively on groundwater for potable supply. However, most of the larger cities within the Great Lakes Basin are situated on the shores of the

Table 6.3. Population data for the ten largest metropolitan areas in the United States part of the Great Lakes Basin, showing growth from 1990 to 2000 but relative stability since 2000 (U.S. Census, 2003; 2013). CMSA, consolidated metropolitan statistical area; MSA, metropolitan statistical area.

Metropolitan Statistical Area	Population in 2010	Percent change in population from 1990 to 2000	Percent change in population from 2000 to 2010
Chicago--Gary--Kenosha, IL--IN--WI CMSA	9,461,105	11.1%	3.3%
Detroit--Ann Arbor--Flint, MI CMSA	5,066,831	5.2%	-7.1%
Cleveland--Akron, OH CMSA	2,780,440	3.0%	-5.6%
Milwaukee--Racine, WI CMSA	1,751,316	5.1%	3.7%
Buffalo--Niagara Falls, NY MSA	1,135,509	-1.6%	-3.0%
Rochester, NY MSA	1,079,671	3.4%	-1.7%
Grand Rapids--Muskegon--Holland, MI MSA	1,161,126	16.1%	6.7%
Syracuse, NY MSA	662,577	-1.4%	-9.5%
Toledo, OH MSA	610,001	0.7%	-1.3%
Kalamazoo--Battle Creek, MI MSA	462,735	5.4%	2.2%
Population change in the 10 largest US cities in the Great Lakes Basin	**24,171,311**	**6.7%**	**-1.0%**

Great Lakes and depend mostly on surface water. Detroit, for example, draws virtually all its water from the Detroit River, the St. Clair River, Lake St. Clair and Lake Huron with the fate of groundwater in the underlying sediments essentially unknown.

Chicago also relies extensively on water from the Great Lakes (Lake Michigan). During the mid- to late-1900's westward expansion of the Chicago suburbs increased the demand for groundwater causing a lowering of regional water levels in the shallow dolomite aquifer (Silurian to Late Ordovician) and Cambrian-Ordovician aquifers (Voelker, 1986). In Illinois, groundwater use has little regulation, and water quality is the primary constraint on how much water cities pump. The drilling of deeper wells raised concerns that deep saline water and/or radium would be drawn into shallow aquifers by improperly constructed wells that were already showing evidence of degradation by urban pollutants. As a result, suburban communities have increasingly turned to Lake Michigan as an alternative source of supply. This is difficult, as applications for permits to draw water from Lake Michigan are being met with strong resistance from regulators who argue that lake-based resources are fully utilised and that available water needs to be managed more efficiently.

A major problem is that urban growth and industrial development throughout the Great Lakes Basin has occurred near lakes and streams such that residence times for polluted groundwater tend to be short (often < 1year) (Pijanowski et al., 2007). As a result, chemical and biological attenuation processes have little opportunity to improve the quality of groundwater prior to its emergence in rivers and lakes. This poses a considerable threat to fish-spawning grounds and similarly sensitive groundwater dependent ecosystems. One endangered species is the Hine's emerald dragonfly (Somatochlora hineana) found in Wisconsin, Illinois and Michigan that lives in calcareous, spring-fed marshes and sedge meadows overlying dolomite bedrock (Fish and Wildlife Service, 2006). The greatest threat to the Hine's emerald dragonfly is urban and industrial development that either degrades the quality of groundwater entering its habitat or destroys its habitat entirely (U.S. Fish and Wildlife Service, 2006).

A complicating issue that tends to be unique to urban areas is aquifer dewatering for construction. In many cases the effects extend to adjacent surface water bodies such as rivers and lakes. Haack et al. (2005) studied two sites in the Lake Erie drainage basin and found that large changes in the groundwater flow dynamics had profound effects on nearshore water temperature, clarity, nutrient and ion chemistry, and thus on habitat quality for fish and invertebrates. At one site, dewatering for a quarry was observed to reverse the natural flow into Lake Erie (Reeves et al.

2004). Nearshore withdrawals of groundwater can also affect the extent to which groundwater mixes with surface water, thereby affecting ambient water chemistry and disturbing aquatic communities. A study of aquatic insects by Diggins and Snyder (2003) showed that a reversal of flow caused by aquifer pumping caused a decrease in insect population. Mills et al., (1994) found that lakeshore sites disturbed by groundwater flow reversal may also be more vulnerable than undisturbed sites to colonization by invasive species such as zebra mussel.

The US Geological Survey (USGS) has been sampling wells in the Great Lakes Basin since the 1900s. During the past 20 years (1994-2014), analyses from 1,426 wells in this basin have been included in the USGS National Water Information System (http://waterdata.usgs.gov/nwis/qw), with most sampled wells representing shallow aquifers in glacial deposits, which are collectively referred to as the glacial aquifer system. Currently, about 73% of the groundwater supply wells within the basin are in the glacial aquifer system. This finding is important as it suggests that most groundwater in the basin can be expected to follow relatively short, shallow flowpaths that are typical of the Glacial Aquifer System (Granneman et al., 2000).

In a study of the water quality of the glacial aquifer system in the United States contaminants from human activities were three times less likely to occur at concentrations of potential concern for human health than contaminants from natural geologic sources; yet, contaminants from human activities are more common in urban areas and often at locally acute concentrations (Warner and Ayotte, 2014). Nitrate, chloride, pesticides, and volatile organic compounds (VOCs) were found to be of greatest concern in urban areas as indicated in the following studies.

- In a study of nitrate in the western Lake Erie Basin, Thomas (2000b) found that 37% of monitoring well samples had nitrate concentrations indicative of human effects such as fertilizer, manure or septic systems and that 57% of samples contained either a pesticide or an elevated nitrate concentration. In 83% of the monitoring well samples isotopic evidence indicated that the well water had been recharged since 1953, which indicates that the groundwater was well connected hydraulically to the land surface. Fractures or sand-and-gravel stringers within the overlying till were considered the probable pathways. In some areas, deeper parts of the groundwater-flow system were also found to be hydraulically connected to the land surface.

- In the glacial aquifer system, about 7% of wells in urban areas had chloride concentrations that exceeded the US Environmental Protection Agency (USEPA) Secondary Maximum Contaminant Level (SMCL) of 250 mg/L (USEPA, 2014) and chronic aquatic life criterion of 230 mg/L (USEPA, 2015), especially during dry periods when groundwater contributes most of streamflow (Warner and Ayotte, 2014). High chloride concentrations in urban groundwater commonly are associated with a combination of road deicers, salt, water softeners, sewage, animal waste and potassium chloride fertilizers (Mullaney et al., 2009). Chloride:bromide (Cl:Br) ratios can be used to isolate the resource (Davis et al., 1998; Thomas, 2000a; Jagucki and Darner, 2001; Panno et al., 2006) with samples having Cl:Br ratios greater than 1,000 and chloride concentrations greater than 100 mg/L likely being indicative of halite used for deicing or water softening in urban groundwater.

- Pesticides were widely detected in shallow aquifers, but concentrations were low (<0.2 µg/L) (Warner and Ayotte, 2014). Pesticides were detected beneath all land-use settings and in both domestic- and public-supply wells. Significantly, public-supply wells near streams showed a greater likelihood of pesticide contamination indicating these wells may capture pesticides through induction of river water. The six most common pesticides in the glacial aquifer system were deethylatrazine (DEA), atrazine, metolachlor, simazine, prometon, and bentazon. Prometon was most commonly detected in urban areas.

- VOCs were detected in more than 20 percent of the glacial aquifer system well samples, but concentrations were less than concentrations of potential concern for human health (Warner and Ayotte, 2014). The greatest frequency of detections and highest concentrations were in shallow groundwater underlying urban areas and in samples of groundwater from public-supply wells. The most common VOCs detected were trichloromethane, toluene, carbon disulphide, tetrachloroethene, 1,1,1-trichloroethane, and methyl tert-butyl ether (MTBE).

An over-reaching problem is that most of the contaminated groundwater underlying the more densely urbanized areas of the Great Lakes Basin is destined to reach the Great Lakes. Very little is known about the timing of this release, how attenuation of the contaminants in the subsurface will affect this release, and the resultant chemical loadings that will occur. Municipalities are certainly aware that contaminated groundwater represents an environmental threat as evidenced by a groundwater ordinance passed by Chicago City Council in 1997 that prohibits the installation of new potable water supply wells for the purpose of limiting the likelihood that individuals will be exposed to potential contaminants by ingesting groundwater (City of Chicago, 1997). Unfortunately, this safety measure deals with only one of many potential exposure pathways, and does not help to safeguard the health of Lake Michigan which is the ultimate source of water for most of its residents.

6.2.2 The Great Lakes Basin within Canada

On the Canadian side of the border, the Great Lakes Basin is confined to the Province of Ontario. In northern Ontario (around Lake Superior, Lake Huron and Georgian Bay) Canadian Shield basement rocks of Precambrian age are overlain locally by unconsolidated glacial deposits (e.g., moraines, eskers, glaciofluvial materials) of variable thickness (Ontario Geological Survey, 2003). Larger urban centres in this setting generally obtain their water supply from surface water sources, with smaller communities and private residences relying on individual wells. Well yields in Precambrian rocks are largely controlled by pressure-release fracturing together with structural discontinuities associated with faulting (Rivera, 2014). In southern Ontario (immediately north of Lake Erie, Lake Ontario and the St. Lawrence River) one of two hydrogeological environments tends to dominate. In the west, above the Niagara Escarpment and in the east along the St. Lawrence River, a thick Paleozoic sequence supports carbonate aquifers capable of supplying high yields of normally good quality water. In central southern Ontario (in the vicinity of the Greater Toronto Area (GTA)) and at various locations above the Niagara Escarpment (including the Kitchener-Waterloo region) glacial deposits of Quaternary age form complex aquifer systems that locally provide excellent yields of high quality water. Typically, these sediments compose layered sequences (till, glaciolacustrine and glaciofluvial deposits) that in some areas exceed 250m in thickness.

Population trends for Ontario are shown on Figure 6.3 and Table 6.4. As shown by Figure 6.3, virtually all the population growth in Ontario since the 1850s has taken place in urban areas, with the heavily urbanised GTA in southern Ontario now hosting close to 50% of the Province's population (Table 6.4). The GTA is predicted to grow steadily in future years while other Ontario cities are expected to remain stable or even show a population decline (e.g., Windsor, Thunder Bay (Statistics Canada, 2011).

Table 6.4. Past, current and projected population in Ontario according to region (from Ontario Ministry of Finance, 2013).

Share of Ontario population (%)	1986	1996	2011	2016	2026	2036
GTA	41.4	43.0	47.3	48.3	50.0	51.5
Central	21.8	22.2	21.6	21.5	21.1	20.9
East	14.0	13.8	13.0	12.9	12.9	12.7
Southwest	14.1	13.4	12.0	11.6	10.9	10.2
Northeast	6.2	5.4	4.2	4.0	3.6	3.2
Northwest	2.6	2.3	1.8	1.7	1.6	1.4

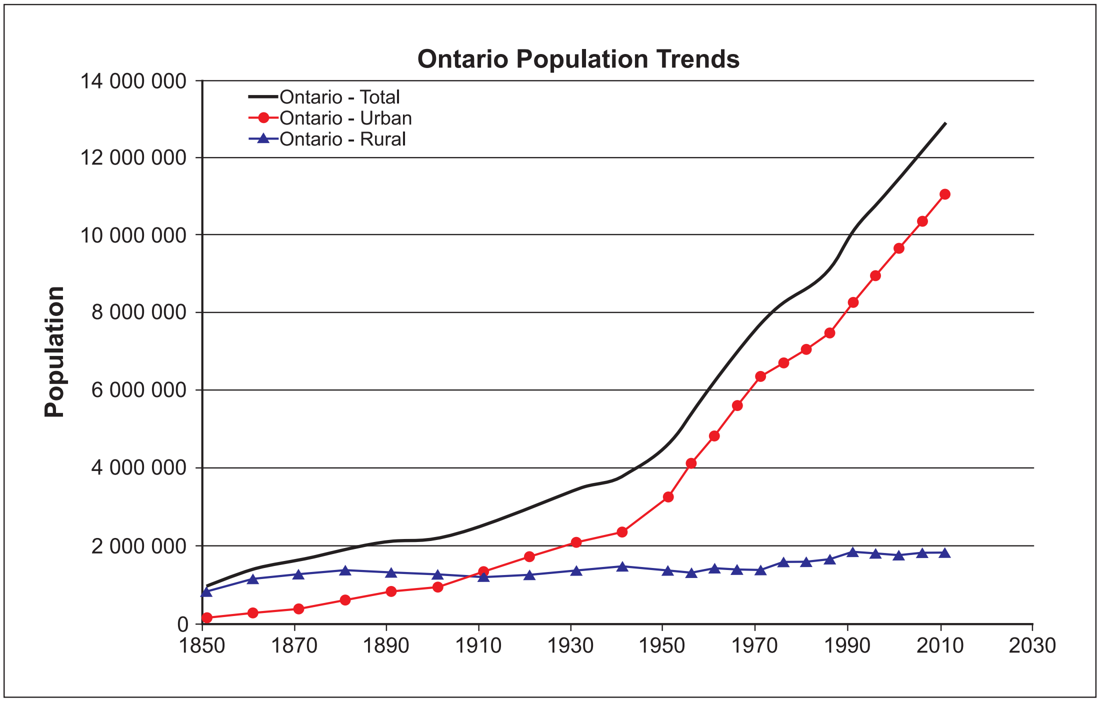

Figure 6.3. Population trends for Ontario, Canada (data from Statistics Canada, 2011).

