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

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

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Report Editors

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Cover photo: Groundwater flowing within a karst cave; Eramosa Karst Conservation Area, Hamilton, Ontario, Canada.

Photo credit: James Roy, Environment and Climate Change Canada

Table of Contents

List of Tables

List of Figures

1 INTRODUCTION

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1.1 Great Lakes Basin and the importance of groundwater

Groundwater and surface water are part of an interconnected water cycle, with the potential for groundwater to discharge into surface water bodies and surface water to enter groundwater systems. These groundwater/surface-water (gw-sw) exchanges may occur at many points from headwater to lake and change over time. As part of this continuum, groundwater contributes substantially to the Great Lakes water quality and quantity, primarily through its contribution to stream base flows. While the magnitude of this contribution has not yet been quantified across the Great Lakes Basin, an International Joint Commission (IJC) study (2010) estimated that groundwater contributes as much as 79 percent from Lake Michigan tributaries to the lake. During dry periods, groundwater may provide a slow release of base flow, which supports minimum flow levels in streams (IJC, 2010; Granneman, 2000). Groundwater also contributes to wetlands and discharges directly into some lakes, including the Great Lakes. In turn, surface waters in streams, wetlands, and lakes can contribute to the recharge of groundwater.

Because of the dynamic connection between groundwater and surface water, processes within, and impacts to, groundwater or surface water can affect the quantity and quality of the other. Groundwater quality can be influenced by point and nonpoint contaminant sources, including landfills, hazardous waste sites, poor septic systems, underground storage tanks, as well as agricultural, urban, and industrial activities (IJC, 2010). These can lead to specific groundwater quality threats, which include contamination from pesticides, nutrients, road salt, pathogens, toxic chemicals, petroleum hydrocarbons, and pharmaceuticals (IJC, 2010). Depending on the residence time of groundwater, which can vary appreciably, pollutants can be retained in the subsurface for periods ranging from weeks to centuries, thus potentially acting as a long-term contaminant source, which can be difficult and costly to remediate. However, under certain conditions (e.g., favorable redox conditions), groundwater can also be an important site of contaminant degradation. This degradation can produce harmful or benign breakdown products, thus, understanding of specific chemical characteristics and degradation processes is essential for the assessment of potential exposure. In many cases, groundwater is of relatively good quality and contributes, via discharge, to maintaining or improving surface water quality (Grannemann and Van Stempvoort, 2016).

The Great Lakes Basin groundwater system is estimated to contain 4,100 km^3 of fresh water, more than the combined volume of Lakes Huron and Erie (Coon and Sheets, 2006, USEPA, 2023). In 2005, an estimated 1.5 billion gallons/day (5.7 billion litres/day) were pumped from the USA side of Great Lakes aquifers (Mills and Sharpe, 2010). Irrigation for agriculture consumes 43% of this total and 14% is for industrial use. Although most Great Lakes cities rely on surface water for water supply, groundwater provides 8.2 million people with drinking water, and it supports irrigation, industries including beverages/bottled water, and recreational activities (Granneman, 2000). Many of these extractions of groundwater are projected to increase, in part due to development and a changing climate. Increased groundwater extractions have the potential to affect both groundwater quantity and groundwater quality, either of which can limit water availability in the Great Lakes region.

1.2 Context

The Great Lakes Water Quality Agreement (GLWQA) was originally signed in 1972 with a focus on surface water and revised in 1978 to address the effects of multiple stressors to groundwater. The revised agreement included Annex 16, which was added to address "pollution from contaminated groundwater" (Francis, 1989). However, no formal process for reporting under this annex was provided. The Great Lakes Water Quality Agreement 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), which included preparation of the *Groundwater Science Relevant to the Great Lakes Water Quality Agreement: A Status Report* (Granneman and Van Stempvoort, 2016). This 5-year update document is a supplement to the comprehensive 2016 document (Granneman and Van Stempvoort, 2016), as a Great Lakes groundwater reference source for Canadian and U.S. governments, policy makers, academia, industry, and the general public.

1.3 Purpose of report

Authored by research scientists in Canada and the United States, the 2016 report offered, "a comprehensive report on understanding of groundwater and its influence on Great Lakes water quality, and on gaps in knowledge to establish science priorities related to groundwater" (Granneman and Van Stempvoort, 2016). The 2016 report addressed the four key charges of Annex 8 and provided key conclusions for each charge, both of which are outlined below:

1. Identify groundwater impacts on the chemical, physical and biological integrity of the waters of the Great Lakes.

Conclusion: groundwater enhances water quality of the Great Lakes, but at the same time, contaminated groundwater adversely affects water quality of the Great Lakes. Another conclusion is that there are still gaps in our understanding of how groundwater affects Great Lakes water quality.

2. Analyze contaminants, including nutrients in groundwater, derived from both point and non-point sources impacting the waters of the Great Lakes.

Conclusion: groundwater provides a treatment or storage zone that can protect Great Lakes water quality, but groundwater also provides a long-term source of contaminants negatively affecting Great Lakes water quality.

3. Assess information gaps and science needs related to groundwater to protect the quality of the waters of the Great Lakes.

Conclusions:

- Advance assessment of regional scale groundwater discharge to surface water in the basin.
- 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.
- Advance monitoring and surveillance of groundwater quality in the Great Lakes Basin.
- Advance research on local-scale assessment of interaction between groundwater and surface water.
- Develop better tools for monitoring, surveillance, and local assessment of groundwater-surface water interaction.
- Advance research on the role of groundwater in aquatic habitats in the Great Lakes Basin.
- Improve the understanding of effects of urban development on groundwater.
- Develop scaled-up models of regional effects of groundwater on Great Lakes water quality.

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.

Conclusion: further studies are necessary to determine the impact of other environmental factors on the Great Lakes' water quality.

Annex 8 requires Canada and the United States to update the initial report on the relevant and available groundwater science at least once every six years. This report represents an update from the original 2016 report, with the following objectives: (1) identify and describe any new or emerging issues, (2) describe advancements made towards meeting the science needs outlined in the 2016 report, (3) update the science needs if necessary and (4) identify any potential opportunities generated from new knowledge or technical advancements. The intent of this updated report is to highlight significant and relevant advancements or constraints, rather than an attempt to provide a comprehensive evaluation of the literature or detail incremental scientific advancements. The chapters were primarily written in 2020 and represent an update of literature from 2016-2020 although some more recent articles may have been added during the review process.

1.4 Chapter overviews

This update report is organized on the different categories of investigation, by chapter, including:

Chapter 2 – Groundwater/surface-water interactions
The exchange of water between the groundwater system and surface water determines how groundwater will affect the physical, chemical, and biological integrity of the Great Lakes. Most streams in the Great Lakes Basin receive groundwater. Groundwater typically discharges to the Great Lakes near the shoreline, although at local scales there can be active exchange of groundwater and surface water. This exchange may occur in areas of differing geochemistry that may promote degradation of contaminants. Groundwater discharge to streams and nearshore areas may provide thermal stability and thereby support habitats. Understanding the processes of groundwater/surface-water exchange underpins the other chapters in the report and relates to additional Annexes under the Great Lakes Water Quality Agreement. The major science needs discussed include (1) advancing research on local-scale interaction, (2) understanding the role of groundwater in supporting habitat, and (3) assessing regional-scale groundwater discharge to surface water and the Great Lakes.

Chapter 3 – Influence of groundwater contaminants on the Great Lakes Basin
Groundwater contaminants as defined here are undesirable substances, both synthetic and geogenic, that are transmitted to groundwater (or to infiltrated surface waters) through human activities or have their natural inputs enhanced through human activities. Chapter 3 is related to Annexes 1-3 of the GLWQA which address Areas of Concern, Lakewide Management, and Chemicals of Mutual Concern. The chapter focuses on the transport of contaminated groundwater to surface waters in the Great Lakes Basin, as well as potential effects on their aquatic ecosystems. It concludes that incremental progress has been made toward the five priorities outlined in the 2016 report: (1) methods for detection and assessment of contaminated groundwater discharges, (2) assessing the remediation potential of the transition zone, (3) sensitivity of transition zone organisms to contaminants, (4) actual ecological effect of groundwater contaminants, and (5) regional-scale contaminant loading to Great Lakes waters. However, concern over some contaminants in

groundwater, notably per- and polyfluoroalkyl substances (PFAS), has increased greatly in the interim, and these issues are discussed in this chapter.

Chapter 4 – Groundwater and nutrients

Nutrients are important groundwater contaminants because of their pervasive influence on water quality. Little is known about groundwater as a transport pathway of nutrients to the Great Lakes. Chapter 4 is related to Annex 4 of the GLWQA which addresses Nutrients. This chapter focuses on updating the four science needs identified in the 2016 report: (1) linking land management and groundwater nutrient loading, (2) understanding the role of 'hot' phenomena (biogeochemically active locations and periods), (3) upscaling site specific information, and (4) compiling basin-wide nutrient assessments in groundwater. As the effects of nutrient inputs to the Great Lakes have been a major concern in recent years, considerable work related to these science needs has been completed. Important gaps in our understanding of the role of groundwater nutrient inputs remain, and there are emerging science needs that were not identified in the 2016 report, which are discussed in Chapter 4. The chapter also includes an updated science priority table to reflect these gaps and emerging needs.

Chapter 5 – Groundwater and aquatic habitats

Storage and discharge of groundwater affect the availability and quality of aquatic habitats in lakes, streams, and wetlands within the Great Lakes Basin by influencing the hydrological, thermal, and chemical characteristics of these surface waters. The important contributions groundwater discharge provides to aquatic habitats are recognized in the terminology "groundwater-dependent ecosystems," which acknowledges a range of groundwater-derived processes that maintain healthy aquatic ecosystem function in lakes, streams, and wetlands. Chapter 5 is related to Annex 7 of the GLWQA which concerns Habitats and Species. It provides a status update on the five priority science needs identified in the 2016 report: (1) mapping groundwater recharge and discharge, (2) integrating groundwater models with other ecosystem models, (3) evaluating the importance of groundwater discharge on species distributions and ecosystem attributes, (4) evaluating the importance of spatial patterns in groundwater discharge on ecosystem attributes, and (5) identifying ecosystems that are vulnerable to changes in groundwater discharge. The authors conclude that although considerable effort has been put into developing an inventory of the Great Lakes' coastal wetlands, groundwater models are still needed to simulate the different groundwater aspects (discharge, flow, and recharge). The priorities have been updated to focus more strictly on the groundwater-habitat connection as well as ensure they are better integrated with priorities in other chapters.

Chapter 6 – Effects of urban development on groundwater

In cities, both above-ground infrastructure such as buildings and paved areas, and underground infrastructure such as foundations, and stormwater and sanitary sewers, have a substantial impact on groundwater quantity and quality. Recent studies on urban hydrology have pointed to the interactions between urban groundwater, sanitary sewers, and stormwater systems. These interactions are related to all six of the priority science needs identified in 2016, including: (1) data collection and analysis for urban groundwater resource management, (2) quantitative information about contaminant sources, (3) monitoring of groundwater quality and risk assessment of potential health risks, (4) baseline data acquisition and monitoring of urban water balances, (5) research on urban groundwater movement, and contaminant fate, and (6) monitoring and research on stormwater management and dewatering. Chapter 6 is related to Annexes 1 and 3 of the GLWQA, Areas of Concern and Chemicals of Mutual Concern, respectively. The authors of this chapter concluded that while important site-specific studies have been conducted, there is still a lack of awareness regarding groundwater, which hinders the assessment of urban groundwater quality and the urban water cycle.

Chapter 7 – Climate change effects on groundwater

Climate change has the potential to alter the physical and chemical properties of water in the Great Lakes Basin and their ecological functions. This chapter is related to Annex 9 of the GLWQA which addresses Climate Change Impacts. Chapter 7 synthesizes existing research associated with the potential effects of a changing climate on the quality (including temperature) and quantity of groundwater in the Great Lakes Basin. Also, it includes analysis of realized and predicted future impacts. This synthesis focuses on what is known about the effects of a changing climate in the Great Lakes Basin in regard to (1) groundwater recharge, (2) groundwater storage, (3) groundwater discharge and groundwater-surface water interaction, (4) exacerbating future urban development impacts on groundwater, (5) groundwater quality, and (6) ecohydrology (including surface water quality). There are still many uncertainties and knowledge gaps concerning the effect of climate change on groundwater resources. The authors suggest that modeling methods be standardized for research involving the Great Lakes Basin.