As the GTA grows and urban sprawl continues, major problems related to groundwater quality are expected to intensify, given the increasing amounts of urban-sourced pollutants that continue to contaminate the shallow Quaternary aquifers. The City of Toronto has never been a large user of groundwater, preferring instead to rely on adjacent Lake Ontario as a reliable, cost-effective source of potable water supply. It was not until the 1980s when seriously contaminated groundwater began to emerge in the form of polluted urban springs (Eyles and Howard, 1988), that awareness for the problem developed. Based on numerical modelling and travel time analysis, Howard and Livingstone (2000) found that most of the more mobile contaminants currently underlying Toronto will find their way to Lake Ontario via primary "intergranular" flowpaths within a 100-year timeframe. However, recent studies in the eastern suburbs of Toronto by Perera et al., (2013) suggest that locally, groundwater travel times can be shortened dramatically by the presence of "urban karst". Contaminants that are chemically retarded or move via deeper flowpaths may not re-emerge for over 500 years. Most of the contaminated water can be expected to enter Lake Ontario via urban streams and rivers as it has been widely observed that direct discharge of groundwater to the Great Lakes is comparatively small (Grannemann and Weaver, 1998; Grannemann et al., 2000; Gerber and Howard, 2002; Haefeli, 1972; Holtschlag and Nicholas, 1998; Neff et al., 2005).

Many of the problems experienced in the GTA are symptomatic of a longstanding undervaluing of groundwater (Galloway and Pentland, 2005) and the key role groundwater plays in the water cycle. In Ontario this mindset changed rapidly after May 2000 when 7 residents of Walkerton, a small town northwest of the GTA, died as a result of drinking bacterially contaminated drinking water. The resulting Commission of Inquiry (CofI) chaired by Justice Denis O'Connor raised considerable awareness for the importance of groundwater and delivered sweeping recommendations on the measures urgently required to safeguard the Province's drinking water supplies (O'Connor, 2002). Source water protection (SWP) efforts that have been developed since the CofI focus on hydrogeological mapping, monitoring and analysis of potential risk associated with the various contaminant sources. This work is managed on a local scale within a SWP Region, but operates under Provincial oversight and funding. Ambient groundwater levels and quality are currently monitored at a series of 474 wells through the Provincial Groundwater Monitoring Network which was initiated immediately following the Walkerton event (http://www.ontario.ca/data/provincial-groundwater-monitoring-network). The current focus of the SWP program is the protection of large supply wells. The program does not currently address groundwater that is destined to enter the Great Lakes, either by direct discharge or by discharge to streams.

The value and importance of good quality monitoring data cannot be overstated. Many large inland urban communities are still reliant on groundwater (e.g., Kitchener, Guelph, Aurora, Newmarket) due to the local presence of productive aquifers, the prohibitive cost of pipelines for a lake-based supply, and provincial legislation restricting inter-basin water transfers (Holysh and Gerber, 2014). These Such communities frequently encounter several of the water quality issues (e.g., Reichert, 1986; Sanderson et al., 1995) documented in the GTA butand some are able to respond very quickly to any pending problems due to the availability of good quality monitoring data and properly calibrated numerical groundwater flow models (e.g., Earthfx Incorporated, 2014) . These types of models could be used more widely in the Great Lakes Basin to better refine estimates of groundwater discharge and contaminant loadings to the Great Lakes.

6.3 Future Prospects

Throughout the Great Lakes Basin, groundwater is an important source of supply for sprawling city suburbs and smaller, rural towns. However, most large cities of the basin do not rely on aquifers as a primary source of potable water supply, and groundwater receives little attention until problems arise. The most serious issues relate to groundwater quality and trigger a concern that shallow groundwater, degraded by a wide range of urban pollutant sources will become an increasing threat to sensitive aquatic ecosystems and will slowly degrade existing sources of fresh water including the Great Lakes. This concern is amplified by the complexity of urban groundwater issues and limited available information which can make predictions unreliable.

On a positive note, much has been learned about the effects of urban development on groundwater during the past 40 years and, in many parts of the world, this knowledge is slowly being incorporated into the urban planning and groundwater management process. In particular, excellent progress has been made on:

- Understanding sources of urban recharge and quantifying components of the urban water balance;
- The development of novel techniques for augmenting aquifer recharge;
- Pollutant source characterization, mechanisms of contaminant release and the behavior of contaminant plumes;
- Disposal methods for all types of domestic and industrial waste;
- Approaches to monitoring;
- Aquifer vulnerability mapping and methods of groundwater protection; and
- Identifying opportunities for integrated / conjunctive use of groundwater and surface water sources.

Moreover, major advances have been made in the development of computer model codes, many of which link seamlessly with urban database systems for the purposes of:

- Performing urban water budget assessments;
- Providing three-dimensional, transient simulations of the aquifer systems;
- Defining well head (source water) protection areas;
- Conducting aquifer susceptibility and vulnerability assessments;
- Predicting groundwater travel times and eventual fate for contaminants in the system;
- Determining "optimal" pumping and water extraction rates and, most importantly;
- Testing and evaluating alternative water management scenarios, and thus supporting pro-active decision-making.

Some of these urban groundwater models (e.g., Wolf et al., 2006; Pokrajac and Howard, 2011) acknowledge the importance of the entire urban water cycle and can simulate the interactions that take place among groundwater, surface water and the complex network of water services including sewers and pressurized water supply systems. To date, such management tools are rarely implemented unless groundwater is used as a resource and therefore deemed in need of protection. In many large cities dependent on lake water for supply (e.g., Toronto), groundwater is paid scant attention and the fate of contaminants entering the urban subsurface is unknown.

For proactive management, polluted urban groundwater needs to be recognized as a credible threat to the long-term health of the Great Lakes Basin. This management will require a sound knowledge base including detailed audits of all chemicals stored within or released to the subsurface, and reliable data relating to groundwater quality and groundwater levels. Such data are often lacking in urban areas throughout the basin. Priority science needs are discussed below and summarized in Table 6.5. Dependable data and properly calibrated groundwater flow models are essential for the reliable prediction of groundwater flow, contaminant fluxes, contaminant travel times and the time sequence of pollutant loadings on receiving surface water bodies.

6.4 Priority Science Needs for Improved Understanding of Effects of Urban Development on Groundwater

i) Data collection and analysis are required for urban groundwater resource management

The misconception that because urban groundwater is rarely used for domestic supply it does not need to be managed or protected has very serious implications for receiving water bodies such as rivers and lakes, and groundwater dependent ecosystems. Remarkably, very few data are available on the extent to which groundwater is used in urban areas throughout the Great Lakes Basin. Such data are essential recognizing that, although groundwater and surface water are inextricably linked, both reservoirs behave very differently and demand different, yet complementary, approaches to management.

There is an urgent need to make greater use of urban groundwater modelling tools to provide guidance on urban groundwater management. Such tools are invaluable for understanding water quantity and water quality changes over time and the potential effects of changing climate and land use.

ii) Quantitative information about contaminant sources is needed

Potential sources of groundwater contamination in urban areas are well established but poorly quantified. Chemical audits documenting the mass of contaminants released to the subsurface in urban areas are needed for all urban areas. Most of these contaminants ultimately enter the Great Lakes. In the absence of water quality monitoring data, such data would allow the potential degradation of groundwater quality to be assessed and long-term contaminant mass loadings on the Great Lakes to be estimated. Notably lacking is reliable quantitative information on septic system discharge and leaking sewer pipes. However, substantially better estimates of contaminant release are needed for all the contaminant sources listed in Figure 6.2 and of other contaminants such as those indicated in Chapter 3.

iii) Monitoring of groundwater quality and risk assessment of potential health risks is needed

Throughout the Great Lakes Basin the quality of urban groundwater is rarely monitored. In many cases, evidence for groundwater quality degradation is provided where groundwater emerges at the end of its flowpath (as surface springs and discharge to rivers and lakes) which is too close and too late for mitigation before entering the Great Lakes. To provide an early warning system, urban groundwater requires comprehensive monitoring. A monitoring focus on shallow groundwater and, where appropriate, the unsaturated zone would be most beneficial. Such data are essential for the development of effective urban groundwater modelling tools (see above). Also, improved understanding of human exposure to degraded groundwater in the urban environment and potential health risks/disease is needed. Of particular concern are new and emerging contaminant and disease threats and potential sources to receptor pathways.

iv) Base data acquisition and monitoring of urban water balances are needed

Urban areas radically change the water balance and introduce new water balance components. These components are well understood but in many cases are not well quantified. Urgent data needs include:

- Sewer exfiltration and infiltration rates;
- Leakage rates from pressurized water supply networks;
- Estimates of excess recharge due to infiltration of stormwater; and

- Water level and streamflow monitoring that will allow inequities in the water balance to be assessed and provide essential input to urban groundwater modelling tools (see above).

v) Research on urban groundwater movement and contaminant fate is needed

Urban groundwater is rarely managed unless it is used for domestic supply. Current emphasis on the protection of only sources of groundwater supply means that urban groundwater processes and pathways are poorly known and that the fate of urban sourced contaminants is not well understood. Recognizing that "urban karst" is an important factor affecting the flow of groundwater and entrained contaminants in urban areas, considerably more research is needed to understand and quantitatively assess the role of "urban karst." The collation of information regarding subsurface infrastructure (e.g., pipes, trenches, subways, etc.) into a single, easily accessed data management system would improve data management. Research is also needed on the potential threats of degraded urban groundwater on aquatic habitats and the timeframes over which this will occur.

vi) Monitoring and research on stormwater management and dewatering are needed

In many Great Lakes Basin urban areas, stormwater is managed by releasing excess surface water to the shallow subsurface, often with the assistance of supposedly "green" infrastructure. The downspout disconnection program legislated in Toronto (City of Toronto, 2015) is a recent example of such "green" infrastructure. Considerably more research is needed to understand the potential effects of releasing stormwater to the subsurface. Effects may include flooding of basements, tunnels and electrical utilities, and accelerated release and transport of contaminants. Although dewatering is essential for many urban construction projects, it is frequently undertaken with minimal consideration for effects on groundwater function and groundwater quality. It is essential that dewatering activities are carefully regulated and that effects are properly monitored and assessed.

Table 6.5 Priority science needs related to groundwater and urban development.

Priority Science Needs	Related needs and information gaps
6A. Data collection and analysis for urban groundwater resource management	• Water-use accounting • Greater use of urban groundwater modelling tools
6B. Quantitative information about contaminant sources	• Chemical audits, base data acquisition and monitoring • Reliable quantitative information on septic system discharge and leaking sewer pipes
6C. Monitoring of groundwater quality and risk assessment of potential health risks	• Improved understanding of human exposure to degraded groundwater and potential health risks/disease
6D. Base data acquisition and monitoring of urban water balances	• Data on sewer exfiltration and infiltration rates, leakage rates from water supply networks, estimates of excess recharge due to infiltration of stormwater
6E. Research on urban groundwater movement and contaminant fate	• Knowledge of "urban karst" • Data management (using an information analysis system), the collation of information regarding subsurface infrastructure • Knowledge - Research on the potential threats of degraded urban groundwater on aquatic habitats
6F. Monitoring and research on stormwater management and dewatering	• Knowledge and monitoring related to stormwater releases, including "green" infrastructure. • Monitoring and management of dewatering

7. CLIMATE CHANGE EFFECTS ON GROUNDWATER

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7.1 Introduction

This chapter synthesizes existing research associated with potential effects of a changing climate on quality and quantity of groundwater in the Great Lakes Basin. Climate change has the potential to alter the physical and chemical properties of waters of the Great Lakes Basin and ecological functions of those waters. The increases in seasonal temperatures and the changes in amount and distribution of precipitation that are projected to occur could lead to fundamental changes to the water cycle and how water is managed.

Changes to the water cycle will likely include the timing and amount of water that recharges the groundwater system. The quality and quantity of groundwater available for drinking water and maintaining valued ecosystems such as cold water fish in streams will also likely be affected. More frequent extreme events such as floods and droughts are projected to occur. Groundwater already provides reliable sources of drinking and irrigation water, and this need is likely to increase due to extreme drought events.

The effects of climate change on the quality and quantity of groundwater in the Great Lakes Basin are poorly understood. This is related to the science being relatively new in this area and the complex nature of relationships between climate change and groundwater.

In this chapter we review what is known about the effects of a changing climate on groundwater; the methodologies to assess the potential effects; and the science needs and gaps.

7.2 Climate and Groundwater: Observations

Instrumental observations show that land and sea surface temperatures have increased over the last 100 years (Cubasch et al., 2013), and global average temperatures are projected to rise another 2 to 4.7°C by the end of the century (Melillo et al., 2014) with even larger changes projected over land masses. This will affect water resources through changes in precipitation, wind speed, relative humidity and the resulting evapotranspiration.

Long term observations of climate and water in the Great Lakes Basin have provided indications of how a changing climate can affect the water balance. Cold season precipitation and air temperature have increased significantly from 1916 through 2007 while cold season snowfall has decreased significantly (Mishra and Cherkauer, 2011). Projected increases in cold season temperatures across the Great Lakes region would decrease the length of the freezing season, which in turn would affect runoff generation and infiltration processes.

Although air temperatures are increasing, soil temperatures during the winter are decreasing, especially at sites downwind from the Great Lakes in snowbelt areas. This is could be due to more variable and thinner snowpacks, which in turn lessens their insulating impact (Isard et al., 2007). This illustrates the complex responses of natural systems to slow atmospheric warming.

There have been statistically significant increases in some precipitation and streamflow gages over the period 1930 to 2000 (McBean and Motiee, 2008). For the western Great Lakes, the 2-year precipitation amount has increased by ~2% per decade, while 100-yr storm amounts have increased by 4% to 9% per decade (Degaetano, 2009). For eastern North America including the Great Lakes Basin, snowmelt runoff occurs earlier by about 5 to 10 days (Hogkins et al., 2007; Burn et al., 2010). However, this is not necessarily the case for all parts of the Great Lakes Basin since in Minnesota the peak flows due to snowmelt were found to be not changing significantly (Novotny and Stefan, 2007).

There are relatively few studies in the Great Lakes Basin that estimate how groundwater recharge varies in both space and time. Groundwater recharge estimates are sensitive to soil temperature, snow accumulation and snow melt. Groundwater has a more complex relationship with climate than surface water (Dams et al., 2012; Green et al., 2011; Scibek et al., 2007).

7.3 Climate, Groundwater and Land Use

As shown in Figure 7.1 the supply and demand of water can be affected by non-climate factors and this will continue in the future under a changing climate. There have been few studies of the cumulative effects of climate change and human activities on groundwater resources to determine what the future holds for groundwater resources (Green et al., 2011). In some areas the effects of human activities will be greater than those caused by a changing climate (Clifton et al., 2010; Holman et al., 2012; Pasini et al., 2012; Price, 2011; Quevauviller, 2011; Cartwright and Simmonds, 2008; Sukhija, 2008; Loaiciga, 2003).

The cumulative effects of climate, population growth, land management and groundwater availability were assessed for the 48 lower states (Sun et al., 2008). This study found that the greatest water stress was caused by climate change, followed by population growth - which was significant at the local level. In some cases land management could aggravate water stress and in other cases could cause a reduction in water stress. A major recommendation of the study was to continue the assessment of climate and land use change and urbanization on water quality and how reduced water quality can affect potable water availability.

The effect on regional climate of the Great Lakes Basin of human activities and land use was investigated by Mao and Cherkauer (2009). They used a large scale distributed hydrological model to simulate hydrological responses to different land-use conditions in the Great Lakes region of Minnesota, Wisconsin, and Michigan, a total area of about 494,000 km^2. Deforestation was most dramatic in the central part of their study domain where five million hectares of deciduous forest have been converted to wooded grasslands and row crop agriculture, which resulted in a 5-15% decrease in ET and a 10-30% increase in total runoff. Northern areas, where land-use change was primarily from majority evergreen to majority deciduous forest, experienced decreases of 5-10% in ET and increases of 20-40% in total runoff. The southern and western parts of the study domain were dominated by a conversion from prairie grasslands to row agriculture crop, resulting in a 10-15% increase in ET and a 20-30% decrease in total runoff. The study does not investigate the effects of changes in evapotranspiration and runoff on groundwater quantity.

The Muskegon River in Michigan provides key fish spawning habitat and was assessed for the effects of projected changes in climate and land use on streamflow and water quality (Wiley et al., 2010). This multi-model study indicated that increased air temperatures caused greater evapotranspiration while increasing precipitation in the winter months increased groundwater recharge. The model indicated that flows in Michigan's Muskegon River are likely to increase as a result of climate change. Nutrient concentrations were predicted to have little change from current levels but nutrient loads and yields increased for both total nitrogen and total phosphorus.

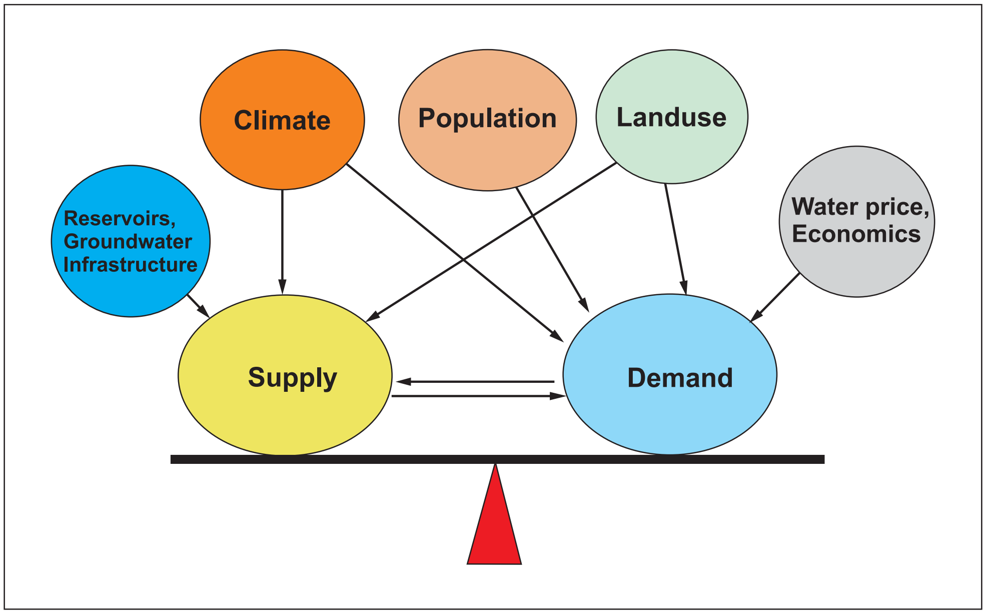

Figure 7.1. Factors affecting water supply and demand and their relations (from Sun et al., 2008).

7.4 Climate, Groundwater and Projections: Assessment of Impacts

7.4.1 Downscaling and Modeling Approach

The management of water resources has relied on the assumption that the water cycle varies within a known range that is based on past observations of temperature, precipitation and streamflow, and assuming those variables will remain within the known range (i.e. "stationarity"). This assumption of stationarity is no longer valid due to the uncertainties of a changing climate where past observations can no longer provide a reliable indication of future conditions (Milly et al., 2008).

For the effective management of water resources, the potential changes to the water cycle can be investigated using the projections from the General Circulation Models (GCMs). However, these projections are based on a global grid size of about 200 km which is too coarse for the regional scale at which water resources management occurs. This is particularly relevant to the Great Lakes Basin since the important effects of the Great Lakes on the regional water cycle are not accounted for at the global scale (Gula and Peltier, 2012).

To provide the required information at a regional scale, "downscaling" techniques have been developed that provide projections at a finer scale. Either statistical downscaling or Regional Climate Models (RCMs) can provide the climate data at a grid scale of 10 to 40 km that can be used for water resources management. Statistical downscaling is based on establishing a statistical relationship between observed data at the finer or local scale and the larger scale climate variables from the GCMs. The statistical method is widely used for hydrological impact studies and can be run on a personal computer. The RCMs are physically based models much like the GCMs and require similar expertise and supercomputers for simulations (Jang and Kawas, 2015).

The future projections for the changes in climate variables such as temperature and precipitation are then used as inputs to hydrological models that simulate all or part of the water cycle. The hydrological models are usually applied at a watershed scale and, to be effective at simulating future conditions, they need to reasonably simulate historical conditions. The hydrological models need to be validated across the range of climate, soils type, hydrogeological conditions that control shallow groundwater flow, land cover, and other landscape conditions.

The hydrological models can be used to quantify the likely effects of a range of projections for a future period including extreme events on the water cycle. Such analyses allow scientists and policy makers to assess the risk of potential future climate scenarios on water resources, and then develop adaptation and mitigation strategies to address these.

Prudhomme and Davies (2009) investigated three sources of uncertainty surrounding climate change impact studies on river flows in the UK: uncertainty in GCMs, in downscaling techniques and in hydrological modeling. They showed that GCM uncertainty is generally larger than downscaling uncertainty, and both are consistently greater than the uncertainty posed from hydrological modeling or natural variability. The climate science community has found that the approach of using the projections from multiple GCMs and RCMs – called an ensemble approach - helps to address this uncertainty.

7.4.2 Decision-Scaling and Robust Decision-Making

The downscaling-modeling approach described above involves uncertainty at each step of the downscaling-modeling chain. The uncertainty begins with the unknown future emissions of greenhouse gas and is increased by the differences in projections of climate change by the many GCMs. To obtain the finer scale information required to assess hydrological effects, multiple methods to downscale GCM projections add to the uncertainty. The effects of these uncertainties are then propagated into the hydrological models (Brown et al, 2011, International Upper Great Lakes Study Board, 2012).

The considerable uncertainty associated with the downscaling-modeling approach has necessitated the development of alternative approaches to assess climate change effects on water resources. As shown in Figure 7.2 the down-scaling modeling approach is a top-down approach beginning with climate projections and ending in the identification of vulnerabilities. In contrast, the decision-scaling approach is bottom-up and begins with populating the vulnerability domain by identifying potential vulnerabilities.

The potential vulnerabilities are defined by stakeholders and experts as thresholds or coping zones for specific parameters of interest such as groundwater level or lake level. A climate domain is then constructed which contains the climate states required to cause the parameter of interest (groundwater level or lake level) to exceed or go beyond the thresholds or coping zones. This is achieved using multiple climate simulations using specific or tailored projections and paleodata that provides extreme past climates. The "plausibility" of the climate state occurring is then given by the frequency it occurs in the climate domain. This approach was used in the development of the plan to regulate flows from Lake Superior in the International Upper Great Lakes Study (Brown et al., 2011).

The next step is to develop a plan or decision that addresses the multiple future climate scenarios. The plan or decision is considered robust if it can manage the different possible futures. The resulting management plan of the system may not be optimal in terms of economic or engineering efficiency, but the functioning of the system continues within established limits or goals. Flexibility through adaptive management should be part of the plan. Continuous and comprehensive monitoring and being receptive to establishing new practices in response to changing conditions is also required (Hallegatte et al., 2012; Groves et al., 2013).

Real option analysis is another method that deals with uncertainty, which has been used for decisions for long term infrastructure. This method was originally developed to identify investment decisions that are resilient across a spectrum of outcomes (Scandizzo, 2011). Real options analysis has been used for the design of a multi-purpose dam in the Blue Nile, Ethiopia (Jeuland and Whittington, 2013), flood risk management opportunities along the Thames Estuary, England (Woodward et al., 2013), and water security for the Krishna Basin in India (Davidson et al., 2011).