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Natural groundwater seepage breaking out at ground surface at the head of the beach area, with iron mineral staining; Wasaga Beach, ON, Canada.

Photo credit: James Roy, Environment and Climate Change Canada

2 GROUNDWATER/SURFACE-WATER INTERACTION

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2.1 Introduction

In the Great Lakes Basin, groundwater serves as source water for private and public drinking-water systems and provides supply for industry and agriculture. It also provides baseflow to streams and exchanges water with wetlands, ponds, lakes, and other features. The discharge and exchange of groundwater with surface water provides many services and values, for example by sustaining flow or water level and regulating temperature of surface water and determining habitat suitability and quality. Groundwater also can be a vector for contaminants or nutrients to surface waters. In the exchange with streams, groundwater becomes tributary water to the Great Lakes, and, along with direct discharge to the Lakes, contributes to the water quality of the nearshore environment and coastal wetlands. In this chapter, the science needs and gaps identified in the Groundwater/Surface-Water Chapter (Conant et al., 2016) of the 2016 Groundwater Science report (Grannemann and van Stempvoort, 2016) are reviewed to highlight recent progress. Specifically, the following sections review recent literature relevant for identification and assessment of groundwater discharge to surface water, impacts of development and pumping on groundwater/surface-water interaction, assessment of groundwater as a provider of services and transport of contaminants, and development and importance of consistent databases. The general role of groundwater in the basin is not reviewed here, and the reader is referred to the 2016 report and other literature for this information (for example, Grannemann et al., 2000; Neff and Nicholas, 2005; Neff et al., 2006). Understanding the groundwater-flow system and how groundwater interacts with surface water is crucial in understanding the significance of groundwater for 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 (Grannemann and van Stempvoort, 2016).

In line with the elements highlighted in the previous report's Groundwater/Surface-Water Chapter (Conant et al., 2016), a conceptual modeling framework identifying hydrological, biogeochemical, and biological factors of groundwater/surface-water systems was subsequently presented by Conant et al. (2019). The major features of the framework highlight interaction between the various factors (Figure 2.1). Three components of the system are identified in the conceptual model, and these components help provide context for the literature reviewed in the following sections of this chapter. The surface-water system includes streams, rivers, lakes, springs, and wetlands. The groundwater system is defined by subsurface material with saturated pore spaces and fractures: that is, it is the part of the subsurface below the water table. The transition zone is the volume of the subsurface where water moves between groundwater and surface water and that includes materials or conditions that can modify the flow, chemical, or ecological condition of the water (Conant et al., 2019). The transition zone also includes the hyporheic zone, which is the volume of material next to and beneath streams and rivers where there is active exchange of groundwater and surface-water. Application of the framework was demonstrated through three case studies: a single groundwater contamination plume discharging to the Pine River in southern Ontario, discharge of non-point source nutrients in eastern Nottawasaga Bay, Lake Huron, and regional-scale consideration of interactions in the Duffins Creek watershed, also in Ontario. Unlike previous classification systems that are setting specific, this one focuses on identifying critical processes and is therefore applicable to many settings.

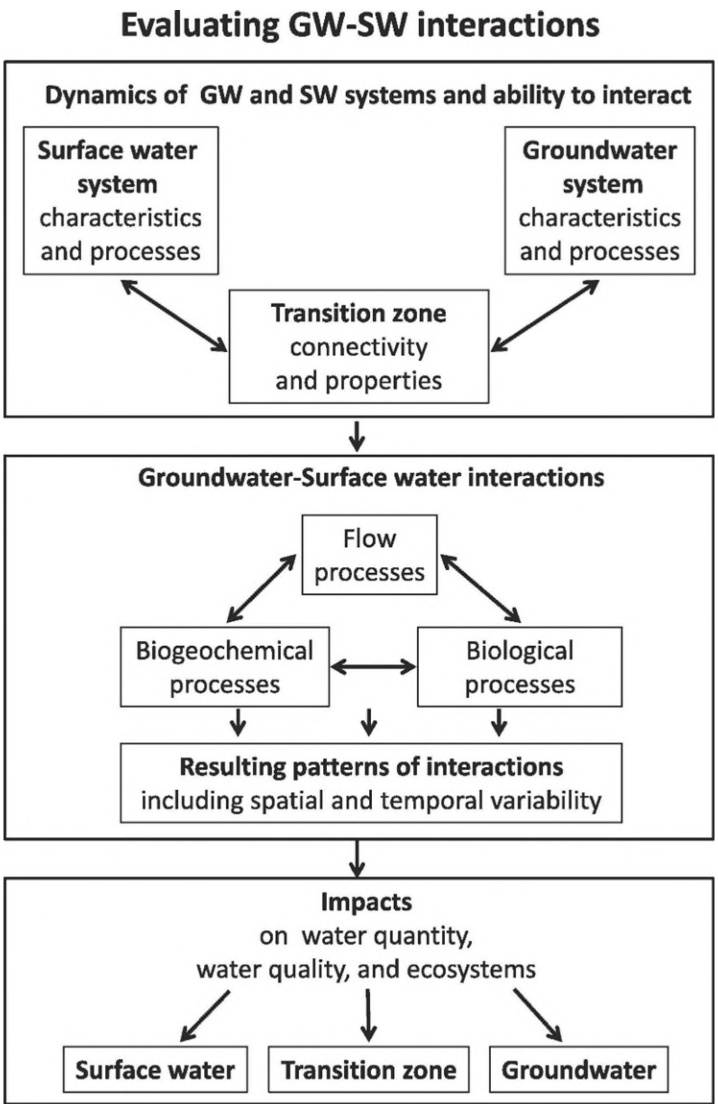

Figure 2.1 Summary diagram showing framework for evaluating and characterizing groundwater(GW)/surface-water(SW) interactions and potential impacts on streams, rivers, and lakes from Conant et al. (2019).

2.2 Priority Science Needs from 2016 Report

The 2016 Groundwater Science Report (Grannemann and van Stempvoort, 2016) included science needs identified by the authors of each chapter. For the groundwater/surface-water interaction chapter, five science needs were identified (Table 2.1).

Table 2.1 Priority science needs related to groundwater/surface-water interaction from 2016 report (Grannemann and van Stempvoort, 2016).

Priority science need	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 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 basin.
2B. Accurately quantify groundwater discharges to surface water	• Understand the effects of human development, land-use, and land-cover change on 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 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. • Identify key field parameters and observations required to identify and monitor streamflow depletion by pumping wells.
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.

In the 2016 report, science needs and information gaps from all the chapters were combined into overarching major science needs. The major needs 1, 4, and 6 were relevant to groundwater/surface-water interaction, and these broad science needs will be used to organize this Chapter. These major needs are provided in Table 2.2.

Table 2.2 Select major science needs relevant to groundwater/surface-water interaction from the 2016 report (Grannemann and van Stempvoort, 2016).

Major science need areas	Priority science need identified in Chapters 2-7 from 2016 report	Relevant chapter from 2016 report
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
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
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

2.3 Updated status and review of priority science needs and information gaps

In this section, we briefly discuss examples from the literature relevant to the major science needs.

2.3.1 Assessing regional-scale groundwater discharge to surface water

Studies focused on regional groundwater-system dynamics help provide information for managers, decision makers, and stakeholders to understand the role of groundwater for water supply, in maintaining wetlands, streamflows, and lake levels, and in the potential transport of nutrients and contaminants.

In 2018, The International Joint Commission Great Lakes Science Advisory Board recognized that the first step in assessing groundwater influence on the water quantity and quality at Great Lakes Basin scale is to develop a satisfactory model of the hydrologic contributions of groundwater to the water balance of the system and reviewed how this could be done through an integration of surface and subsurface hydrological processes on the basin scale (Great Lakes Science Advisory Board, 2018). As a result, International Joint Commission's Great Lakes Science Advisory Board-Research Coordination Committee led the development of a conceptual framework for basin wide groundwater-surface water numerical models. The framework provided detailed scientific and technical guidance for numerical model development and emphasized the need for better information on water budgets in high-use areas and increased investment in basin-scale monitoring and modeling for sustainable water management. It also highlights the necessity for tools with seasonal to annual resolution for stakeholders and resource managers to address specific questions (Great Lakes Science Advisory Board-Research Coordination Committee, 2022).

A very detailed hydrogeologic model was developed as part of the Southern Ontario Groundwater Project (Frey et al., 2020). This model focused on simulating monthly surface water flow rates and groundwater levels with a variety of spatial and temporal resolutions. The foundation for the model is a detailed hydrostratigraphic framework developed for the study area. Results from high- and low-resolution models are presented with limited difference between results. This study framed the work by Xu et al. (2021) who developed the first fully integrated groundwater/surface-water model for the entire Great Lakes Basin. This basin-wide model accounts for hydrologic seasonality. It was applied towards the characterization of groundwater-lake interactions in the five Great Lakes under monthly normal climatology. Simulation results indicated that direct groundwater discharge accounts for a small component of lake basin supply; ranging from 0.6 percent for Lake Ontario to 1.3 percent for Lake Michigan, with an overall average of 0.8 percent for all lakes combined (Xu et al., 2021), and these values are consistent with the discussion by Grannemann et al. (2000). Simulation results also demonstrate that groundwater-lake interactions are strongest along the shoreline and vary temporally in response to seasonal fluctuations in both lake levels and terrestrial groundwater levels in nearshore regions. In winter, direct groundwater discharge dominates the groundwater-lake interactions in both the distal and nearshore lakebed areas. In summer, the combined effects of rising lake levels and lowering terrestrial groundwater levels lead to notable reductions in direct groundwater discharge through nearshore areas. Direct groundwater discharge is also shown to vary spatially, with highest rates associated with areas containing thick Phanerozoic hydrostratigraphy, as opposed to Precambrian basement rock. The results of these studies help illustrate the spatial and temporal variability of direct groundwater discharge to the Great Lakes which can be important in understanding its influence on nearshore water quality and ecology.

One challenge for regional-scale analysis is how to simulate transport of contaminants by groundwater at a higher resolution than a regional model that necessarily averages conditions. Methods to extract inset models were developed and applied to an existing regional groundwater-flow model of the Michigan Basin to estimate travel times and groundwater age distributions (Feinstein et al., 2018). Five settings in the Michigan Basin were examined and groundwater age distributions were estimated using a particle-tracking algorithm. This work demonstrated how the regional groundwater-flow model could be used in more local analysis to provide information relevant to fate and transport in the groundwater system.

Direct discharge of groundwater and the potential for nutrient loading to the Great Lakes through the U.S. part of the Great Lakes Coastline was found to be highest for Lake Erie and lowest for Lake Superior (Knights et al., 2017). The authors used a water-budget approach to estimate vulnerability for direct nutrient loading. This approach is most relevant for the shallow, unconfined, aquifers near the Great Lakes. The vulnerability was assessed by considering the estimated discharge rates and land-use within recharge zones identified as directly contributing to the lakes with agricultural land use assumed to contribute nutrients to the system. The authors also conducted field sampling at a site identified to be in a vulnerable area near Lake Erie. Measured discharge rates from the field were lower than the water-budget estimates, and the authors noted the importance of field sampling for understanding and quantifying fluxes at both local and regional scales.

Water budget components and storage changes were assessed with a coupled subsurface-land surface, process-based, model (PAWS) for the Grand River and Saginaw River watersheds in Michigan (Niu et al., 2014). The model was able to simulate different hydrologic components and states including surface runoff, channel flow, groundwater, ET, soil moisture, soil temperature and changes in storage. Vegetation growth dynamics also were simulated. The model results matched well with ground observations, MODIS and GRACE data. Trend analysis indicated that storage is increasing in both watershed over the past decade. The study also found that changes in water storage were dominated by changes in water volumes in the vadose zone and the unconfined aquifer with little contribution from surface water or groundwater in the confined aquifer.

2.3.2 Advancing research on local-scale interaction between groundwater and surface water

Groundwater may transport contaminants or nutrients to surface-water and the Great Lakes, and this section focuses on how understanding the local-scale processes can help to address the potential effects of these contaminants and nutrients. Groundwater/surface-water interactions at the watershed scale are expected to be more complex than those described at the regional scale. Regional-scale assessments are unable to capture variation in groundwater/surface-water exchange controlled by watershed and local scale variations in geology, topography, land-cover, water-use, stream or lake geometry, and streambed or lakebed conductance. These factors can produce gaining and losing sections of streams that on a regional scale are strictly gaining or losing. At local scales, hyporheic exchange becomes important and different parts of a stream can experience gaining and losing conditions, and these conditions can change with changes in groundwater level or streamflow. Groundwater discharged to streams and the Great Lakes includes water that has taken longer or shorter flowpaths to reach the discharge point resulting in a mixture of water with different geochemistry. Understanding the relation between groundwater flowpaths, groundwater/surface-water exchange, and their influence on geochemical mixtures can help in assessing the potential benefit of management actions in the watershed aimed at mitigating groundwater contamination.