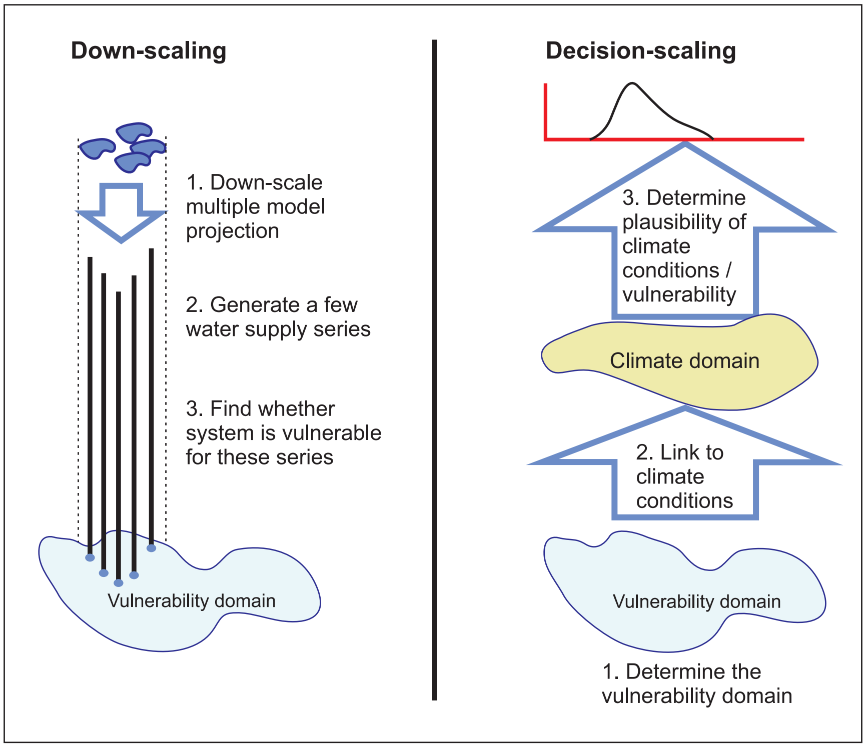

Figure 7.2. Down-scaling and decision-scaling approaches for modeling. The down-scaling modeling on the left is a top-down approach that begins with the projections from GCMs and ends with identifying vulnerabilities. Uncertainty grows with each step. The decision-scaling approach begins with a bottom-up analysis to identify vulnerabilities and ends with climate information to inform a decision (from Brown et al., 2011).

Other potential methods for assessing climate change effects in the face of wide or deep uncertainty include the scenario-neutral approach, information-gap decision theory (IGDT), and risk-informed decision-making (Garcie et al., 2014). A comprehensive evaluation of the methods and guidance for selecting the most appropriate method for a particular water resources problem is lacking.

7.5 Groundwater Quality

There are few studies that investigate the effects of climate change on groundwater quality in the Great Lakes Basin. Such efforts are hampered by the lack of data providing nutrient loadings throughout the Great Lakes Basin and the lack of water quality data (see Chapter 4). Changes to recharge rates and soil temperatures could affect the transport of contaminants (Green et al., 2007). The complexity of the fate and transport of subsurface contaminants was also described by Bloomfield et al. (2006) in their investigation of the effects of climate change on the behavior of pesticides in surface water and groundwater in the UK. A conclusion of their work is that the effect of climate change on pesticide fate and transport is likely to be highly variable and difficult to predict. The indirect effects such as land-use change driven by changes in climate may have a more significant impact on pesticide fate and transport.

A simple but effective measure for groundwater quality is temperature. For streams and rivers that receive significant amounts of groundwater discharge, the relatively consistent temperature of the shallow groundwater is important for maintaining conditions for cold water fisheries. A thermal modelling study used an equation for subsurface heat transport to assess the potential effects of rising surface temperature due to climate change on shallow groundwater (Kurylyk et al., 2015). It was found that the shallow groundwater temperature would rise at a slower rate and that the temperature rise was dependent on subsurface thermal properties, depth to groundwater, and the velocity of the groundwater.

Assessing the effects of climate change on groundwater quality requires assumptions about future practices involving contaminants (Chapter 3), nutrient application rates and timing (Chapter 4), and forms of urban infrastructure (Chapter 6). Multiple scenarios must be considered to evaluate the compounding effects of management changes on groundwater. The assessment of future groundwater quality also depends on the processes that affect contaminants in the vadose zone, saturated groundwater and the transition zone (Chapters 2 and 3). The science need is to comprehensively understand the processes so that projected climate factors can be used in fate and transport models to understand the potential effects of a changing climate.

Green et al. (2011) state that relatively few studies of climate change effects on groundwater have focused on groundwater quality. Groundwater quality can be a complex function of the chemical, physical, and biological characteristics of a watershed. It is expected that groundwater quality will not only respond to changes in climate but also to how urban and rural development proceeds. Investigation of the effects of a number of urban and rural development scenarios on groundwater would be required to determine the range of potential effects on water quality.

7.6 Groundwater Quantity

Although studies have examined the potential effects of climate change on groundwater and surface water hydrology, there continues to be uncertainty about the magnitude and even the direction of changes to groundwater recharge or levels in the Great Lakes Basin. The studies summarized in Table 7.1 show that groundwater recharge or levels can either decrease or increase.

Several studies (Wiley et al. 2010; Jyrkama and Sykes 2007; Rahman et al. 2012) project increases in streamflow during winter months. Some areas will be subjected to greater changes in recharge rates, while others will experience lesser change. The degree of effect is controlled by groundwater levels, characteristics of the ground surface, and the nature of the underlying soils.

The results from these studies demonstrate that we do not currently have the ability to quantitatively predict the magnitude or direction of the effects of climate change on groundwater resources with a high degree of confidence (Kurylyk and MacQuarrie, 2013).

Groundwater storage volumes are likely to be less sensitive to climate changes than river discharge and aquifer recharge (Sulis et al. 2011). Storage variations will likely be larger for shallow groundwater that is more directly exposed to fluctuations in precipitation and evapotranspiration. Croley and Luukkonen (2003) found that the direction of change in recharge depended on the GCM chosen to develop the climate that drives the hydrology model. Increasing pumping rates due to more need for irrigation may overwhelm changes in recharge; however there has been little projection of changes in irrigation demand for the Great Lakes Basin.

7.7 Science Gaps and Needs

i) Assessment of climate change effects

Water resources planning can no longer rely on past observations to inform the future. It is also known that the downscaling modeling approach for determining climate change effects on groundwater results in a range of magnitudes and even direction of potential change. The wide or deep uncertainty associated with these climate change effects requires that different assessment and planning methods be used. The new methods that are available need to be evaluated and guidance should be developed to facilitate their adoption.

ii) Uncertainty analysis

The few studies on the effects of climate change on the groundwater quantity in the Great Lakes Basin are incomplete in that none provide a complete uncertainty analysis. Such an assessment is complex because of the multiple

Table 7.1 Summary of groundwater climate change impact studies in the Great Lakes Basin.

Source	Area	Climate Model/Scenario	Hydrological Model/Method	Results
Croley and Luukkonen (2003)	Grand River basin of the Lansing Michigan area	Two GCMs: the Canadian Centre for Climate Modeling and Analysis global coupled model (CCCMA GCM) and the United Kingdom Hadley Centre for Climate Prediction and Research second coupled ocean atmosphere GCM (Hadley GCM).	MODFLOW. Recharge for the model was estimated using the base-flow component of streamflow estimates obtained using the Great Lakes Environmental Research Laboratory (GLERL) hydrological modeling system.	19.7% decrease in recharge using the CCCMA GCM predictions and a 4.1% increase using the Hadley GCM prediction. In general, groundwater levels in the Saginaw aquifer were predicted to decline in the CCMA GCM projection and increase slightly in the HADLEY GCM projection.
Piggott et al., 2005	Southwestern Ontario	Two contrasting climate change model/scenarios: Canadian Centre for Climate Modelling and Analysis, or CCCMA, and Hadley Centre general circulation models and are representative of the period of 2070 to 2099.	Method determined indices of base-flow due to groundwater discharge and then modeling the relation of groundwater discharge to climate. 174 watersheds	CCCMA scenario had a 19 percent decrease in discharge while the Hadley Centre scenario resulted in a 3 percent increase.
Jyrkama and Sykes (2007)	Grand River, Southwestern Ontario	No downscaling, the model input parameters using IPCC TAR predicted GCM changes to the regions climate.	HELP3 was used to calculate the spatially varying daily groundwater recharge rates by linking it to ArcView GIS	Average recharge rate predicted to increase by approximately 100 mm/year from 189 mm/year to 289 mm/year over the 40-year study period.
Sulis et al., 2011	des Anglais catchment in southwestern Quebec	Canadian Regional Climate Model (CRCM) Emissions Scenario A2	CATHY is a coupled physically based, spatially distributed model for surface-subsurface simulations	Significant increase in winter season recharge due to a higher rain/snow ratio caused by higher temperatures, less recharge in the spring due to an earlier and less intense snowmelt, a general decrease over the summer due to increased evaporation, and an increase in the fall due to increased precipitation
Wiley et al. (2010)	Muskegon River watershed in Michigan's Lower Peninsula	The A1B scenario model from the IPCC AR4and a monthly delta change method to downscale the observed weather record.	Muskegon River Ecological Modeling System, set of independent component models targeted toward various aspects of the Muskegon River ecosystem including the The Integrated Landscape Hydrology Model for recharge.	Increasing precipitation in the winter months led to increases in groundwater recharge rates.
Rahman et al. (2012)	Canard River watershed that drains into the Detroit River in southern Ontario	LARS-WG weather generator to generate daily future weather data for the watershed using the Canadian Regional Climate Model (CRCM) outputs under the SRES A2 scenario for the years 2041 to 2070.	Soil Water Assessment Tool (SWAT)	Streamflow would increase significantly in spring and winter, but would decrease in the fall. Groundwater system was not studied but their analyses do support the conclusion that the A2 scenario would result in an increase in the quantity of groundwater flowing through the watershed.

modeling steps that are required. Adding considerably to the complexity is the need to consider the model, data and parameter uncertainty in each modeling step from the selection of an emission scenario to the calculation of the response of the watershed.

iii) Extreme events

Absent from literature is any quantification of extreme weather with the typical qualitative prediction being that storm events in the future may be less frequent and more intense or that there may be periods of prolonged drought. The quantification of extreme events and drought only has meaning in a probabilistic analysis. The complexity of the analysis is that the statistics for either extreme events or drought are not spatially stationary but are likely unique to a given watershed.

iv) Development of integrated models

There is also a clear need to continue developing process based models that can predicatively simulate the impacts of changes in climate on groundwater and surface water resources both in terms of quantity and quality. Interactions between climate and groundwater are most commonly simulated by coupling GCMs with hydrological models (Kurylyk and MacQuarrie, 2013). Since groundwater levels are directly coupled to land-energy feedbacks (Maxwell and Kollet, 2008) it may be more appropriate to directly simulate the groundwater recharge response to climate change within the land surface model of the GCM, or to embed hydrological models into the land surface models of regional climate models. An alternative would be for groundwater scientists to help improve the groundwater components of the existing GCM land surface models (Gulden et al., 2007).

Accurately describing the coupling between climate and hydrology requires incorporation of the full range of hydrological processes including groundwater recharge, and discharge; evapotranspiration based on variable plant phenology; and fluxes to and from ephemeral wetlands; hydrological processes need to be considered interactive components of the climate system (Lofgren et al., 2013). Surface water and groundwater have traditionally been modeled independently, however these are clearly coupled and should thus be considered in an integrated manner (Kornelsen and Coulibaly, 2014; Peterson et al., 2013).

v) Future land and water use scenarios

Climate change will likely affect the quantity and quality of groundwater and surface water in the Great Lakes Basin (Clifton et al., 2010). In some areas the effects of non-climate factors on groundwater such as land and water use and changing practices may have more influence on quantity and quality. However, there is a need for water resource planning to consider the cumulative effects of climate and future land water use scenarios on future water supplies (Sun et al., 2008).

vii) Climate change effects on groundwater quality

Only a few studies have investigated the effects of climate change on groundwater quality in the Great Lakes Basin. The assessment of how, when and where of these effects is critical for developing plans to ensure the security of water supplies for drinking, industry, and irrigation. To address important factors of land and water use, the assessments should be conducted at local to regional scales.

viii) Groundwater monitoring

Based on existing data and studies, there remains insufficient information on the relationship between long-term climate change and groundwater recharge, although several studies have examined the relationship between seasonal or decadal climate variations and groundwater levels (Rivard et al., 2009). There should be an increase in field-based studies that track climate change-induced effects on groundwater levels and quality (Kurlyk and MacQuarrie, 2013).

ix) Integrated monitoring

To adequately assess the effects of climate change on hydrology, there needs to be much more collection of hydrological data including streamflow, groundwater levels, soil moisture and temperature, stream and groundwater temperatures, as well as water quality variables. Increasing the number of stations collecting such data for long time periods provides a basis to evaluate linkages between climate and hydrology, and to validate models that can quantify the reasons for observed changes.

Table 7.2. Priority science needs related to climate change and groundwater.

Science Needs	Related needs and information gaps
7A. Development and application of methods for uncertainty analysis for each step of the down-scaling modeling approach	Identification of GCMs, RCMs, and hydrologic models that are relevant to the Great Lakes Basin.
7B. Development of methods for identifying and assessing changing frequency and intensity of extreme events, e.g., flood and drought	Identification of Intensity-Duration-Frequency curves using climate model projections; Application of drought and flood indices to GCM/RCM output; Statistically significant trends on changing frequency of extreme events.
7C. Development and application of integrated models for climate, surface water and groundwater. Better land surface models for GCMs	More long term groundwater level and quality validating models and assessing climate and land use change; Geologic, land cover and water use and water level data for model development.
7D. Development and application of future land and water use scenarios for modeling effects on groundwater resources.	More integrated monitoring of the water cycle to provide data to allow impact assessment; Integrated data platform to allow access to the variety of physical, infrastructure, and population data to generate scenarios and models.

8. CONCLUSIONS AND SUMMARY OF MAJOR SCIENCE NEEDS

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A key question that is addressed by this report can be summarized as follows: Does groundwater improve or adversely affect Great Lakes water quality? As discussed in Chapters 2, 3 and 4, the flow of groundwater to streams in the Great Lakes Basin or directly to the Great Lakes can serve to either improve or degrade water quality, and in some areas, groundwater may simultaneously contribute both negative and positive effects. For example, along a single stream or lakeshore, plumes of contaminated groundwater may emanate from point sources, surrounded by uncontaminated groundwater, both types discharging to the same surface water environment. This simple example illustrates the complex relationships between groundwater and Great Lakes water quality, and the fact that providing an answer to the above question is not easy or obvious. This chapter provides a range of responses to the above question, as conclusions of this report, by focusing the relevant information that is presented previously in Chapters 2-7.

8.1 Conclusions

(i) Groundwater enhances water quality of the Great Lakes

As discussed in Chapter 2, the discharge of groundwater to streams flowing into the Great Lakes, and directly to the Great Lakes, contributes significantly to the replenishment of the water supply of the lakes. Although data are sparse, groundwater generally has not been adversely impaired by contaminants, such as excessive levels of nutrients or chloride in relatively pristine areas of the Basin. This includes areas around Lake Superior and north of Lake Huron, and undeveloped, mostly forested areas throughout the Great Lakes Basin such as in the northern Lower Peninsula of Michigan. The discharge of groundwater, notably from these pristine areas, to streams flowing into the Great Lakes, or directly to the Great Lakes, helps maintain the water quality of the lakes.

The discharge of this groundwater plays a crucial role in maintaining the water quantity, quality and temperature of habitats (Chapters 2, 5), some of which (perennial streams, coastal fens) are groundwater dependent ecosystems. The ambient chemistry of discharging groundwater is beneficial to some lakeshore communities (Chapt 5).

(ii) Contaminated groundwater adversely affects Great Lakes water quality

As described in Chapters 3, 4 and 6, in developed areas of the Great Lakes Basin, when groundwater is contaminated by activities such as urban development, mining or agriculture, groundwater can have a negative effect on the water quality of streams flowing into the Great Lakes, on the lakes themselves and on aquatic habitats in these water bodies. Groundwater contamination may remain long after the sources of that contamination have been removed. In areas where land use has changed, little evidence may exist for problems at ground surface. As explained in Chapters 3, 4 and 6, discharge of groundwater is an important vector (path) for some contaminants that affect the Great Lakes. Chemicals that are transported by groundwater to the Great Lakes tend to be both relatively persistent and mobile, because they are easily dissolved in water.

(iii) Groundwater provides a treatment or storage zone that can protect Great Lakes water quality

In various ways, groundwater provides a subsurface treatment zone that naturally attenuates, immobilizes or removes many contaminants (Chapters 3 and 4). These attenuation processes often are enhanced in the transition zone (Chapter 3) and other hot zones and hot moments (Chapter 4). However, science gaps remain about the fate of contaminants in groundwater. For example, the ability of microorganisms to remove contaminants in the subsurface depends on the local conditions and the type of contaminant; often the available laboratory tests on which our current understanding of the fate of contaminants is based does not pertain directly to groundwater conditions.

(iv) Groundwater provides a long-term source of contaminants negatively affecting Great Lakes water quality

When contaminants are not degraded or removed, the groundwater can act as a subsurface reservoir that becomes a long-term source of contaminants, which may result in problematic, stable levels of contaminants in groundwater discharging to streams or nearshore areas of the lakes, long after the sources of these contaminants are eliminated or reduced.

(v) There are gaps in our understanding of how groundwater affects Great Lakes water quality

With respect to management and protection of water quality in the Great Lakes Basin, past work on vulnerability of water resources has focused on vulnerability of either groundwater or surface water separately. New approaches that provide more comprehensive tracking and accounting for the flow of contaminants in the environment are needed. Fluxes of chemicals (including nutrients) from groundwater to surface water, and also from surface water to groundwater (for example during bank storage) are important considerations for new approaches. As discussed in the following section (cf. Table 8.1), more comprehensive assessment and reporting on the effects of groundwater on water quality of the Great Lakes will require science advancements in eight different areas:

- assessing regional scale groundwater discharge to surface water;
- assessing the geographic distribution of known and potential sources of groundwater contaminants relevant to Great Lakes water quality, and the efficacy of mitigation efforts;
- monitoring and surveillance of groundwater quality in the Great Lakes Basin;
- advancing research on local-scale interaction between groundwater and surface water;
- developing better tools for monitoring, surveillance and assessment of groundwater – surface water interaction;
- advancing research on the role of groundwater in aquatic habitats in the Great Lakes Basin;
- improving the understanding of effects of urban development on groundwater; and
- developing scale-up models of regional effects of groundwater on Great Lakes water quality.

These science activities are linked. For example, new interpretations (models, insights) often lead directly to rethinking what is required for monitoring, which may result in the design and implementation of new tools to collect field data. In order to be effective, the science activities need to be closely linked to policy and programs, such that program managers and policy makers have the knowledge and tools needed to make informed, science-based decisions related to groundwater and water quality in the Great Lakes Basin.

Addressing some of the science gaps will require ongoing (long-term) science activities. This is, in part, due to ongoing urban development and changes in land use and infrastructure, which can have large effects on groundwater, including the quantity of groundwater discharge, hence also on the water budget and water quality of the Great Lakes (Chapter 6). Climate change may affect groundwater, notably the rates and timing of both recharge and discharge of groundwater to surface water in the Great Lakes Basin (Chapter 7).

Large uncertainties are associated with modeling of climate and associated hydrological responses of groundwater and surface water in the Great Lakes Basin. Consequently, very little can be said today about what effects climate change will have on groundwater, and about how these changes will affect the quantity and quality of water in the Great Lakes (Chapter 7). Future collection of climate data, coupled with groundwater monitoring, will allow revision and refinement of the modeling of these relationships. However, it is anticipated that climate change in the Great Lakes Basin will be accompanied by land use changes, which may have an even greater effect on groundwater quantity and quality than the direct effect of climate change, thus adding to the complexity of the challenges that will continue to be addressed by future science activities.

8.2 Summary of Major Science Gaps and Needs

This final section summarizes and provides a concluding discussion of eight major areas of information gaps and science needs, based on those identified previously in Chapters 2-7 (Table 8.1).

Science Need Area 1: Advance assessment of regional-scale groundwater discharge (quantity) to surface water in the Basin

Understanding how groundwater is affecting Great Lakes water quality will require more accurate regional- to basin-wide scale accounting for the flux of groundwater to streams and directly to the Great Lakes. More specifically, this will require more accurate water balances and field measurements to determine groundwater contributions for the Great Lakes, lakes and ponds, and wetlands in order to assess relative importance of groundwater sources to each.

A first-order regional-scale assessment of groundwater quantity fluxes to surface water in the Great Lakes Basin as base-flow has been provided by Neff et al. (2005). On the U.S. side of the Great Lakes some of the sites evaluated by Neff et al. (2005) have been updated and can be used to determine regional trends in groundwater discharge. In municipal areas where groundwater is a source of drinking water, Source Water Protection plans have been implemented as management tools to help protect groundwater. The impact of groundwater withdrawals on streamflow is also being assessed on a case-by-case basis in Michigan and similar withdrawal assessment tools are being evaluated in other states.

On the Ontario side of the Great Lakes Basin, in developed areas, relevant information has been assembled at the scale of subwatersheds, which are managed by individual Conservation Authorities. In these subwatersheds, the Source Water Protection plans have provided regional-scale assessments of groundwater flow systems and water budgets, including discharge to streams, and in some cases estimates of direct discharge to shores of the Great Lakes. These assessments vary in complexity (Tier 1 to Tier 3). However, in the relatively pristine northern portion of the Great Lakes Basin in Ontario, where few Source Water Protection plans have been developed, very little information is available on the groundwater flow systems or about the efflux of groundwater to streams and the Great Lakes. Here initial estimates of groundwater fluxes to streams would generally rely on estimates of base-flow provided by the base-flow index approach (Neff et al., 2005).

As their names imply, Source Water Protection plans in Ontario mainly focus on the protection of groundwater and surface water as sources of drinking water. Thus, assessments of fluxes of groundwater to surface water are minor components of these studies. These assessments use various methods to calculate base-flow using stream hydrographs. The interpretations warrant revisiting to ensure that they adequately account for other components of base-flow, such as drainage from lakes, wetlands and reservoirs and the discharge of treated wastewater.

Science Need Area 2: Establish science-based priorities to advance the assessment of the geographic distribution of known and potential sources of groundwater contaminants relevant to Great Lakes water quality, and the efficacy of mitigation efforts

Understanding of how groundwater is improving or adversely affecting Great Lakes water quality will require compilation and assessment of locations of known or suspected sources of groundwater contamination, that are considered to have potential, direct impact on the water quality in nearshore areas of the Great Lakes, and in streams flowing to the Great Lakes. An emphasis could be placed on large industrial sites (legacy and current), urban developments, and areas of widespread, regional use of chemicals such as salt, fertilizers and pesticides. This assessment also could include an evaluation of the efficacy of mitigation efforts, including changes in regulations, practices, remediation prevention and containment approaches, and introduction of beneficial management approaches, with respect to groundwater contamination at these locations.

This science-based assessment could be periodically updated, incorporating new knowledge that is obtained by science activities outlined in the following science need areas (3-7).

Science Need Area 3: Advance monitoring and surveillance of groundwater quality in the Great Lakes Basin

Understanding of how groundwater is improving or adversely affecting Great Lakes water quality will also require compilation and assessment of the available groundwater quality data in the Basin. The existing monitoring networks likely have significant gaps with respect to information about both non-point and point source contaminants, and spatial disparity (Chapter 3). For example, it is possible that these networks will need to be augmented by enhanced local-scale (e.g., site specific) groundwater surveillance or monitoring in urban and industrial areas. Consideration should be given to unconventional approaches, such as sampling shallow groundwater by temporary drive points in urban riparian zones and along urban shores (Roy and Bickerton, 2010, Roy and Malenica, 2013). Monitoring should be expanded, in terms of the range of contaminants analyzed, to include "emerging concern" chemicals (Chapter 3).

A major challenge is that much of the site specific monitoring data that has been collected in the Basin (e.g., at contaminated sites) is not available in the public realm (Chapter 3). In some cases, it may be possible to incorporate or access information from existing, privately-owned or NGO-operated monitoring wells in such areas, rather than requiring new, expensive installations. In some cases, information gathered about contaminated groundwater may be directly relevant to Areas of Concern (AOCs) in the Great Lakes (see Annex 1 of the GLWQA; Environment Canada, 2013b). Furthermore, the larger scale, cumulative effects of these contaminants are relevant to Lakewide Management Plans (see Annex 2 of the GLWQA; Environment Canada, 2013b).

Science Need Area 4: Advance research on local-scale assessment of interaction between groundwater and surface water

A more detailed understanding of groundwater – surface water interaction is needed to adequately assess the effect of groundwater on water quality and aquatic habitats in the Great Lakes. This would require include local-scale field studies that consider not only the quantity of groundwater discharge but also the fluxes of contaminants between groundwater and surface water, and the various processes that attenuate these contaminants.