Watershed-scale studies

Several recent studies investigated groundwater discharge to the Great Lakes or other large lakes, in Ontario. Lacustrine groundwater discharge to a large inland lake, Lake Simcoe, was quantified by applying a steady state mass balance model to radon-222 (^{222}Rn) data obtained along the lake's shoreline (Wallace et al., 2020). Overall, lacustrine groundwater discharge to Lake Simcoe was estimated to be 7 to 16% of the total volume of tributary inputs during summer with high spatially variability. Similar results were found for groundwater discharge to Nottawasaga Bay, Lake Huron, where the groundwater discharge was estimated to be 5-13 percent of the mean annual discharge from the Nottawasaga River (Ji et al., 2017). In both studies, the groundwater discharge was found to vary spatially around the receiving water body with generally higher fluxes at the shore that decrease with distance offshore as expected from general flow patterns. Local hydrogeology and the lithology of sediments, however, were shown to be important in controlling the location of areas of higher discharge (hotspots). These types of study findings can help to inform potential management actions and designing sampling schemes for other glacial lakes.

Most studies of groundwater discharge to inland lakes in the basin or the Great Lakes have concentrated on diffuse groundwater discharge, but focused discharge could be potentially significant in certain areas, as highlighted by notable sinkholes that discharge groundwater from the underlying aquifer in Lake Huron (Baskaran et al., 2016). Although the volume of water discharged through these sinkholes is relatively small compared to other fluxes to the lake, the anoxic, reducing, high sulfate, and high chloride groundwater being discharged creates conditions for unique microbial mats similar to those found in deep-sea marine vents. High chloride levels are also observed in Lake Ontario, and groundwater as a contaminant pathway was recently investigated by Mackie et al. (2022). Although many studies have been conducted to investigate sources and inputs of chloride to Lake Ontario, these studies have focused on either surface water systems or groundwater systems independently with no integration and consideration of their interconnection. Mackie et al. (2022) identified the need for regional scale monitoring of chloride and flows within groundwater and surface water systems to support the development of road salt use best management practices.

An example study focused on groundwater exchange with a stream was summarized for the lower portion of the Whitemans Creek subwatershed (130 km^2), a tributary of Grand River located in in southern Ontario. This system was studied with a coupled land-surface/groundwater model to assess local groundwater dynamics and evaluate potential climate change impacts (Larocque et al., 2019). The water budget analysis indicates no or very little infiltration and recharge during summers, with stream baseflow likely driven by elevated groundwater levels supplied by snowmelt. These groundwater levels slowly decrease during this period. Although the average declared groundwater pumping is small compared to other water-budget fluxes, the average permitted groundwater pumping rate (largely for agricultural purposes) was on the order of the average recharge, posing a risk of creek drying during low-flow periods.

Potential response to climate change of the groundwater system on a watershed scale was investigated by Persaud et al. (2020). The authors used Hydrogeosphere to develop a coupled groundwater/surface-water model for the Upper Parkhill watershed in Ontario. Several climate projections were applied to the model after calibration to produce forecasts of the mid-century change of monthly water budget components. For groundwater, the simulated values included groundwater level (hydraulic head), surface discharge, and net exchange flux. Results indicated that surface discharge was more sensitive to climate forcing and changed more than groundwater level or net exchange flux. Overall resiliency of the groundwater system was noted, however the authors cautioned that potential for localized changes exist. For more discussion on climate impacts and groundwater, see Chapter 7 of this report.

Field and hyporheic zone studies

Recent studies focused on the local scale have addressed a range of groundwater/surface-water interactions. Dynamic local fluxes driven by seasonal changes, storms, and waves, were found to influence groundwater and surface-water quality by establishing reactive conditions (hot zones or hot moments) that differ from long-term average conditions. These reactive conditions can mediate redox reactions and biogeochemical processes, effecting the fate of nutrients and contaminants in the subsurface. Example local-scale studies include sulfate-impacted wetland (Ng et al. 2017, 2020) and coastal beaches on Lake Erie (Rakhimbekova et al., 2018) and Lake Ontario (Malott et al., 2017).

A fully integrated groundwater/surface-water flow model was developed to simulate fractured bedrock spring flows that support the habitat of endangered species in Quebec (Levison et al., 2014). Flow rates for the four simulated springs, located at different elevations, were simulated for the recent past and predicted under future climate change scenarios for an ecological modeling of salamander populations (Girard et al., 2015). Results for the modeled sites indicate that springflow will increase with climate change by 2050 and continue to provide habitat for the endangered species. The authors note, however, that other factors such as changes in land use or increases in water withdrawals could impact the groundwater discharge via springs and the habitats. This type of hydrological modeling representation and approach can be used for guiding research in other areas as it is relevant for investigating the sustainability of groundwater-dependent ecosystems.

Studies have continuously focused on improving the accuracy of quantification of groundwater discharges to surface water through tracer-based and non-tracer based baseflow separation. To determine the most optimal approach, Cheng et al. (2022) estimated baseflow through existing graphical and digital filter methods, using actual streamflow data from a gauging station at the Alder Creek Watershed, Ontario and synthetic streamflow data at ten study locations within the same watershed simulated with HydroGeoSphere. Results indicated that baseflow hydrographs varied seasonally and spatially along the creek, and that optimal baseflow estimation approach may vary accordingly with environmental factors such as land use, topography, geology, slope, and hydraulic parameters. Field studies using unconventional tracers also have been conducted to determine the source of groundwater contamination (Popp et al., 2021). In this study, artificial sweeteners were used to help distinguish groundwater contamination from landfill leachate from contamination by wastewater and the importance of stream sinuosity and hyporheic flows in this relatively homogeneous setting were highlighted.

As outlined in the conceptual framework by Conant et al. (2019), understanding how contaminants or nutrients are transported from land-surface application to the Great Lakes will require an understanding of the groundwater system, groundwater/surface-water interaction processes, and, finally, surface-water transport processes. Gaining this understanding relies on developing monitoring and sampling groundwater and surface-water concentrations programs, where the sampling strategy can influence how conditions in the transition zone between and aquifer and stream are assessed as reported by Lee-Cullin et al., 2018. Two sampling schemes were investigated: high temporal resolution local sampling done by collecting many samples at few points along a stream network to capture local-scale variability, and longitudinal sampling done by distributing a similar number of samples across locations along the stream network to assess the dynamics of flow and contaminant fluxes. The authors found that longitudinal sampling might give a better representation of overall stream network conditions because sampling more locations, even if the same number of samples were taken, helped identify biogeochemical patterns in the network.

Research effort also has been dedicated to developing better reconnaissance methods to rapidly and cost-effectively characterizing spatial heterogeneity and temporal variability in groundwater-surface water exchanges. For instance, Robinson et al. (2022) conducted a study demonstrating the efficacy of combined DC resistivity and induced polarization (DC-IP) imaging in characterizing streambed architecture and interpretating groundwater-surface water exchange patterns. The study, conducted along a 50-meter stream reach in the headwaters of Kintore Creek, Ontario, utilized a high-resolution, underwater 3D DC-IP survey with corresponding measurements of temperature differences, vertical head gradients and porewater sampling. This study highlights the complementary benefits of combined DC and IP, with IP providing clearer insights into mineralogy compared to DC resistivity, which may be influenced by variable porewater quality resulting from spatially varying groundwater flow paths, residence times and geochemistry.

2.4 Summary and Priority Science Needs

Groundwater/surface-water exchange links the groundwater system to surface waters and the Great Lakes. Groundwater often serves as a high-quality water source that can help mitigate contamination of surface water, stabilize temperature for surface-water features, and provide potable water supply across the Great Lakes Basin. In some parts of the basin, however, groundwater may be contaminated by nutrients, geogenic contaminants, or anthropogenic contaminants, and understanding of how these constituents move through the groundwater system can help to assess the risk imposed to the Great Lakes. The broad science needs for groundwater/surface-water interaction identified in the 2016 report (Conant et al., 2016; Grannemann and van Stempvoort, 2016) remain despite progress in several areas. Recent regional-scale modeling has advanced tools for studying regional-scale groundwater discharge to surface water in the Basin, and these models may serve as testbeds for further study. For example, regional models that currently simulate seasonal conditions could be extended to transient models capable of simulating response to observed or forecast climatic conditions. Methods to relate measurements and modeling over spatial scales from field scale, watershed scale, and regional scale could be developed. Several studies identify research gaps in methods development to improve sampling strategies.

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3 INFLUENCE OF GROUNDWATER CONTAMINANTS ON THE GREAT LAKES BASIN

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3.1 Introduction

This chapter is an update to Chapter 3 (Conant et al., 2016a) from the 2016 GLWQA Groundwater Annex report (Grannemann and Van Stempvoort, 2016), of the same name, which provided a summary of the relevant and available science concerning the influence of groundwater contaminants on the Great Lakes Basin and identified future science needs on this topic. The objectives of this update are to i) identify and describe any new or growing issues on this topic, ii) describe the progress made towards the science needs outlined in Chapter 3 of the 2016 report, and iii) update the science needs if necessary. The intent is to highlight significant and relevant advancements or lack thereof, but not to delve into the details of incremental scientific progress. A thorough description of the topic and main issues relevant to the Great Lakes was provided in Chapter 3 of the previous report. Therefore, only a brief overview of the topic is provided in this short Introduction here, along with a summary of the previous chapter's key findings and identified priority science needs (provided again here in Table 3.1).

As was the case for Chapter 3 (Conant et al., 2016a) in the previous report, the focus of this chapter is on the direct transport of contaminants in groundwater to wetlands, streams, rivers, and lakes of the Great Lakes Basin. However, there is also some discussion of contaminants in surface waters that enter the subsurface and may then subsequently discharge back to it, as in hyporheic zones, bank storage events, and recharge after overbank flooding for streams, and mixing within sediments of the swash zone for lakes. The contaminants as defined here are undesirable substances, both synthetic and natural, that are released to the groundwater (or to the infiltrated surface waters) through human activities or have their natural inputs enhanced through human activities. Though not a topic of discussion in this chapter, it is important to note that uncontaminated groundwater inputs can reduce the concentrations of contaminated surface water through dilution, thereby having a positive effect on water quality of surface waters of the Great Lakes Basin.

Human activities including agriculture, industry, and urbanization can lead to the contamination of groundwater. Groups of common anthropogenic groundwater pollutants identified in the 2016 report included nutrients, salts (e.g., road salt), metals, petroleum hydrocarbons and fuel additives, chlorinated solvents and additives, radionuclides, pharmaceuticals and other emerging contaminants, pesticides, and microbiota (including pathogens). The set of emerging contaminants has many types of chemicals, many of which are growing in concern and will be discussed further in Section 3.2. Human activities can also enhance the concentrations or transport of naturally occurring toxic or hazardous substances in groundwater, such as methane, radon, brines, arsenic or mercury (e.g., mining, dewatering, oil and gas extraction, and contaminated site remediation). Some instances of groundwater contamination may be confined to a single "site" (point source) while others are spread across large areas (non-point source, e.g., road salt, agricultural fertilizers and pesticides). Often various types or sources of contamination overlap, leading to complicated mixtures, which is especially the case in urban areas. It is important to note that much groundwater contamination likely goes undetected and uncharacterized.

The discharge of groundwater to surface water bodies or terrestrial seeps feeding them can be an important but often hidden pathway for mass loading of contaminants to surface waters in the Great Lakes Basin. Discharge zones of contaminated groundwater will be areas of direct exposure to different parts of an aquatic ecosystem, with the endobenthic zone likely experiencing the highest (undiluted) concentrations. The surface water may then transport the received contaminants to distant locations (e.g., downstream), potentially impacting additional ecosystems and water uses. However, mechanisms within the groundwater flow system, including the groundwater - surface water transition zone, may act to attenuate (retain, transform or remove; e.g., by degradation, sorption, mineral precipitation, uptake into biota) some types of contaminants (though some degradation products may be relatively more toxic than the parent contaminant). Many of these mechanisms can likewise attenuate surface water-derived contaminants that enter the subsurface (e.g. "iron curtain" mechanism in nearshore aquifers or "river's liver" phenomenon of the hyporheic zone), improving the water quality of the returning flows. However, these zones may then act as legacy stores of some types of contaminants, with the threat of future releases.