This new field-based research could focus on riparian zones along streams and in nearshore areas of the Great Lakes, including coastal wetlands, beaches, and developed urban shorelines, to directly assess the interaction of groundwater and surface water, and the effect of these exchanges on aquatic habitats. These local scale studies would consider heterogeneity (hydraulic properties of sediments, contaminant sources), seasonality and events, processes at and near the interface between groundwater and surface water (e.g., streambed, shoreline). This analysis would have to take into account that exchange of groundwater and surface water is not unidirectional in either space or time: even during base-flow conditions, different stream reaches may be either "gaining" or "losing" (experiencing net discharge of groundwater or net recharge to groundwater), and there are seasonal and weather-related events and reversals, such as episodic recharge in low lying areas during spring melt and bank storage of stream water (as riparian groundwater) associated with precipitation events. The goal of these local-scale studies would be to develop better conceptual and numerical models of the interaction of groundwater with surface water in different hydrogeological and land use settings in the Great Lakes Basin, and water quality aspects of this interaction, as well as how these interactions affect aquatic habitats.

In part, these local-scale studies could be aimed to provide a better understanding of the importance of near-stream, shallow groundwater flow systems. More specifically, there is a need to determine the relative role of localized near-stream groundwater flow systems, compared to longer, deeper flowpaths in aquifers in the Great Lakes Basin. If the interpretation of Pijanowski et al. (2007) is correct, then the water quality of streams in Great Lakes Basin may be proportionately more affected by discharge of contaminated groundwater that has recharged in urban areas, which tend to be located near streams, compared to groundwater derived from recharge in larger areas under agricultural use, which, on average, travels further and longer before reaching streams. Some of the local-scale studies should directly address the information gaps and uncertainties associated with land use and infrastructure, especially in urban areas, but also in rural areas (e.g., tile drains).

Some of these studies could also assess how spatial and temporal variations in stream chemistry along stream reaches are related to groundwater discharge. Maintenance of local-scale research sites as nodes within monitoring networks would greatly contribute towards a better understanding of how changes in land use, climate, and other factors affect the water quality of the Great Lakes, and of how effectively groundwater flow systems can buffer (attenuate) the changes in the quantity and quality of water in the Great Lakes, in response to such changes. Dedicated research sites would be very useful for ongoing testing and revision of the local-scale conceptual and numerical models of groundwater – surface water interaction.

Science Need Area 5: Develop better tools for monitoring, surveillance and local-scale assessment of groundwater – surface water interaction

Development of better tools and protocols for inexpensive, relatively nonintrusive studies of groundwater – surface water interaction at the local (reach) scale is needed to support the monitoring, surveillance and research outlined above (Science need areas 3,4).

Science Need Area 6: Advance research on the role of groundwater in aquatic habitats in the Great Lakes Basin

Detailed site specific studies are needed on groundwater effects (including dependency) on aquatic communities, particularly benthic communities, and groundwater-dependent communities in streams and coastal wetlands. Investigations on how different ecological and microbial communities respond to the chemical constituents of shallow groundwater, including contaminants, would provide important information on the role of groundwater in aquatic habitats.

Science Need Area 7: Improve the understanding of effects of urban development on groundwater

Quantitative data are lacking on the components of the complex water cycle in urban areas of the Great Lakes Basin. Information is particularly sparse about the role of groundwater in this cycle, including how urban groundwater is affected by infrastructure, including sewer networks ("urban karst"), stormwater management systems, and extraction, including dewatering. Quantitative information is also lacking about urban sources of groundwater contamination, about concentrations of contaminants in groundwater and about fluxes of contaminants from discharging groundwater to streams and lakes in urban areas. Addressing all of these science gaps by implementing an array of new monitoring and research activities would greatly improve understanding of the effects of urban groundwater on receiving water bodies and on aquatic ecosystems. There is also a need to expand the use of comprehensive groundwater modelling tools to provide guidance on urban groundwater management. These modeling approaches would incorporate the effects of subsurface infrastructure (e.g., pipes, trenches, subways, etc.), and would enable a better understanding of water quantity and water quality changes over time, the potential effects of changing climate and land use. This would support risk assessment related to the effects of groundwater on surface water quality and ecosystems in urban areas.

Science Need Area 8: Develop scaled-up models of regional effects of groundwater on Great Lakes water quality

Another vital link of an improved, integrated science approach would be to develop and revise regional-scale numerical models that incorporate the above, regional-scale discharge assessments, monitoring and surveillance data and local-scale research activities. The challenge would be to upscale the enhanced understanding of local-scale processes (based on the local-scale studies) in order to assess regional-scale time-averaged efflux of groundwater (quantity and contaminants) to the Great Lakes, either directly or indirectly through the tributaries. This type of modeling will provide a very useful assessment of the regional-scale effects of groundwater on Great Lakes water quality and aquatic habitats.

This regional-scale, integrated modeling of the fate of contaminants in the Great Lakes Basin would have to take into account their storage and attenuation in groundwater (and associated solid phases), including the role of the transition zone, as described in Chapters 2, 3 and 4. The assumptions of these models would have to be based on local-scale field investigations of the fluxes of these contaminants between groundwater and surface water, as described above. The challenge would be to select appropriate numerical approaches to provide a regional, time-averaged scale of interpretation. Perhaps the regional scale modeling could incorporate more detailed, physically based modeling of processes at local scale, but would need to provide a way of scaling up, in which more simplified model assumptions are required (see Chapters 2 and 7). Upscaling in time will limit the ability to incorporate effects of episodic events, such as spring snowmelt and storms. Appropriate methods would be selected for upscaling in order to avoid erroneous degradation of the physical basis of the model and loss in reliability of the results (Chapter 7). Somehow this regional-scale modeling would have to incorporate concepts that account for localized processes and short-term events, including reversals (e.g., bank storage), and ways to assess the importance of such variations in affecting groundwater and its effects on surface water and aquatic habitats in the Great Lakes Basin.

Table 8.1. Relationships between major science needs presented in this chapter and the priority science needs identified in Chapters 2-7.

Major science need areas	Priority science need identified in Chapters 2-7	Relevant chapter
1 Assessing regional- scale groundwater discharge to surface water	2B. Accurately quantify groundwater discharges to surface water	2
	2C. Identify significant groundwater flowpaths to surface water and delineate groundwater discharge zones	2
	5A. Map groundwater recharge and discharge.	5
2 Assessing the geographic distribution of known and potential sources of groundwater contaminants relevant to Great Lakes water quality, and the efficacy of mitigation efforts	4A. Linking land management and groundwater nutrient loading	4
	6B. Quantitative information about contaminant sources	6
3 Monitoring and surveillance of groundwater quality in the Great Lakes Basin	4D. Basin-wide assessment of groundwater	4
	6C. Monitoring of groundwater quality and risk assessment of potential health risks	6
4 Advancing research on local-scale interaction between groundwater and surface water	2A. Appropriately characterize spatial heterogeneity and temporal variability in groundwater/surface water exchanges	2
	2E. Characterize and understand the role of transition zone processes on the quality of surface water	2
	3B. Assessing the remediation potential of the transition zone	3
	4B. Role of hot phenomena with respect to groundwater nutrient fluxes	4
5 Developing better tools for monitoring, surveillance and assessment of groundwater/surface water interactions	3A. Methods for detection and assessment of contaminated groundwater discharges	3
6 Advancing research on the role of groundwater in aquatic habitats in the Great Lakes Basin	2D. Determine critical relationships between groundwater discharge and aquatic ecosystem health	2
	3C. Sensitivity of transition zone organisms to contaminants	3
	3D. Actual ecological effects of groundwater contaminants	3
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Glossary

Below are definitions of some terms, both scientific and non-scientific, many of which are related to groundwater, hydrology and ecology. These are provided here for information purposes, not as official legal definitions. Where applicable, use of one of the following numbered sources is indicated by the corresponding number provided at the end of each definition (although exact wording has sometimes been changed):

[1]United States Environmental Protection Agency
(**http://iaspub.epa.gov/sor_internet/registry/termreg/searchandretrieve/termsandacronyms/search.do**)
[2]American Society of Civil Engineers, 1985, Manual 40 – Ground water management
[3]USGS Water Basics Glossary (**http://water.usgs.gov/water-basics_glossary.html**)
[4]Water Information Coordination Program (**http://acwi.gov/wpinfo.html**)
[5]Kansas Geological Survey (**http://www.kgs.ku.edu/Extension/glossary.html**)
[6] Water Encyclopedia – Science and Issues (**http://www.waterencyclopedia.com/**)
[7]Central Lake Ontario Source Protection Area Assessment Report
(**http://www.ctcswp.ca/the-science-ctc-assessment-reports/central-lake-ontario-spa-assessment-report/**)
[8]Canadian Environmental Assessment Agency, Cumulative Impact Monitoring Program
(**https://www.aadnc-aandc.gc.ca/eng/1100100023828/1100100023830**)
[9]USGS Water Science Glossary of Terms (**http://water.usgs.gov/edu/dictionary.html**)
[10] Environment Canada, Groundwater (**http://www.ec.gc.ca/eau-water/default.asp?lang=En&n=300688DC-1**)
[11]Merriam Webster Online (**http://www.merriam-webster.com/**)
[12]Fisheries and Oceans Canada (**http://www.dfo-mpo.gc.ca/species-especes/act-loi/habitat-eng.htm**)

Acidic (acid mine) drainage: Is the formation and movement of highly acidic water rich in heavy metals. This acidic water forms through the chemical reaction of surface water (rainwater, snowmelt, pondwater) and shallow subsurface water with rocks that contain sulfur-bearing materials, resulting in sulfuric acid. Heavy metals can be leached from rocks that come in contact with the acid, a process that may be substantially enhanced by bacterial action. The resulting fluids may be highly toxic and, when mixed with groundwater, surface water and soil, may have harmful effects on humans, animals and plants.[1]

Adfluvial: Migrating between lakes and rivers or streams.

Absorption: The process by which substances in gaseous, liquid or solid form dissolve or mix with other substances.[2] (The verb form is absorb.)

Adsorption: Adherence of gas molecules, ions or molecules in solution to the surface of solids.[2]
(The verb form is adsorb.)

Aerobic: Pertaining to, taking place in, or caused by the presence of oxygen.[3]

Alluvial: Pertaining to processes or materials associated with transportation or deposition by running water.

Ambient groundwater conditions: Baseline water-quality characteristics that can be used to investigate long-term trends in resource conditions. The parameters measured in baseline-monitoring programs provide a set of descriptive data on general groundwater conditions.[4]

Anaerobic: Pertaining to, taking place in, or caused by the absence of oxygen.[3]

Anammox: Abbreviation for anaerobic ammonium oxidation. A microbial process of the nitrogen cycle.

Anoxic: Being depleted of dissolved oxygen. This condition is generally found in areas that have restricted water exchange.

Aquifer: A geologic formation (or group of geologic formations) that is porous enough and permeable enough to transmit water at a rate sufficient to feed a spring or a well.[5]

Aquifer vulnerability mapping: A tool that can be used to protect groundwater resources and their ultimate use. Aquifer vulnerability maps identify areas where contamination of surface water or at the land surface is more or less likely to result in the contamination of groundwater.

Attenuation (of contaminants): Can be split into two components, physical or chemical. Physical attenuation is the dilution and dispersion of contaminant concentrations in surface waters or groundwater. Chemical attenuation is the collective assemblage of reactions that causes contaminant concentrations to decrease in surface waters or groundwater. Attenuation of chemicals is complicated, and specific to the particular contaminant class.[6]

Bank storage: The change in the amount of water stored as groundwater, often in an aquifer, adjacent to a surface water body resulting from a change in stage of the surface water body.[3]

Base flow: The sustained flow of a stream, usually groundwater inflow, to the stream channel.[3]

Bedrock: A general term used for solid rock that underlies soils or other unconsolidated materials.[3]

Bedrock geology: The study of the solid rock underlying unconsolidated surface material. Also refers to description of bedrock types.[7]

Benthic: Occurring at the base of bodies of water: lakes, streams.

Benthic invertebrates: Small aquatic organisms that live in stream sediments and are a good indicator of water quality and stream health.[7]

Bioaccumulation: The biological sequestering of a substance at a higher concentration than that which it occurs in the surrounding environment or medium. Also, the process by which a substance enters organisms through the gills, epithelial tissues, dietary, or other sources.[3]

Biomagnification: A process where chemicals are retained in fatty body tissue and increase in concentration over time. Biomagnification is the increase of tissue accumulation in species higher in the natural food chain as contaminated food species are eaten.[1]

Bioswale: A relatively wide, shallow, open channel, typically vegetated with turf grasses, with a slight gradient. These systems are designed to let water flow slowly through the turf grasses. The roughness of the turf slows the runoff velocity and provides some filtration and settling of suspended solids. Runoff volumes can also be reduced through infiltration depending on the porosity of the underlying soils. Swales can be designed with underdrains to convey excess runoff from saturated soils.[1]

Biota: All living organisms of an area.[3]

Catchment: The groundwater and surface water drainage area from which a woodland, wetland, or watercourse derives its water.[7]

Climate: The average weather conditions of a place or region throughout the seasons.[7]

Combined storm-sewer system: Sewers that carry both sanitary waste and stormwater.