The previous report concluded that 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*."

This lack of knowledge is not unique to the Great Lakes Basin. The identification of groundwater discharge areas to surface waters is not a simple task, and is hampered by limited methods and resources. It is even more challenging then to characterize those discharge areas with contaminated groundwater and to quantify inputs of contaminants to surface waters, especially at a larger scale. While there is good understanding of the transport and attenuation mechanisms of many contaminants in groundwater systems, details of the groundwater flow pathways broadly and at a regional scale is still lacking in most areas. Furthermore, there remains a general lack of scientific understanding of the dynamics of exposure to the various parts of the ecosystem and their susceptibility to groundwater-sourced contaminants, especially for benthic-dwelling organisms, even without considering the confounding effects from other stressors such as thermal regime and water flows/levels, both of which can be influenced by groundwater – surface water interactions, land use and climate change.

In addition to these conclusions, Chapter 3 of the 2016 report (Conant et al., 2016a; Table 3.7) identified five priority science needs; these are provided here in Table 3.1. Note that inherent to these needs is simultaneous advancement on the science needs outlined in Chapter 2 (Conant et al., 2016b), as improved understanding, measurement, and modeling of groundwater - surface water interactions will strongly benefit the advancement of related science on groundwater contaminants.

Table 3.1 Priority science needs related to groundwater and contaminants listed in Table 3.7 from Chapter 3 (Conant et al., 2016a) of the 2016 report (Grannemann and Van Stempvoort, 2016).

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 two 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

A relevant question is whether this contaminants-focused chapter would be notably different had the 2016 report (Conant et al., 2016a) been written today instead of ~ 5-6 years ago. The answer is “not by much”. The previous report was very comprehensive and no major issues were missed. However, the importance or concern over some contaminants has grown in the interim, particularly the per- and polyfluoroalkyl substances (PFAS), as will be discussed in Section 3.2. Although progress has been made, there have been no major advancements in our understanding of the issues around groundwater contaminants impacting the Great Lakes Basin, or the tools applied to them, or in the science needs associated with this topic, over the past five years (except for PFAS). The reasons for this are manifold. In some topic areas there is little research being done, particularly in those requiring an interdisciplinary team (e.g., hydrogeologists and ecotoxicologists). Such research is challenging and often has fewer funding options. Some of these science needs require advancements in other areas before major progress can be made, for example, in the development of tools or models to characterize groundwater discharge patterns to surface water bodies at a regional scale. The research is mostly progressing incrementally or filling in minor gaps in knowledge or improving quantification of processes understood qualitatively. These are necessary and important advancements, but generally are at a finer level of detail than was targeted in the 2016 state of science report (Grannemann and Van Stempvoort, 2016).

3.2 New or Growing Contaminant Concerns:

Nine key types of groundwater contaminants were listed and described in Table 3.1 of the 2016 report (Conant et al., 2016a); these are salts, nutrients, metals and metalloids, petroleum hydrocarbons and fuel additives, chlorinated solvents and industrial additives, pharmaceuticals and other domestic chemicals, radionuclides, pesticides, and pathogens. A further breakdown was given for contaminants of emerging concern (CECs) in Table 3.4. These groupings remain largely unchanged. One major change is the importance of the PFAS group of chemicals (which includes the well-known perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA)) as contaminants in groundwater (Murray and Salim, 2019) and the science and data collection efforts made recently to address this potential contaminant threat. The growing PFAS issue will be discussed in detail directly in the following subsection, to both explain the issue surrounding this class of compounds and to illustrate how quickly steps can be taken to develop science and data on important groundwater contaminant issues such as this one. Other contaminants new to the scene or gaining in importance will be briefly discussed in subsection 3.2.2. Some of these emerging contaminants or new ones to be identified will become a serious concern for groundwater impacts on surface waters of the Great Lakes. This underscores the importance of 1) continued research, even if it is perceived as incremental at the time, and 2) the need for scientific goal setting (like this document) to guide and focus the work.

3.2.1 Per- and Polyfluoroalkyl Substances (PFAS)

PFAS, commonly referred to as "forever chemicals" because many of these compounds do not easily break down in the environment, are CECs receiving increasing attention because of their widespread occurrence and their potential human health and ecological effects at very low concentrations. PFAS are a large group of synthetic organic compounds (> 5000) that contain at least one fully fluorinated methyl or methylene carbon atom without any H/Cl/Br/I atom attached to it (OECD, 2021. Many of the more commonly known PFAS have a chain of fluorinated carbons. There are also a multitude of 'precursor' compounds (some also PFAS) that can degrade or transform in the environment into various (other) persistent PFAS. PFAS were first brought into commerce in the 1950s (Buck et al., 2011). Resistant to heat, water, and oil, they have had a multitude of uses over the past half-century in industrial applications, in manufacturing of consumer products (e.g., water- and stain-repellent clothing and textiles, non-stick cookware, cleaning products, personal care products, and construction materials), and in firefighting foams used to fight fuel fires. PFAS have been found in all components of the environment, from soil, water, and air, to fish and wildlife and humans, including in the Arctic (Murray and Salim, 2019). Many of the PFAS are persistent, bioaccumulative, and toxic, which has led to ecological and human health concerns, with recent restrictions on some (mostly long-chained fully fluorinated) PFAS (Sunderland et al., 2018 and references therein). However, restrictions regarding the use of long-chain PFAS have led to greater use of short-chained PFAS (Dauchy, 2019), which tend to be more mobile in groundwater and thus can migrate further distances. There have been recent suggestions to manage the PFAS as a class or as groups, rather than as individual compounds (e.g., Blum et al., 2015). There is still much uncertainty about the human and ecological health risks associated with this diverse group of chemicals (Sunderland et al., 2018).

While substantial scientific research on certain PFAS in the environment occurred through the first decade of the 2000s, PFAS as a contaminant in groundwater has only received substantial scientific focus in the last decade (but for a few studies, e.g., Moody et al., 2002). Only two of the most extensively produced, studied, and detected PFAS, that being PFOS and PFOA, were noted amongst the list of contaminants of emerging concern in the 2016 report (Table 3.4; Conant et al., 2016a); both have also been designated as Chemicals of Mutual Concern under Annex 3 of the GLWQA and are listed as Persistent Organic Pollutants under the Stockholm Convention. The number of PFAS and their precursors investigated have since grown. Principal sources of PFAS contamination of groundwater identified to date include: i) industrial facilities that have produced (not in Canada), processed, or used PFAS, ii) locations where PFAS-containing firefighting foams have been stored or used, iii) solid waste management facilities (e.g., landfills), and iv) wastewater treatment and disposal locations, and related infrastructure (ITRCweb.org, updated September 2020). In the past 5 years especially, significant strides have been made in identifying other potential PFAS sources of groundwater contamination, including more abundant point sources (e.g., septic systems; Schaider et al., 2016) and also non-point (atmospheric release) sources (e.g., Brandsma et al., 2019; Schroeder et al., 2021). Other potential non-point sources require investigation, such as the application of wastewater sludge (biosolids) onto agricultural fields and other lands, which is highly prevalent in the Great Lakes Basin.

The primary driver behind the push to investigate PFAS contamination of groundwater is the concern for human health, with a focus on drinking water from wells (e.g., Hu et al., 2016; Guelfo and Adamson, 2018; Kleywegt et al., 2020). However, recognition of groundwater as a pathway for PFAS to contaminate surface waters and potentially harm aquatic ecosystems is increasing. For instance, Ruyle et al. (2021) concluded from their study of Cape Cod watersheds in Massachusetts (outside Great Lakes Basin) that “legacy PFAS in slowly moving groundwater constitute a large source to the downstream coastal environment, representing a substantial lag between environmental PFAS releases and inputs to marine ecosystems”. Instances of PFAS-contaminated groundwater affecting surface waters of the Great Lakes Basin have also been identified (Moody et al., 2002; Awad et al., 2011; de Sola et al., 2012; Schwichtenberg et al., 2020; Propp et al., 2021).

Significant advancements have also been made recently in the understanding of PFAS fate and transport in the subsurface (see review by Hatton et al., 2018), such as the particularly strong retention in the vadose zone (above the water table) (e.g., Sharifan et al., 2021), and in potential groundwater remediation strategies (Xu et al., 2021). Reports of PFAS plumes extending several km have been made (e.g., Weber et al., 2017), illustrating the persistence and mobility of some PFAS compounds in groundwater systems. However, there have also been some indications of biotransformation of those PFAS deemed “recalcitrant” (e.g., Huang and Jaffé, 2019; O’Carroll et al., 2020), though this avenue of investigation is in its early stage. Researchers are now also looking into different types of PFAS, like ultra-short-chain PFAS (Björnsdotter et al., 2019) and replacement compounds such as Gen-X (Brandsma et al., 2019), and analytical measures of the total PFAS in a sample (see review of Nakayama et al., 2019).

It is not known how many PFAS-contaminated sites are in the Great Lakes Basin. Any estimate ultimately depends on the degree to which states/provinces have investigated PFAS contamination or the types of activities likely to lead to PFAS contamination, but also the definition of a "site". As noted by Simon (2020), application of "low" drinking and groundwater standards for PFAS (parts per trillion) potentially leads to more "sites". State/provincial and federal agencies are taking actions to identify PFAS-contaminated groundwater sites, though these only target a small subset of the more commonly analyzed PFAS (e.g., PFOS, PFOA). These actions differ by jurisdiction, but may include sampling/monitoring of drinking water, soils, and groundwater; surveys of entities that potentially manage PFAS (including military bases); and various regulatory means (e.g., toxics release reporting, hazardous waste reporting, PFAS foam use reporting, etc.).

3.2.2 Other Contaminants of Growing Interest

Several other contaminants found in groundwater have received new or growing scientific interest over the past five years. These include phytoestrogens, which are agricultural crop-derived compounds (Thomson et al., 2020), which were not included amongst the emerging contaminants in the 2016 chapter (Conant et al., 2016a). The presence in groundwater of the more-recently developed group of pesticides called neonicotinoids has also garnered recent scientific attention (Wisconsin - Bradford et al., 2018; Ontario - Browne et al., 2020). Only one compound of the organophosphate esters (OPE) was noted in the 2016 chapter; however, lately OPE have been receiving broader interest as a group of emerging contaminants affecting groundwater through contamination by septic wastewater (Schaider et al., 2016) and landfills (Propp et al., 2021), for examples. The incidence of antimicrobial resistant bacteria in groundwater systems has also been highlighted recently as a major concern that requires much additional research (Andrade et al., 2020). Currently, there appears to be no published studies on the transport of the SARS-CoV-2 virus (causes COVID-19) in groundwater systems.

Finally, it is worth noting the substantial and still-growing scientific focus on microplastics and their adsorbed contaminant load, though substantial transport through groundwater systems is likely to be important for karst and highly fractured aquifers predominantly, but may also occur for urban karst. Panno et al. (2019) reported microplastic (largely fibers) in karst groundwater systems in western and southern Illinois, USA (outside the Great Lakes Basin), with other tracers suggesting a septic wastewater source. Additionally, the potentially-temporary retention of microplastics resulting from sediment filtering associated with groundwater – surface water interactions may be important for their long-term fate and transport in surface water systems (e.g., Drummond et al., 2020).

Table 3.2 State, provincial, and federal actions to identify and document PFAS groundwater contamination and sources (2022).

	Actions that Identify Sources	CAN	ON	U.S.	MI	MN	WI	NY	PA	OH	IN	IL
Inventory	Database on locations of known or potential contamination					✓	✓		✓			
	Surveys on chemicals management						✓	✓	✓			
Sampling	State/province-wide sampling at public water systems				✓	✓	✓			✓	✓	✓
	Targeted sampling at public water systems		✓					✓	✓			
	Unregulated contaminant monitoring			✓		✓						
	Ambient soil and groundwater monitoring			✓		✓	✓					
	Drinking water sampling at or near military bases								✓	✓	✓	
	Site-specific ground and water monitoring near sites of known impact		✓		✓	✓	✓	✓	✓	✓		
	Influent, effluent, and sludge sampling at wastewater treatment plants					✓	✓					
Regulation	Toxics release inventory			✓								
	Regulation as hazardous substances			✓				✓				
	Groundwater/leachate sampling at active/inactive landfills					✓	✓	✓	✓			

3.3 Research Specific to the Great Lakes Basin

In Table 3.5 of the 2016 report (Conant et al., 2016a), published scientific papers involving field studies of groundwater contaminants impacting surface waters of the Great Lakes Basin were listed. This list, which aimed to capture all the relevant papers but may have missed some, provided some sense of the amount of science being performed on this topic overall and those contaminants or sources that had received the greatest attention. Table 3.3 below provides an update on papers published since 2015. This shows a strong focus on nutrients and, relatedly, wastewater, which takes up much more of the focus here than for the 2016 report. This likely reflects the major concerns with nutrients and the resultant eutrophication and harmful algal bloom issues threatening the Great Lakes (discussed further in Chapter 4). Road salt was a major focus in earlier years, but has received much less attention recently, though the issue continues to persist and is not fully understood. The issue of arsenic accumulation and release along lakeshores is a new area of exploration. Perhaps surprisingly, there are few papers addressing contaminants of emerging concern, including PFAS, on this list.