Cold water fish: : Fish that require maximum daily mean temperatures less than 20±1°C. The maximum temperature criterion varies slightly between the classification systems used in Ontario (19°C: Fisheries and Oceans Canada, 2008) and in Michigan and Wisconsin (20.7°C: Lyons et al., 2009). Cool water and warm water fish are also defined based on other temperature criteria.

Coliform bacteria: Bacteria that are naturally present in the environment and used as an indicator that other potentially harmful bacteria may be present.[1]

Colloid: Of or pertaining to very small, finely divided solids that do not dissolve and remain dispersed in a liquid due to their small size and electrical charge.[1]

Conductivity: The quality or power of conducting or transmitting.

Confining unit: A body of impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers that restricts the movement of water into and out of the aquifers.[3]

Contaminant: An undesirable substance, usually an element, compound or microorganism that is released to the environment by human activity. In groundwater and surface water, contaminants generally occur as solutes or suspended particles (e.g., colloids). They include synthetic substances and naturally occurring substances that reach unusually high concentrations in water because of human activities. (see contamination)

Contamination: The introduction of harmful substances that are called contaminants (see above) into the environment as the result of human activities. Contamination of groundwater may occur when synthetic substances are released to surface or near surface environments, or when naturally occurring substances are released to the same environments by human activities and technologies. Examples of the latter include extraction of hydrocarbons and formation water from wells, and mining of salt. Contamination may occur as the result of geochemical reactions in these environments, for example when mine waste rock is stored at surface, or when the water table is lowered.

Critical habitat (for aquatic species): "Critical habitat is vital to the survival or recovery of wildlife species. The habitat may be an identified breeding site, nursery area or feeding ground. For species at risk, these habitats are of crucial importance".[12]

Cumulative effects: Changes to the environment that are caused by an action in combination with other past, present and future human actions.[8]

Denitrification: A process by which oxidized forms of nitrogen such as nitrate (NO_3^-) are reduced to form nitrites, nitrogen oxides, ammonia or free nitrogen: commonly brought about by the action of denitrifying bacteria and usually resulting in the escape of nitrogen to the air.[3]

Dense non-aqueous phase liquids (DNAPLs): A group of chemicals that is insoluble and denser than water.[1]

Discharge (of groundwater): See groundwater discharge.

Discharge area: An area where subsurface water is discharged to the land surface, to surface water, or to the atmosphere.[3]

Dispersion: the extent to which a substance (solute, colloid) that is introduced into a groundwater system spreads as it moves through the system.[3]

Dissimilatory (nitrate reduction): To reduce nitrates or nitrites to gaseous products such as nitrogen, nitrous oxide, and nitric oxide; brought about by denitrifying bacteria.

Drainage area: The drainage area of a stream at a specified location is that area, measured in a horizontal plane, that is enclosed by a drainage divide.[3]

Drainage system: A drain constructed by any means, including works necessary to regulate the water table.[7]

Ecosystem: A natural community of plants and animals within a particular physical environment that is linked by a flow of materials throughout the non-living (abiotic) as well as the living (biotic) section of the system.[7]

Effluent: Outflow from a particular source, such as a stream that flows from a lake or liquid waste that flows from a factory or sewage treatment plant.[3]

Efflux: Outflow from, for example, discharge of groundwater.

Embayment: A recess in a coastline forming a bay.

Emerging contaminants: These compounds may not be "new" compounds, but advances in analytical techniques mean they are now being detected at frequencies or concentrations that are significantly different than expected and little or nothing is known about their environmental effects. Examples of emerging contaminants are provided in Table 3.4. By definition, chemicals continue to be added to the list of emerging contaminants and, therefore, there is no single list of emerging contaminants.[1]

Erosion: The process whereby materials of the Earth's crust are loosened, dissolved, or worn away and simultaneously moved from one place to another.[3]

Esker: A long ridge or mound of sand, gravel and other sediment, typically having a winding course, deposited by a stream flowing on, within, or beneath a stagnant or retreating glacier or ice sheet.

Eutrophication: The process by which water becomes enriched with plant nutrients, most commonly phosphorus and nitrogen.[3]

Evapotranspiration: The process by which water is discharged to the atmosphere as a result of evaporation from the soil and surface water bodies, and transpiration by plants.[3]

Exposure: Contact made between a chemical, physical or biological agent and the outer boundary of an organism. Exposure is quantified as the amount of an agent available at the exchange boundaries of the organism (e.g., skin, lungs, gut).[1]

Flowpath: An underground route for groundwater movement, extending from a recharge (intake) zone to a discharge (output) zone such as a shallow stream.[3]

Flow-through (stream or lake): A reach of stream or a pond or lake where groundwater discharges up into the surface water on one side (i.e., is gaining groundwater) but surface water from the stream or lake flows down into the subsurface (e.g., aquifer) on the opposite side of the surface water body (i.e., is losing surface water).

Fluvial: Pertaining to a river or stream.[3]

Freshwater: Water that contains less than 1,000 milligrams per liter (mg/L) of dissolved solids.[3]

Gaining stream: A stream or reach of stream whose flow is being increased by inflow of groundwater.[2]

Geology: The science of the composition, structure and history of the Earth. Geology thus includes the study of the material of which the Earth is made, the forces which act upon these materials and the resulting structures.[7]

Geomorphic change: Pertaining to changes to the form or general configuration of the Earth or its surface features.[3]

Geomorphology: The scientific study of the origin of land, riverine and ocean features on the Earth surface.[7]

Glaciation: The covering of an area or the action on that area, by an ice sheet or by glaciers.[7]

Glacial deposits: Sediments that are deposited by glaciers or by glacial meltwater. Landforms dominated by glacial deposits include moraines, eskers, till plains, and glacial lake plains (see also: till, glaciofluvial deposits, glaciolacustrine deposits, esker, moraine).

Glaciofluvial deposits: Sediments deposited by glacial meltwater streams.

Glaciolacustrine deposits: Sediments deposited by glacial meltwater lakes.

Gradient: A change in the value of a quantity (e.g., temperature or concentration) with a change in a given variable and especially per unit distance in a specified direction.[11]

Great Lakes: The five (large) lakes located in Canada and United States: Lake Ontario, Lake Superior, Lake Huron, Lake Erie, and Lake Michigan.

Great Lakes connecting channels: The large rivers that connect the Great Lakes, which include the St. Marys, St. Clair, Detroit, Niagara and St. Lawrence Rivers.

Groundwater: Water that flows or seeps downward and saturates the soil or rock, supplying springs and wells.[9]

Groundwater discharge: The flow of groundwater to the surface environment, where it enters water bodies or unsaturated soils, and sometimes is detectable as seeps or springs.

Groundwater flow system: a volume of the subsurface in which the groundwater flows in a relatively uniform pattern (i.e., flow lines are subparallel), typically from recharge area(s) to discharge area(s). The flow system is considered to be shallow if all of the groundwater flow occurs at shallow depths. It is referred to as a deep flow system, if most of the groundwater flow occurs in the deep subsurface.

Groundwater recharge: The replenishment of groundwater by movement of water to the water table from soils or surface water bodies by either (a) natural processes, such as the infiltration of rainfall and snowmelt through soil, and the seepage of surface water from lakes, streams and wetlands, (b) from human interventions, such as the use of storm water management systems.[7]

Groundwater residence time: The length of time water spends in the groundwater portion of the water cycle.[10]

Habitat: The part of the physical environment in which a plant or animal lives.[3]

Hot moments: Short periods of time that exhibit disproportionately high biogeochemical activity relative to longer intervening time periods (cf. hot spots) (McClain et al., 2003).

Hot spots: Localized zones in the subsurface (soil, sediment) that show disproportionately high biogeochemical activity relative to the surrounding area (McClain et al., 2003).

Hydraulic (properties): With respect to groundwater, the properties of a rock or sediment that govern the entrance of water and the capacity to hold, transmit, and deliver water, such as porosity, effective porosity, specific retention, permeability, and the directions of maximum and minimum permeabilities.[1]

Hydraulic conductivity: The capacity of a rock, sediment or other material to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.[3]

Hydraulic fracturing: A well stimulation process used to maximize the extraction of underground resources, including oil, natural gas, geothermal energy, and even water.[1]

Hydraulic gradient: The change of hydraulic head per unit of distance in a given direction.[3]

Hydraulic head: The height of a free surface of a body of water above a given point beneath the surface.[3]

Hydrogeology: The study of the movement and interactions of groundwater in geological materials.

Hydrogeological: Adjective, pertaining to the hydrogeology of a system.

Hydrograph: A graph showing variation of water elevation, velocity, streamflow, or other properties of water with respect to time.[3]

Hydrological (properties): Pertaining to the hydrology of a system (e.g., watershed).

Hydrology: The science that deals with water as it occurs in the atmosphere, on the surface of the ground, and underground.[3]

Hyporheic zone: The saturated transition zone between surface water and groundwater bodies that derives its specific physical and biogeochemical characteristics from active mixing of surface water and groundwater to provide a habitat and potential refuge for obligate and facultative species.

Hyporheos: A set of aquatic organisms that have adapted to and inhabit the hyporheic zone.

Ichthyoplankton: Eggs, fry and larvae of fish.

Infiltration: The downward movement of water from the atmosphere into soil and porous rock.[3]

Influx: Inflow to, for example, influx to surface water of discharging groundwater.

Information gap: Information gaps are considered to be a lack of data rather than a lack of scientific understanding, meaning it is known how the system works but there is insufficient data or measurements to answer the questions being asked. To resolve science needs, one often needs to fill a variety of information gaps first, but at times the reverse is true where the information gaps exist and science does not have the techniques or ability to measure and collect the information that is needed.

Inorganic: Containing no carbon; matter other than plant or animal.[3]

Infrastructure: The system of public works of a country, state or region.[11]

Interflow: The runoff infiltrating into the surface soil and moving toward streams as shallow, perched groundwater above the main groundwater level.

Intergranular flowpaths: Paths of groundwater flow in pore spaces between grains of sediment.

Interstitial organisms (biota): Organisms that inhabit the spaces between grains in sediment.

Invertebrates: An animal having no backbone or spinal column.[3]

Impact: Often considered the consequence or effect, the impact should be measurable and based on an agreed set of indicators.

Karst: A type of topography that results from dissolution and collapse of carbonate rocks such as limestone, dolomite, and gypsum, and that is characterized by closed depressions or sinkholes, caves, and underground drainage.[3]

Knowledge gaps: Lack of referenced materials or expertise to assess certain characteristics of the specific watershed that can be adequately described without tabular or spatial data.

Land use: A particular use of space at or near the earth surface with associated activities, substances and events related to the particular land-use designation.[7]

Leachate: A liquid that has percolated through soil containing soluble substances and that contains certain amounts of these substances in solution.[3]

Leaching: The removal of materials in solution from soil or rock; also refers to movement of pesticides or nutrients from land surfaces to groundwater.[3]

Local, Local-scale: Of, relating to, or characteristics of a particular place.[11]

Losing stream: A stream or reach of a stream in which water flows from the stream bed into the ground.[2]

Low flow: The flows that exist in a stream channel in dry conditions.

Macroinvertebrate: An animal having no backbone or spinal column that is visible to the naked eye.

Macrophyte: An aquatic plant large that is visible to the naked eye.

Macropore: Any pore sufficiently wide to allow water to flow unimpeded by capillary action.

Microbial: Of, pertaining to, or characteristic of a microorganism.

Microorganism: A microscopic organism, including bacteria, viruses, and algae.

Model: An assembly of concepts in the form of mathematical equations or statistical terms that portrays a behavior of an object, process or natural phenomenon.[7]

Model calibration: The process for generating information over the life cycle of the project that helps to determine whether a model and its analytical results are of a quality sufficient to serve as the basis of a decision.[7]

Monitoring: Repeated observation, measurement, or sampling at a site, on a scheduled or event basis, for a particular purpose.[3]

Moraine: A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited chiefly by direct action of glacial ice.[3]

Naturally occurring processes: Processes that occur in nature and that are not the result of human activity. For example, erosion along a stream that provides a source of drinking water or the leaching of naturally occurring metals found in bedrock into groundwater.[7]

Nitrification: A microbial process by which reduced nitrogen compounds (primarily ammonia) are sequentially oxidized to nitrite and nitrate.[1]

Non-aqueous phase liquid (NAPL): A group of chemicals that is insoluble in water, including light and dense NAPLs.