Many of the studies in Table 3.3 are focused on identifying a general issue or on understanding underlying processes, with the work situated in the Great Lakes Basin simply for convenience of location (close to the University or Research Institute). Still, many of these are definitely relevant to the Great Lakes Basin because the climate and geological conditions are obviously applicable. But few of the studies are directed to collecting or producing data specific to the Great Lakes Basin (or even its major sub-basins), such as calculating overall loads of contaminants from groundwater or identifying broad impairments of specific regions. Some studies may lead to this, as for the development of a regional GIS-based model for predicting nutrient loads to Ontario streams from septic systems (e.g., Oldfield et al., 2020a). Also, some larger-scale data collection may be performed by the federal and provincial/state agencies and may not be published in scientific journals.

In addition, Chapter 3 of the 2016 report (Conant et al., 2016a) also addressed potential groundwater linkages to the Great Lakes Areas of Concern (AOCs). In the intervening years, only 6 sites in the U.S. and 1 site in Canada showed expenditures on Remediating Hazardous Waste Sites, Brownfields, and Contaminated Groundwater (but with no breakdown as to what work was actually for remediation of groundwater contaminants) (Hartig et al., 2020).

Not all of the Priority Science Needs require that the research be performed within the Great Lakes Basin to be applicable to understanding or predictions of the impacts of groundwater contaminants on Great Lakes Basin surface waters. However, such studies would be highly relevant. Additionally, some of the Priority Science Needs call for science activities specific to the Great Lakes Basin.

Table 3.3 Studies published in the peer-reviewed scientific literature after 2015 that report on field observations of groundwater contaminant discharge to surface waters of the Great Lakes Basin.

Contaminants	Study	Receiving water(s) / area
Arsenic	Rakhimbekova et al., 2018 Rakhimbekova et al., 2021a	Lake Erie, Lake Huron and Lake Ontario shorelines (Ontario)
Fecal bacteria (swash zone accumulation)	Wu et al., 2017 Vogel et al., 2016	Lake Ontario & Lake Huron shorelines
Chloride (road salt)	Roy, 2019	Various Ontario streams and lakeshores

Landfills (including CECs)	Propp et al., 2021	Various Ontario streams, ponds, wetlands, lakeshores
Nutrients	Maavara et al., 2018	portion of the Grand River (Lake Erie basin)
	Rixon et al., 2020, Mackie et al., 2021	Lake Huron basin (Ontario)
	Cassilas-Ituarte et al., 2019	Lake Erie basin (Ohio)
	Knights et al., 2017	U.S. Great Lakes coastline
Septic systems (largely nutrient focus)	Baer et al., 2019	Lake Huron (Ontario)
	Oldfield et al., 2020b	Lake Erie basin (Ontario)
	Roy et al., 2017	Georgian Bay (Lake Huron, Ontario)
	Spoelstra et al., 2017, 2020	Lake Erie and Georgian Bay basins (Ontario)
	Rakhimbekova et al., 2021b	Lake Huron (Ontario)
PFAS	Schwichtenberg et al., 2020	Small lake in Michigan

3.4 Scientific Progress on the 2016 Science Needs

Five science needs related to gaps in scientific knowledge and insufficient information with respect to groundwater contamination in the Great Lakes Basin were identified in the 2016 report. The aim was to direct monitoring, research, and other investigation efforts to key areas that would lead to improved protection of the water quality of the Great Lakes waters. This section provides a short assessment of the progress made toward fulfilling these needs over the past five years.

3.4.1 Methods Development

The first science need (3A; Table 3.1) dealt with improving or developing methods for the detection and assessment of contaminated groundwater discharges. This has strong ties to required advancements in field techniques and numerical models for detecting and assessing groundwater discharge areas (within the scope of Chapter 2). However, some specific developments for contaminants have been made over the past five years. One example is the development of a streambed point velocity probe and its application to groundwater contaminant discharge zones (Cremeans et al., 2018), which aims to better characterize the contaminant mass discharging across the streambed. Another example is the measurement of novel tracers of groundwater contaminants in surface waters for identifying and quantifying contaminant inputs, such as the use of acesulfame to trace wastewater inputs from septic systems (Oldfield et al., 2020b). More broadly, this area of research has seen a continuing trend of using multiple, complementary tools of different types (e.g., hydrogeological, geophysical, temperature-based, geochemistry, tracers, etc.) to produce more complete investigations.

Related to methods development, is the need to properly assess sites with potential contaminant problems, develop appropriate conceptual model(s) for the situation, and apply appropriate monitoring or remediation methods to address them. To this end, Conant et al. (2019) produced a "framework" to provide guidance on contamination involving groundwater – surface water interactions, that can act as a guide for applying the best available methods.

3.4.2 Remediation in the Transition Zone

Research continues on the fate, transport and remediation potential of the stream transition (or hyporheic) zone (science need 3B; Table 3.1) for legacy contaminants such as nitrate and chlorinated solvents, and with some greater emphasis on emerging contaminants (e.g., Schaper et al., 2018), typically more for suboxic and anoxic conditions. In a study with broader implications, Harvey et al. (2019) recently introduced the reaction significance factor and showed that intermediate levels of hyporheic connectivity, rather than the highest or lowest levels, are the most efficient ones in removing nitrogen from river networks. Furthermore, Lewandowski et al. (2019) recently concluded that "Although the capacity to reduce nitrate loads by hyporheic restoration in individual stream reaches might be small, the cumulative nitrate removal capacity over longer reaches or stream networks can be significant under favorable environmental conditions". However, hyporheic restoration is still not explicitly incorporated into large scale models of contaminant fate in rivers (Lewandowski et al., 2019). Similarly for lakes, studies continue to explore hydrological mixing and geochemical changes associated with nearshore swash zone circulation (e.g., Malott et al., 2016, 2017) and to demonstrate this zone's ability to attenuate contaminants, such as microcystin, a toxin produced by algal blooms (Danner et al., 2018). Along with these investigations into processes, researchers are also continuing to work on designing structures and methods to enhance the remediation potential of these zones, though more research is needed, particularly with respect to the retention of microplastics (Lewandowski et al., 2019).

3.4.3 Susceptible Organisms

There has been little research published on the topic of understanding the sensitivity of organisms to toxic contaminants in groundwater (science need 3C, Table 3.1), which is especially needed for those living in the sediment (endobenthic zone, hyporheic zone), as these zones typically will experience the largest concentrations and often with lower dissolved oxygen concentrations. There is still little known about what species and/or life stages are most at risk and to what types of contaminants. This is important information for guiding the application of water quality guidelines and for conducting site assessment and monitoring where contaminated groundwater discharges to surface waters. However, there has been a greater recognition and evaluation of groundwater inputs of nutrients on aquatic plant and periphyton (algae and other microbes growing on plants and sediment bottom) and the competitive balance between the two in littoral zones, through shading effects (e.g., Périllon and Hilt, 2016, 2019).

3.4.4 Documenting Ecological Effects

There has been very limited research conducted on demonstrating and assessing actual ecological impacts from groundwater-sourced contaminants discharging to surface waters (science need 3D, Table 3.1). Groundwater-centric research tends to end with illustrating and quantifying the contaminant mass discharge, and possibly evaluating potential exposure concentrations to aquatic ecosystems. Ecotoxicology-centric work tends to be restricted to lab-based assessments of contaminant toxicity, primarily from sources (e.g., landfill leachate) rather than discharging groundwater. One recent study (Roy et al., 2017) demonstrated some potential subtle impairments in the endobenthic community associated with overlapping petroleum and chlorinated solvent groundwater plumes discharging to a river in eastern Canada. Confounding factors complicated the single snapshot assessment. Likewise, Sonne et al. (2018) reported lower meiobenthic organism numbers from groundwater discharge zones impacted by organic contaminants, potentially linked to enhanced iron and arsenic release. Here again, confounding factors along with limited sample sites prevented definitive linkages. Both sets of authors highlighted the need to develop improved field methodologies combining groundwater and ecosystem measures to properly target this largely unexplored exposure condition.

3.4.5 Regional-scale Contaminant Loading

Relating to science need 3E (Table 3.1), the quantification of regional-scale contaminant loading via groundwater is a worthwhile target for some contaminants (e.g., road salt, nutrients, recalcitrant emerging contaminants like PFAS), to provide broader insight into effects of broad-scale sources and the relative role of the groundwater pathway. An example of this in the past five years is the water-balance approach used by Knights et al. (2017) to identify areas along the entire Great Lakes U.S.-side coastline that are vulnerable to high groundwater-sourced nutrient loads. A calculation of actual loadings of the nutrients was not attempted. This requires much scientific and method advancement to connect appropriate contaminant source data and sophisticated hydrological models that account for the physical flow and contaminant transport and fate processes (including in the transition zones). No specific examples of this type of work that targeted the Great Lakes Basin were found for the past five years. It would also be useful to see a comparison study between regional scale groundwater surveys with monitoring well networks and groundwater discharging to surface waters, to better determine what data sets are most relevant to calibrate and validate this modeling approach.

Though not emphasized in the 2016 chapter (Conant et al., 2016a), it also seems necessary and perhaps more attainable to provide semi-quantitative estimates of loading and to identify areas with a greater concentration of or potential impact from direct contaminated groundwater discharge for a wider variety of key contaminants. This can still allow for identification and predictions of groundwater contaminant impacts (i.e., where, when, and how much) on water quality and ecosystem health, and might be more applicable for contaminants that react within the surface water environment (e.g., nutrients, metals, radionuclides, degradable organic contaminants).

A key part for this science need is identifying the sources of groundwater contamination. While the locations of confirmed and potential groundwater contaminant sources and sites are often known, these are not currently readily consolidated from the myriad of data repositories storing this information. One recent developing exception is that of the PFAS sources discussed above, with most states/provinces in the Great Lakes Basin currently compiling location information for the primary point-source sites (Table 3.2) in a relatively short period. This demonstrates that with concerted effort, such compilations could likely be completed for other priority groundwater contaminants, though with greater uncertainty for those with substantial non-point inputs (e.g., road salt, nutrients) or wide-ranging small point sources (e.g., septic systems). However, in those cases, generalized GIS-based input models may be sufficient to answer relevant questions and provide semi-quantitative estimates of broad-scale loading. For example, Oldfield et al. (2020a) applied a GIS tool to estimate an upper range of nutrient (N and P) inputs from septic systems in the Lake Erie basin in Ontario.

3.5 Updated Priority Science Needs

The five priority science needs identified in the 2016 report (Table 3.1) are just as important and relevant as they were five years ago. There appears to be no major gap or newly developed issue that requires an additional science need, but for continued focus on newly-emerging contaminants (like PFAS) and consistent diligence in looking out for new groundwater contaminant threats. Additionally, changes in the natural and built environment that could impact groundwater contamination and its transport and discharge to surface water bodies must be considered in monitoring and research study planning. These changes may result from changes in agricultural practices (best management practices), urbanization (including greater implementation of low-impact-development, which favours groundwater recharge over surface runoff), wetland restoration, and climate change. Many of these are discussed in greater detail in the Chapters that follow. It should be emphasized that future investigations should deal with the full range of receptors, including lakeshores, wetlands, and riparian areas, and not just streams and rivers.

One of the conclusions from Chapter 3 of the 2016 report (Conant et al., 2016a) was that: “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.” There appears to be little evidence of this type of work occurring, but perhaps for research into ecological impacts of nutrients supplied by groundwater to freshwaters (predominantly in Europe; e.g., Périllon et al., 2017; Périllon and Hilt, 2019, but not exclusively; e.g., Naranjo et al., 2019). This requirement is still essential today, but needs to be fostered and supported to fully address the science needs surrounding groundwater contaminant impacts on Great Lakes waters.