Non-point source: A source (of any water-carried material) from a broad area, rather than from discrete points.[3]

Non-point source contaminant: A substance that pollutes or degrades water that comes from diffuse sources such as the atmosphere, roadways and runoff.[3]

Nutrient: Any inorganic or organic compound needed to sustain plant life.[3]

Organic: Containing carbon, but possibly also containing hydrogen, oxygen, chlorine, nitrogen, and other elements.[3]

Organism: A living thing, such as a vertebrate, insect, plant or bacteria.

Overland flow: The flow of rainwater or snowmelt over the land surface toward stream channels.[3]

Oxic: A process, condition, or environment in which oxygen is involved or present.

Paleodata: Data from some former period of geologic time.

Parallel flow reach (zero exchange reach): A reach of stream where there is no exchange of groundwater or surface water across the streambed (i.e., is neither gaining groundwater nor losing surface water). Groundwater flows parallel to the stream channel and does not enter it.

Particulate transport: The movement of particles in subsurface water.[3]

Partitioning: The distribution of a reactive solute between solution and other phases.

Pathogen: Any living organism that causes disease.[3]

Peak flow: The maximum instantaneous discharge of a stream or river at a given location. It usually occurs at or near the time of maximum stage.[9]

Percolation: The downward movement of water in the ground through porous soil and cracked or loosely packed rock.[7]

Periphyton: Microorganisms that coat rocks, plants, and other surfaces on lake bottoms.[3]

Permeability: The capacity of a rock for transmitting a fluid; a measure of the relative ease with which a porous medium can transmit a liquid.[3]

Permeable: Capable of being permeated or penetrated, especially by liquids or gases.

Physiography: The study or description of landforms.

Point source: Originating at any discrete source.[3]

Point source contaminant: Any substance that degrades water quality and originates from discrete locations such as discharge pipes, drainage ditches, wells, concentrated livestock operations, or floating craft.[3]

Porosity: The ratio, usually expressed as a percentage, of the total volume of voids of a given porous medium to the total volume of porous medium.

Precipitation: Any or all forms of water particles that fall from the atmosphere, such as rain, snow, hail and sleet.[3]

Preferential flowpath (groundwater): Refers to the uneven and often rapid movement of water and solutes through porous media, typically soil, characterized by regions of enhanced flux such that a small fraction of media (such as wormholes, root holes, cracks) participates in most of the flow, allowing much faster transport of a range of contaminants, including pesticides, nutrients, trace metals, and pathogens.

Preferential habitat: The habitat chosen by an organism in preference to other habitats.

Productivity (biological): Rate of production, especially of food or solar energy by producer organisms.[7]

Receptor: The exposed target in danger of incurring a potential impact.[7]

Recharge (of groundwater): See groundwater recharge.

Redd: A spawning nest made by a fish, especially a salmon or trout.

Refuge: An area in which a population of organisms can persist through a period of unfavorable conditions (e.g., waters that are too warm in summer months).

Regional aquifer: An aquifer that extends over large areas or a group of virtually independent aquifers that have so many characteristics in common the studies of a few of these aquifers can establish common principles and hydrogeological factors that control the occurrence, movement, and quality of groundwater throughout these types of aquifers.

Regional scale modeling: Modeling performed at a regional (large) scale or for a particular region.

Remediation: Actions taken to respond to a hazardous material release or threat of a release that could affect human health or the environment. For example the removal of pollution or contaminants from environmental media such as soil, groundwater, sediment or surface water.[1]

Residence time (of groundwater): See groundwater residence time.

Restoration: Changing the existing function and structure of a habitat so that it is similar to historical conditions.

Return flow: That part of irrigation water that is not consumed by evapotranspiration and that returns to its source or another body of water.[3]

Riparian areas (zones): Vegetated areas close to or within a water body that directly or indirectly contribute to fish habitat by providing a variety of functions such as shade, cover, and food production areas.[7]

Riverine: Relating to or resembling a river.[7]

Runoff: Water that moves over land rather than infiltrating the ground. Runoff is greatest after heavy rains or snowmelts, and can pick up and transport contaminants from landfills, farms, sewers, industry and other sources.[7]

Salmonid: Any of a family (Salmonidae) of elongate bony fishes (as a salmon, trout, grayling, whitefish) that have the last three vertebrae upturned.[11]

Saturated zone: A subsurface zone in which all the interstices or voids are filled with water under pressure greater than that of the atmosphere.[3]

Scale: A graduated series or scheme of rank or order.[7]

Seiche: An oscillation of the surface of a landlocked body of water (as a lake) that varies in period from a few minutes to several hours.[11]

Septage: The liquid and solid materials pumped from a septic tank during cleaning operations.[1]

Shallow aquifer: An aquifer (usually unconfined) that is near the land surface.

Shallow flowpaths (of groundwater): An underground route for groundwater movement that is near the land surface.

Science needs: Areas where there is a lack of understanding about how the system works, such as basic processes or relationships among components of the system.

Sediment: Particles, derived from rocks or biological materials, that have been transported by a fluid or other natural process, suspended or settled in water.[3]

Seep: A small area where water percolates slowly to the land surface.[3]

Sinkhole: Any depression in the surface of the ground or lake bottom, with or without collapse of the surrounding soil or rock, which provides a means through which surface water can enter the ground and therefore come in contact with groundwater. Sinkholes often allow this contact to occur quite rapidly and do little to filter any contaminants the surface water may contain.[7]

Slope: Ground that forms a natural or artificial incline.

Snowpack: A seasonal accumulation of slow-melting packed snow.[11]

Solubility: The total amount of solute species that will remain indefinitely in a solution maintained at constant temperature and pressure in contact with the solid crystals from which the solutes were derived.

Solute: A substance that is dissolved in another substance, thus forming a solution.[9]

Sorption: All processes which remove solutes from fluid phases and concentrate them in or on the surfaces of solid phases. (The verb form is sorb.)

Spring: A water body formed when the side of a hill, a valley bottom or other excavation intersects a flowing body of groundwater at or below the water table, below which the subsurface material is saturated with water.[9]

Stenothermal: Capable of surviving over only a narrow range of temperatures.

Stormwater: Rainfall that does not infiltrate the ground or evaporate because of impervious land surfaces but instead flows onto adjacent land or watercourses or it routed into drain or sewer systems.[1]

Stream: A general term for a body of flowing water; natural water course containing water at least part of the year. In hydrology, it is generally applied to the water flowing in a natural channel as distinct from a canal.[9]

Subsurface: Below the land surface, synonymous with underground.

Subwatershed: An area that is drained by an individual tributary into the main watercourse of a watershed.[7]

Surface water: Water that is on the Earth's surface in lakes, rivers and other streams and wetlands. As water moves in a cycle (water cycle), groundwater and surface water are exchanged, particularly through processes of discharge and recharge.

Surface runoff: Runoff that travels over the land surface to the nearest stream channel.[3]

Terrestrial: Living on or growing on land.[7]

Thermal: Of, relating to, or caused by heat.[11]

Thermal habitat: An ecological area that falls within the thermal tolerances of a particular species.

Thermal inertia: The degree of slowness with the temperature of a body approaches that of its surroundings and which is dependent upon its absorptivity, its specific heat, its thermal conductivity, its dimensions and other factors.[11]

Thermal limit: Upper and lower water temperatures at which metabolic activities are restricted resulting in death.

Thermal niche: Preferred water temperature range of organisms.

Thermal refuge: Area typically associated with groundwater or hyporheic inputs within a stream channel, inputs of cooler tributary flows or springs, and/or smaller cool water areas associated with undercut banks or similar features where the presence of soils results in a substantial cooling of the water. Such areas can provide shelter or protection of cool-water dependent species.

Thermal regime: The characteristic behavior and pattern of temperature.[7]

Till: A tough, unstratified clay loaded with stones originating from finely ground rock particles that were deposited by glacial activity.[7]

Topography: The general configuration of a land surface or any part of the Earth's surface, including its relief and the position of its natural and man-made features.[3]

Transition zone (of groundwater and surface water exchange): The zone of transition from a groundwater dominated system to a surface water dominated system. It includes, but is not limited to the zone where the groundwater and surface water mix as well as any groundwater/surface water interface that may be present. It is applicable to all types of surface water bodies in contact with groundwater. The transition zone is a dynamic and active biogeochemical zone that has the ability to alter the quality of the groundwater passing through (e.g., attenuate some contaminants and nutrients).

Transport (by groundwater): The movement of substances (largely solutes and colloids) along groundwater flowpaths.

Travel time: Can refer to either groundwater or a contaminant in groundwater. Travel time of groundwater is an estimate of the time required for a unit volume of groundwater to move from one specific point along its flowpath in the subsurface to another. Travel time of a contaminant in groundwater is the estimated time for this contaminant to travel along the same flowpath. This may be longer than the groundwater travel time due to attenuation. Tributary: A river or stream flowing into a large river, stream or lake.[3]

Uncertainty: Known gaps in data/information about, or deficiencies in methods of assessment. It reflects the degree of confidence in the data used to understand a behavior of an object, process or natural phenomenon or to predict a future outcome based on scenarios.

Unconfined aquifer: An aquifer whose upper boundary is the water table.[7]

Unconsolidated: Used to describe deposits of loosely bound sediment that typically fills topographically low areas. Underground storage tank: A vessel located beneath the ground surface, but not within a building, that is used to store fuel or chemicals.

Unsaturated flow: The movement of water in a porous medium in which the pore spaces are not filled to capacity with water.[3]

Unsaturated zone: A subsurface zone above the water table in which the pore spaces may contain a combination of air and water.[3]

Urban karst: "The three dimensional, largely hidden, dense systems of urban water networks that include a potentially important network of buried headwater streams give rise to a highly connected network in which groundwater (slow) flows are interspersed with faster groundwater and surface water flows which resemble a karst hydrologic system.)" http://besurbanlexicon.blogspot.ca/2012/07/urban-karst.html

Vadose zone: The zone between the land surface and the water table; unsaturated zone.

Volatile organic compounds (VOCs): These comprise a wide range of chemicals that have a high vapor pressure at average room temperatures and pressures. Examples include automotive fuel and petroleum-based solvents (including many chlorinated solvents). Many VOCs are dangerous to human health or cause harm to the environment. VOCs are numerous, varied, and ubiquitous. VOCs are typically not acutely toxic, but instead have compounding long-term health effects.

Volatilization: To make volatile; to cause to pass off in vapor.[11]

Wastewater treatment plant: A facility that treats to sanitary sewage. Also known as a sewage treatment plant.[7]

Water budget: The movement of water within the water cycle can be described through a water budget or water balance. It is a tool that when used properly allows the user to determine the source and quantity of water flowing through a system. From a groundwater perspective, the key components of a water budget are infiltration, contribution to base flow, deeper groundwater flow outside the study area and groundwater taking.[7]

Water cycle: The continuous movement of water from the oceans to the atmosphere (by evaporation), from the atmosphere to the land by condensation and precipitation, and from the land back to the sea (via streamflow).[7]

Watershed: The land area drained by a river or stream.[3]

Water table: The top of the water surface in the saturated part of an aquifer.[9]

Well (drinking water): An engineered device created to access subsurface water as a source of drinking water.

Well (deep): A well that was drilled and completed in a deep aquifer (usually confined).

Well (monitoring): Provides an access point for measuring groundwater levels and to permit the procurement of groundwater samples that accurately represent in-situ groundwater conditions at the specific point of sampling.[1]

Well (municipal): An engineered device designed to access subsurface water as a source of municipal drinking water.

Well (pumping): A well that is actively being used to extract water from the ground using a pump.

Weathering: The process whereby earthy or rocky materials are changed in color, texture, composition or form (with little or no transportation) by exposure to atmospheric agents.[3]

Well capture zone: The area in the aquifer that will contribute water to a well in a certain time period. It is often measured in days and years. Area at the ground surface is also included if the time period chosen is longer than the travel time for water in the aquifer and the groundwater recharge area is incorporated.[7]

Wellhead: The top of a structure built over a well; the point at which water exits the ground.[1]

Wetland: Land that is seasonally or permanently covered by shallow water, as well as land where the water table is close to or at the surface. In either case, the presence of abundant water has caused the formation of hydric soils and has favored the dominance of either hydrophytic plants or water tolerant plants. The four major types of wetlands are swamps, marshes, bogs, and fens.[7]

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