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Characteristic iron and manganese oxide staining associated with a groundwater seep emanating from an old landfill.

Photo credit: James Roy, Environment and Climate Change Canada

4 GROUNDWATER AND NUTRIENTS

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4.1 Introduction

Nutrients, nitrogen (N) and phosphorus (P) in particular, are one of the most impactful classes of contaminants to the Great Lakes. Although essential to aquatic life for growth, when present in excess, nutrients can cause detrimental effects to water quality through eutrophication, toxicity, and algal blooms (Phosphorus Reduction Task Force, 2012). The problems caused by excess nutrients impact both human and ecological health and impairment of recreational uses of lakes and streams in the Great Lakes Basin. While management efforts over the past decades have reduced nutrient loading to the Great Lakes from certain major point sources (e.g., wastewater effluent), eutrophication continues to occur (International Joint Commission, 2013). Phosphorus is typically the limiting nutrient for growth in freshwaters and therefore it has been the primary nutrient of concern in the Great Lakes (Phosphorus Reduction Task Force, 2012). However, nitrogen also influences primary productivity and algal blooms, and co-management of N and P loads (e.g., N:P ratio) may be needed to reduce eutrophication and in particular harmful algal bloom toxicity (Dierkes, 2019, Paerl et al. 2016, Paerl et al. 2020) in the Great Lakes Basin.

The groundwater flow system has been identified as a relatively poorly understood transport pathway of nutrients to the Great Lakes, both through direct inputs along lake shorelines and indirectly as a major component of stream flow discharging to the Great Lakes (Grannemann et al. 2000). Furthermore, the impact of groundwater on algal bloom dynamics is complex and potentially underestimated (Brookfield et al. 2021). Nitrogen-based nutrients in groundwater are typically in the form of nitrate (NO_3^-), ammonium (NH_4^+), and dissolved organic nitrogen (DON; Wang et al. 2018), of which nitrate tends to be dominant and the most mobile groundwater nutrient. Phosphate (PO_4^{3-}) is a common form of phosphorus in groundwater, and its mobility is highly dependent on groundwater redox conditions (Domagalski and Johnson, 2011, 2012). Phosphate is also the most biologically available, or reactive, form of phosphorus. The major sources of excess nutrients in groundwater in the Great Lakes Basin are fertilizers for agricultural and non-agricultural (e.g., domestic use, golf courses) uses, animal manure, septic systems, leaky sewers, landfills, and certain types of industrial sites (e.g., chemical manufacturing) (Robinson, 2015). Riparian zones, the interface between the land and surface waters, are biogeochemical hotspots and often act as buffers by removing nutrients, especially nitrate, from groundwater prior to discharge to surface waters (McClain et al. 2003, Bernhardt et al. 2017).

Chapter four (Robinson et al. 2016) of the 2016 report (Grannemann and Van Stempvoort, 2016) identified four Priority Science Needs related to groundwater and nutrients (Table 4.1).

4.2 Priority science needs identified in 2016 report

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 quality
4B. Role of hot phenomena (biogeochemically active locations and time periods) 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

4.3 Updated status on priority science needs

In this section, we briefly discuss examples of recently published research that addresses the previously identified priority science needs related to groundwater nutrients in the Great Lakes Basin.

4.3.A. - Linking land management and groundwater nutrient loading

While numerous reports and scientific studies have highlighted the linkage between land-use practices and groundwater nutrient pollution, the magnitude and timing of these activities in delivering nutrients to surface waters via groundwater pathways are often not well understood (e.g., Brookfield et al. 2021). Agricultural land use and management practices can have varying effects on nutrient leaching to aquifers depending upon the crop types, fertilization (amounts, types, and timing) and soil moisture conditions (Council of Canadian Academies, 2013). Recent studies by McDowell et al. (2015), Schilling et al. (2016), Green et al. (2018), Esmaeili et al. (2020), and Saleem et al. (2020) evaluated several agricultural practices to determine their effect on nitrate and dissolved phosphorus leaching. Results indicated that select crop rotations and fertilization practices can reduce excess nutrient accumulation in soils and thereby reduce leaching to aquifers (McDowell et al. 2015). For example, Green et al. (2018) re-constructed historical nitrate loading in a Lake Michigan watershed, finding evidence that nitrate leaching losses from mineral fertilizers may have decreased by approximately three-fold between 1945 and 2006, while leaching losses from manure may have increased by about tenfold during that period. Quantifying best management practice (BMP) effectiveness with respect to groundwater quality is complicated by variability in hydrogeologic, climatic, and land management factors, and may benefit from combining monitoring and modeling analyses (Green et al., 2018; Esmaeili et al., 2020; Saleem et al., 2020). Moreover, evaluations of BMP effectiveness at reducing nutrient leaching to aquifers require extensive time periods (multiple years to decades) of monitoring to reduce uncertainty associated with natural variability (McDowell et al., 2015; Esmaeili et al., 2020). Additional work is needed to better quantify how economically tractable land management practices (e.g., crop rotations, cover crops, timing of fertilizer and manure applications) relate to nutrient leaching losses (Esmaeili et al. 2020, Green et al. 2018), though some states have already attempted to quantify relative nutrient loss improvements attributable to specific BMPs (Iowa State University, 2019) while others have developed generalized guidelines (Felix-Gerth and Rhees, 2021).

Non-agricultural sources of nutrients, such as septic systems, continue to be evaluated for their role in nutrient loading to streams and lakes. Estimates from recent studies (Roy et al., 2017; Spoelstra et al. 2017; Baer et al. 2019; Hamlin et al., 2020; Oldfield et al., 2020a,b; and Rakhimbekova et al., 2021) suggest that septic systems are a small component of total nutrient loading (up to 5% for phosphorus and from 0 to 2% for nitrate) to the Great Lakes and their tributary streams. However, septic systems may be important sources of nutrients to sheltered embayments without other major external inputs (Rakhimbekova et al., 2021).

Septic-derived groundwater nutrient inputs to the lakes may also be higher where septic systems are poorly functioning, designed, or situated. Recent studies have shown that both active and decommissioned septic systems contribute nutrients to the Great Lakes and the magnitude of this source is likely to increase in the future due to slow groundwater travel times, oversaturation of soils with P, and increased leaching losses if septic system performance declines due to poor maintenance (Roy et al., 2017; Spoelstra et al. 2017; Baer et al. 2019; Oldfield et al., 2020a,b; Rakhimbekova et al., 2021).

Several recent studies (e.g. Roy et al., 2017; Green et al., 2018; Casillas-Ituarte et al., 2020; Esmaeili et al., 2020; Johnson and Stets, 2020; Oldfield et al., 2020b; Rakhimbekova et al., 2021) have documented the role of legacy nutrients (those generated under historical management practices and subsequently leached from soils or retained in aquifers or stream sediment) on water quality by refining understanding of typical time lags associated with nutrient transport through the unsaturated zone and saturated aquifer systems. Green et al. (2018) estimated that transport through the unsaturated zone often accounts for 20% of the total time lag between infiltration and arrival at surficial aquifer wells. Martin et al. (2021) developed a novel method that couples nitrogen source maps with groundwater transport times to create estimates of the timing and magnitude of nitrogen flux to surface waters of Michigan's Lower Peninsula, including Lakes Erie, Huron and Michigan. The findings are framed by management timelines for elected officials (<5 years), career managers (5-30 years), and advocacy groups (>30 years) to help stakeholders identify priority management areas that match their timeframe of influence. Examples of forecasting nutrient transport and loading to wells and surface waters (Nolan et al., 2018; Saleem et al., 2020; Martin et al., 2021) illustrate the influence of legacy nutrients on delaying future water quality improvements across the Great Lakes region, and highlight the added challenges caused by delayed action.

4.3.B. Role of hot phenomena with respect to groundwater nutrient fluxes

Biogeochemically active locations (hot spots) and time periods (hot moments), collectively referred to as hot phenomena, play a disproportionate role in governing the fate of groundwater nutrient discharge to water bodies. The high spatial and temporal variability associated with these hot phenomena complicates understanding and prediction of groundwater nutrient inputs to the Great Lakes and their tributaries. One of the key hot phenomena that can affect the delivery of groundwater nitrogen to Great Lakes tributaries is riparian zone denitrification, which predominantly converts nitrate to inert nitrogen gas. Zhao et al. (2021) provide a review of nitrogen removal pathways in hyporheic and riparian zones, and many of these processes are also applicable to groundwater discharge zones in nearshore areas of the Great Lakes. Stelzer (2015) noted the important role of available carbon in streambed sediment for facilitating denitrification, which historically could be influenced by wetland loss and stream channelization in the Great Lakes region. Hill (2019) also provides a review of the current state of knowledge on nitrate removal in riparian buffer zones and notes that further research is needed on the effects of nitrate removal at the watershed scale and how riparian zones are likely to respond to land use and climate change. Less is known regarding the removal of phosphorus in riparian zones with recent studies suggesting that riparian zones may act only as temporary phosphorus storage zones (not a final sink) whereby phosphorus trapped in the riparian zone may be re-mobilized to the dissolved phase and delivered to surface waters via groundwater flow when environmental conditions change (e.g., high water tables) (e.g., Dupas et al., 2015; Gu et al., 2017; Vidon et al., 2019). Four nested subwatersheds with varying land use in rural southern Ontario were monitored to identify peak periods and areas of nitrogen and phosphorus export (Irvine et al., 2019). The study concluded that future land management practices and the identification of hot phenomena should consider potential differences between N and P export controls and develop strategies for achieving desired target loads for each nutrient individually. Irvine et al. (2019) is one of a growing number of studies that demonstrate the importance of identifying critical areas and periods in which to focus nutrient management efforts to maximize the environmental benefit.

Detailed information, both spatially and temporally, is needed to detect and quantify the impacts of hot phenomena on nutrient loading to the Great Lakes. A review paper by Bernhardt et al. (2017) examined the body of literature that cited the original "hot spots and hot moments" paper by McClain et al. (2003) and found relatively few examples of rigorous statistical or modelling approaches that would allow scientists to identify and simulate the impact of hot phenomena on ecosystem processes. As such, the impact of hot phenomena on groundwater nutrient loading to surface waters of the Great Lakes Basin remains a science gap. Bernhardt et al. (2017) further propose that the terms "hot spots" and "hot moments" be updated to "ecosystem control points" to reflect the fact that these phenomena must be of sufficient magnitude to have an ecosystem-level impact and that spatial and temporal heterogeneity are linked. Briggs and Hare (2018) suggest that focused groundwater flow paths, such as through large bedrock fractures and karst, that manifest themselves at the surface as preferential groundwater discharges can have a major influence on surface waters and therefore these features should be considered as ecosystem control points. Groundwater conduits, including agricultural tile drains, are discussed further in Section 4.4 as an emerging science need with respect to groundwater nutrient delivery to the waters of the Great Lakes.

4.3.C. Upscaling of site-specific knowledge

Although numerous small-scale studies have investigated groundwater nutrient cycling and transport in the Great Lakes Basin, methods are needed to scale this scientific knowledge to quantify groundwater nutrient impacts to surface waters at the stream, watershed, and Great Lakes Basin scales.

Transferring knowledge gained from site-specific investigations to regional scales on the order of the Great Lakes watershed is challenged by heterogeneous land use, land management, soils, geology, hydrogeology, hydrology, and climatic drivers across the watersheds. For example, Roy et al. (2017), Spoelstra et al. (2017), Baer et al. (2019), and Spoelstra et al. (2020) quantified the contribution of septic systems to surface water nutrient loads at specific sites in the basin, which when combined with GIS methods for mapping and quantifying septic system loads (Oldfield et al., 2020b), may help to fill gaps in quantifying the contribution of septic system nutrient loading across the Great Lakes. Further gap analyses can help with prioritizing research efforts, while recent developments in machine learning and deterministic modeling may offer effective methods for quantitatively up-scaling data and knowledge gained at small scales for larger-scale assessments. For example, Tesoriero et al. (2017), Nolan et al. (2018), and Stackelberg et al. (2020) leveraged state and federal databases in combination with geographical information and local groundwater flow model results to estimate nitrate, iron, pH (and other constituents) levels across space, depth, and time at multiple scales across the glacial aquifer of the northern USA. Similar methods could be employed across the Great Lakes region and can be augmented with groundwater flow model output to improve predictive power (Fienen et al., 2015; Starn and Belitz, 2019; Starn et al., 2021). Similarly, GIS methods (Oldfield et al., 2020b) and numerical models of groundwater flow have been used to inform nutrient transport through aquifers and surface waters (Hwang et al., 2019; White et al., 2020; Rakhimbekova et al., 2021). A recent Great Lakes Science Advisory Board Research Coordination Committee report (2018) lends support for further development of such tools across the Great Lakes. Finally, decision support tools built upon analytical models (e.g., Green et al., 2018), machine learning models (e.g., Nolan et al. 2018) or numerical models (e.g., White et al., 2020) of groundwater flow and reactive transport hold promise for assisting resource managers with understanding the effects of management actions and groundwater lag times on future nutrient concentrations or loads, with development already started in the Great Lakes Basin (Juckem et al., 2021).

Generalizing relationships between landscape controls and nutrient leaching to groundwater may also facilitate up-scaling of site-specific research, as positive correlations between agricultural land use and high nutrient loads have been previously identified (Robertson et al., 2019). However, correlating specific land uses with water quality outcomes, let alone quantifying those relationships, is challenging due to the level of spatial, temporal, and quantitative detail required of measurements for both the hydrologic systems as well as the management practices themselves (Esmaeili et al., 2020). Despite these challenges, recent progress has been made in terms of refining landscape controls on nutrient fluxes to groundwater. Gardner et al. (2020) highlighted how differences in crop rotations, soil and geologic conditions, and weather patterns across three sites in southwestern Ontario influenced nitrate leaching. Saleem et al. (2020) expanded upon this by using deterministic models to demonstrate that crop rotation-based BMPs, which interrupt continuous corn or corn/soybean rotations by introducing less nitrogen intensive crops (winter wheat and red clover), can substantially reduce nitrate leaching to aquifers across a variety of climatic conditions. However, Esmaeili et al. (2020) noted that BMP effectiveness is difficult to measure due to weather patterns that can mobilize legacy nutrients stored in the soil, and that multi-year to multi-decadal monitoring is needed for improved quantification.

In order to maximize return on research and mitigation efforts, it may be beneficial to identify priority watersheds with respect to the impact of groundwater on nutrient delivery to Great Lakes waters. Prioritization can be based on a number of factors including, i) the potential for groundwater to be an important pathway for delivering high nutrient loads to surface waters in the watershed, and ii) the amount of related data collection and research already conducted in the watershed. Watersheds with a high potential for delivering relatively large loads of nutrients to a Great Lake via groundwater can be identified using a number of methods, such as stream gauging and nutrient sampling combined with baseflow indices (e.g., Neff et al. 2005), or surface water-focused nutrient yield modeling (Robertson et al., 2019). Less is known about inputs of nutrients to nearshore areas of the Great Lakes via direct groundwater discharge. Knights et al. (2017) describe a novel method for estimating the vulnerability of each lake to direct groundwater-borne nutrient discharge from small coastal watersheds. In addition to the work by Knights et al. (2017), more research could be done to assess the role of groundwater-borne loading to streams, thereby potentially identifying priority watersheds in terms of their current or future potential for nutrient loading via groundwater pathways. Watersheds that could be prioritized for additional research could also be identified based on factors that build on previous or ongoing activities to maximize the return on research investment. These factors could include previous assessments of major nutrient loads (described above), patterned land use that could simplify monitoring efforts, watersheds already highly instrumented and/or previously instrumented with extensive historical data, or watersheds with high potential for landowner cooperation with researchers (e.g., farmer-lead initiatives). Several nutrients-related initiatives led by Canadian government departments have adopted a priority watersheds concept by focusing on the Lake Erie basin or sub-watersheds within it (e.g., Agriculture and Agri-Food Canada's [AAFC] Watershed Evaluation of Beneficial Management Practices [WEBs] and Living Labs programs; Environment and Climate Change Canada's [ECCC] Great Lakes Nutrient Initiative [GLNI] and the Great Lakes Action Plan [GLAP]). Similarly in the United States, the Natural Resources Conservation Service (NRCS), Environmental Protection Agency (EPA), and state agencies have partnered through the National Water Quality Initiative (NWQI) to identify priority watersheds across the country. For the Great Lakes, priority watersheds have been identified to help focus work done as part of the Great Lakes Restoration Initiative.

4.3.D. Basin-wide assessment of groundwater

Assessment of the impact of groundwater nutrients on surface water quality in the Great Lakes Basin requires detailed information on nutrient leaching losses, basin hydrogeology, and groundwater biogeochemistry, particularly for shallow, unconfined aquifers. Future assessments of groundwater-derived nutrient issues at the scale of the Great Lakes Basin would benefit from the standardization of sample collection and analysis methods amongst the member States and Ontario.

The 2017 and 2019 State of the Great Lakes reports (SOGL; ECCC & EPA 2017, 2021) include a groundwater quality assessment for the Great Lakes Basin. These assessments are based on nitrate and chloride data from shallow wells (<40m below ground surface) collected between 2000-2015, and they identify a need for the enhancement of existing monitoring networks to fill in gaps in the spatial and depth coverage of these networks. The lack of a suitable well network for the monitoring and assessment of shallow groundwater is an issue in large portions of the Lake Superior and Lake Huron basins (SOGL 2019). Future reports in this series will also aim to assess trends in groundwater nitrate and chloride concentrations in the Basin using current and historical data. Other recent large-scale assessments of groundwater quality in the Great Lakes Basin that examine nutrient parameters include a study in southern Ontario by the Ontario Geological Survey (Colgrove and Hamilton, 2018) and by Erickson et al. (2019) in the United States. Also, in the United States, Knights et al. (2017) used large-scale, high-resolution hydrographic data along with hydroclimatic models and land use data to identify coastal areas that are vulnerable to high groundwater-borne nutrient loads along the U.S. shoreline of the Great Lakes.

To estimate groundwater nutrient loading to the Great Lakes, by both direct (nearshore discharge) and indirect (baseflow to streams) routes, information on the concentration of nutrients in groundwater must be used in conjunction with integrated groundwater/surface water and biogeochemical models. The current state of groundwater modelling for the Great Lakes Basin and plans for the development of an integrated groundwater/surface water model for the Basin were the subject of a recent report to the International Joint Commission by the Great Lakes Science Advisory Board Research Coordination Committee (2018).

4.4 Emerging science needs

Recent research suggests that the distinct geochemistry of groundwater discharge to streams and lakes may have a larger influence on algal blooms occurring in surface water than previously considered. For example, Brookfield et al. (2021) highlight that, compared with surface runoff, groundwater typically contains higher concentrations of micro-nutrients (e.g., iron, silica) that are important for some algal species and that groundwater provides a steadier source of nutrients, particularly during drought conditions. Groundwater nutrients tend to be predominantly in the dissolved form and have a differing N:P ratio than many surface waters. Groundwater's physical and geochemical characteristics may play a critical role in affecting the growth, decline, and toxicity of nuisance and toxic algal bloom occurrence (Paerl et al. 2016, Paerl et al. 2020). Thus, the role of groundwater discharge on harmful algal bloom dynamics is identified as an emerging science need.

Preferential pathways or conduits of groundwater flow can rapidly move water and dissolved constituents from the sub-surface to surface waters. These conduits can be natural (e.g., large bedrock fractures, karst features, faults) and man-made (e.g., agricultural drainage tiles) and are often poorly represented in watershed models (Briggs and Hare 2018). Tile drains are widely used to rapidly remove excess water from agricultural fields that would otherwise have poor drainage. By intercepting shallow groundwater, tile drains are an important mechanism for rapidly transporting nutrients leached from agricultural fields to nearby surface waters (Dinnes et al. 2002, Goeller et al. 2019), with minimal potential for geochemical transformation during transport within the tiles or during discharge through sediments below lakes and streams. At three sites in the Lake Erie basin, Hanrahan et al. (2020) examined nutrient loss from agricultural drains with respect to site environmental and management characteristics and concluded that different factors impact N and P loss via tile drains, and nutrient-specific management scenarios are needed to mitigate these impacts. Williamson et al. (2019) used remote sensing to map tile drain networks at an edge-of-field site in the Lake Erie watershed, suggesting that augmenting the method with regional air photos or satellite imagery might provide a tool for basin-wide mapping. Natural conduits, such as large bedrock fractures and karst features can also lead to rapid transport of nutrients and other contaminants to wells and water bodies (Briggs and Hare 2018, Borchardt et al. 2019, and Borchardt et al. 2021). In such cases, conduits that connect areas of rapid infiltration with focused discharge locations (springs, submerged vents) may be the primary transport pathway at local and sub-regional scales (Briggs and Hare 2018). Because of their ability to promote the rapid subsurface transport of nutrients with little or moderate (Husic et al. 2020) geochemical transformation along the flow path, the impact of tile drains and other groundwater conduits on watershed nutrient budgets is identified as an emerging science need for the Great Lakes.

4.5 Updated priority science needs table

As discussed above, progress is being made towards addressing the priority science needs related to groundwater nutrient issues that were identified in the 2016 report (Table 4.1). That said, information gaps remain, and additional research is needed in order to develop a more complete understanding of the contribution of groundwater nutrient inputs to surface waters and their impact on Great Lakes ecosystems. The updated priority science needs presented in Table 4.2 expand upon those identified in the 2016 report to include the role of groundwater on nuisance and harmful algal bloom dynamics, and characterization of rapid transport through tile drains and natural conduits. Additionally, one policy-type statement in 4A about *acknowledging* the link between land management and nutrient loading is removed to keep the focus on science priorities.

Table 4.2 Updated priority science needs related to groundwater and nutrients.

Priority Science Needs	Related needs and information gaps
4A. Linking land management and groundwater nutrient loading	• 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 quality

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 and biogeochemical 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
4E. Effect of groundwater on algal bloom dynamics	• Refine understanding of how the unique physical and geochemical characteristics of groundwater influence nuisance and harmful algal blooms.
4F. Impact of tile drains and natural groundwater conduits on nutrient loading	• Map tile drain networks and identify areas of known or suspected significant natural conduits • Quantify nutrient loading to surface waters from tile drains and natural groundwater conduits. • Refine understanding of biogeochemical processing, if any, of nutrients along tile drain and conduit pathways. • Quantify how capture of infiltrated nutrients by tile drains modifies infiltration of nutrients to the water table.

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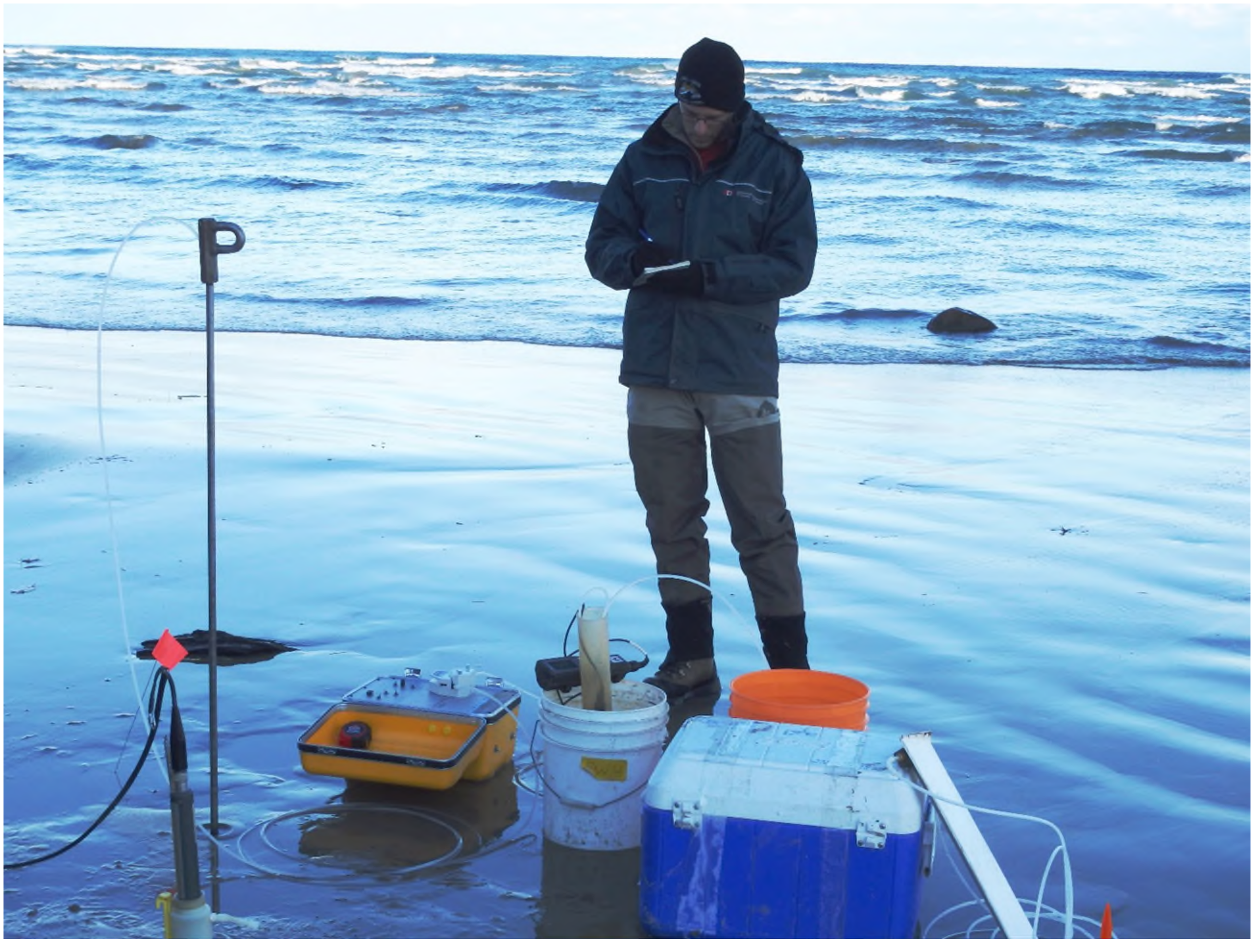

Shallow groundwater sampling during Environment and Climate Change Canada research investigating the loading of phosphorus via direct groundwater discharge to Georgian Bay, Lake Huron (Ontario, Canada).

Photo credit: John Spoelstra, Environment and Climate Change Canada

5 GROUNDWATER AND AQUATIC HABITATS IN THE GREAT LAKES BASIN

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5.1 Introduction

Groundwater within the Great Lakes Basin has been described as the sixth Great Lake (Cohen 2009). Its storage and discharge impact the availability and quality of aquatic habitats in lakes, streams, and wetlands within the Great Lakes Basin by influencing the hydrological, thermal, and chemical characteristics of these surface waters (Grannemann et al., 2000). From the hydrological perspective, groundwater discharge can provide a year-round, continuous supply of water to ecosystems, maintaining flows or water levels during winter and dry periods, thereby moderating drought effects. Given that groundwater temperatures tend to fluctuate less than those of surface waters, groundwater discharge acts as a thermal buffer, providing a source of heat in the winter and a cooling effect in the summer. The chemistry of groundwater influences aquatic habitats as a source of minerals and micronutrients, reflecting the geology of the materials it flows through prior to discharge (Kløve et al., 2011). However, groundwater can also be a source of contaminants and excess nutrients to discharge zones, especially when the groundwater is derived from relatively shallow flow paths that are impacted by anthropogenic land use activities (Kornelsen and Coulibaly 2014). The important contributions groundwater discharge provides to aquatic habitats are recognized in the terminology "groundwater-dependent ecosystems" (GDEs), which acknowledges a range of groundwater-derived processes that maintain healthy aquatic ecosystem function in lakes, streams, and wetlands.

In lakes, direct (lacustrine) groundwater discharge typically occurs in the nearshore environment and diminishes with distance offshore (Kornelsen and Coulibaly 2014). The nearshore functions as a transition zone between the terrestrial system and the open water environment of lakes and is the zone most affected by pollution runoff, water level fluctuations, and shoreline development (Haack et al., 2005). The amount of nearshore groundwater discharge and how quickly it is diluted in the nearshore lake water depends on several factors, including the local geology, shoreline physiography, and in-lake circulation patterns (Haack et al., 2005). These groundwater discharge zones within lakes may be important habitats for fish and invertebrates to carry out parts of their life cycles (Haack et al., 2005).

The annual discharge of streams and rivers can consist of a significant, although variable, fraction of groundwater (e.g., 40-75%, Neff et al., 2005). The slow and constant discharge of groundwater to streams maintains baseflow between precipitation events and during the winter, and this indirect discharge via tributary flow is the largest source of groundwater to the Great Lakes. The thermal buffering effects of groundwater discharge maintain thermal refugia for aquatic species as ice-free areas (including under surficial ice cover) during the winter and cool water zones in the summer (Power et al., 1999). Furthermore, the degree of groundwater input at the watershed scale is the primary driver in determining the overall stream discharge and summer temperature regimes and, therefore, is a key factor for determining if the stream is a warm vs. cool vs. cold water fish habitat (McKenna et al., 2018). At the local scale, distinct groundwater discharge zones in streams are important habitats for fish and benthic invertebrates (Power et al., 1999; Hunt et al., 2006). Salmonid fish species such as trout and salmon take advantage of the thermal and chemical stability of local groundwater discharge areas by using them as spawning sites and seasonal refugia (Power et al., 1999). Groundwater also strongly influences stream chemistry and, if contaminated, can be detrimental to the quality of aquatic habitats. Finally, groundwater levels and dynamics can influence the type of riparian vegetation in floodplain wetlands bordering streams, with implications for vegetation composition and subsequent bank stability, shading, and organic matter inputs (Groeneveld and Griepentrog, 1985).

Wetlands are very ecologically diverse and productive, and groundwater plays an important role in supporting wetland habitats within the Great Lakes basin (Crowe and Shikaze, 2004). Of the five main types of wetlands (open water wetland, marsh, swamp, fen, and bog), groundwater discharge is typically associated with fens. However, groundwater levels can also affect the hydrology of the other, surface water dominated wetlands, which are not otherwise directly impacted by groundwater discharge to the same degree as fens. Inland and coastal wetlands are biogeochemical hotspots, providing ecosystem services such as the filtering out of pollutants and sediments, providing spawning habitat, nutrient cycling and retention, and moderating the impacts of floods and droughts (Mitsch and Gosselink, 2015). Coastal wetlands are particularly important in the Great Lakes, providing habitat for numerous rare and threatened plants and animals (e.g. Cohen et al., 2010). A related and typically smaller ecosystem, the groundwater spring, can have its own unique flora and fauna (Kløve et al., 2011).

Finally, an aquatic ecosystem that was not discussed in the original report (Chu et al., 2016) is the groundwater ecosystem itself, which includes subsurface karst and cave systems and the interstitial space within aquifers (Soares et al., 2021), extending from the shallow sediments of surface water bodies to several kilometers in depth (Danielopol et al., 2003). These ecosystems contain unique macroscopic animal life (e.g., blind fish, translucent crabs in cave systems; various crustacea, arthropods, isopods, molluscs, or nematodes) (Humphreys, 2009). The groundwater ecosystem has not yet received substantial attention across North America, but it has been the focus of many studies across Europe and in Australia (Humphreys, 2009). The latest progress in this area focuses on incorporating genomic assessments (e.g., Boyd et al., 2020), investigating impairments from toxic contaminants (e.g., Di Lorenzo et al., 2019) and from land use changes (e.g., Español et al., 2017), and assessing how these organisms may influence or be influenced by hydraulic properties of groundwater flow systems (e.g., Hose and Stumpp, 2019).

5.2 Priority science needs identified in 2016 report

Chapter five (Chu et al., 2016) of the 2016 report (Grannemann and Van Stempvoort, 2016) identified five Priority Science Needs related to groundwater-dependent aquatic habitats (Table 5.1).

Table 5.1 Priority science needs related to aquatic habitats (Chu et al., 2016).

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 with 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

5.3 Updated status on priority science needs

Groundwater dependency is complex to assess. First, there is a gradation in relative contribution to different surface waters that can differ substantially across spatial scales. Also, the importance of the groundwater contribution may not match its relative contribution of water to the system. For example, a cool stream with minor groundwater input may be more susceptible to small changes in the groundwater contribution compared to a cold stream with major groundwater inputs.

To understand the potential impacts of natural and anthropogenic changes on groundwater-dependent aquatic habitats, groundwater models are needed to simulate groundwater recharge, flow, and discharge to the surface water bodies (rivers, wetlands, and lakes). A recent report to the IJC reviews the current state of hydrological modelling relevant to the Great Lakes basin and proposes an action plan to develop an integrated groundwater-surface water model for the Great Lakes basin (Great Lakes Science Advisory Board, Research Coordination Committee 2018).

There are several potential ways in which aquatic groundwater-dependent ecosystems within the Great Lakes Basin can be identified and characterized. These include field-based mapping, remote sensing, related parameter maps or indices (like stream base flow index), and numerical modeling. Considerable effort has already gone into developing an inventory of the coastal wetlands of the Great Lakes. The results of these efforts include:

- the Great Lakes Coastal Wetland Monitoring Program (GLCWMP) implemented by the Great Lakes Coastal Wetland Consortium (GLCWC; https://www.greatlakeswetlands.org/Map.vbhtml) (Ingram et al., 2004)
- the Ontario Great Lakes Coastal Wetland Atlas (Ball et al., 2003)
- the McMaster Coastal Wetland Inventory (MCWI; https://greatlakeswetlands.ca/learn/wetland-inventories/)
- Great Lakes coastal wetland and land use map developed using remote sensing (Bourgeau-Chavez et al., 2015)
- Mapping and characterization of coastal wetlands as part of the Michigan natural Features Inventory (e.g., Albert, 2003; Cohen et al., 2010)

Although the databases listed above include all coastal wetlands of sufficient size, a subset of these are specifically dependent on groundwater discharge and could potentially be identified based on some of the recorded wetland attributes (e.g., wetland type, dominant vegetation). Knights et al. (2017) used hydroclimatic models and high-resolution hydrographic data to map estimated groundwater discharge along the entire USA coastline of the Great Lakes. When used in combination with existing mapping of GLs coastal wetlands, the approach of Knights et al. (2017) could help identify groundwater-dependent ecosystems.

Similarly, identification, classification, and mapping of inland wetlands are available on various platforms, such as Ontario GeoHub (https://geohub.lio.gov.on.ca/) and Michigan's Wetlands Map Viewer (https://www.mcgi.state.mi.us/wetlands/mcgiMap.html). Watershed characteristics such as topography and hydraulic parameters of the surficial geology have been used to estimate the groundwater dependency of riparian forests in Michigan and the relation to tree species composition in these habitats (e.g., Baker et al., 2003; Baker & Wiley 2004, 2009).

For inland lakes, the Midwest Glacial Lakes Partnership (https://midwestglaciallakes.org/) has built a mapper for 40,000 lakes in MN, WI, and MI that places each lake within its upstream drainage catchment and local buffer contexts, and contains available data on limnological character and fish community structure. This system has not emphasized groundwater but could be linked with regional models to achieve this task of mapping groundwater-dependent lake ecosystems and expanded to include the rest of the Great Lakes Basin.

It is well known that groundwater discharge to streams strongly influences stream temperature and there is a direct link between water temperature and habitat suitability for various fish species. Within the Great Lakes Basin, and in Michigan and Wisconsin specifically, numerous studies have demonstrated this relationship and classified streams and stream habitats according to thermal regime (e.g., Wehrly et al., 2003, 2006; Zorn et al., 2002, 2011; Seelbach et al., 2006; Lyons et al., 2009). More recently, McKenna et al. (2018) expanded on these concepts to create a river size-temperature classification system for the entire USA Great Lakes drainage, a system that could be expanded to the entire Great Lakes Basin. This classification system includes the identification of groundwater inputs by estimating the summer baseflow yield and can be used to predict stream and fish sensitivity to alterations in flow, including changes in groundwater discharge. Ontario has also formally proposed the development of a river ecosystem mapper and classification system, which includes classification of thermal regimes related to base flow index (Melles et al., 2013). The localized groundwater discharges that are often associated with critical habitats for fish spawning and thermal refugia are more difficult to map using large-scale tools such as remote sensing or basin-scale models. Identifying and mapping these features in the GLB likely requires a coordinated effort of collecting local knowledge from landowners, conservation authorities, anglers, etc.

To prioritize conservation efforts, groundwater-dependent aquatic habitats need to be assessed with respect to their vulnerability to environmental change. To be effective for predicting impacts to groundwater-dependent ecosystems and assessing vulnerability, groundwater-surface water models need to be integrated with other ecosystem models and other tools to understand the physical, hydrologic, hydraulic, and chemical influence of groundwater on aquatic habitats more accurately. Several recent studies demonstrate progress toward evaluating the vulnerability of wetland and stream ecosystems to various stressors. Bourgeau-Chavez et al. (2015) used remote sensing techniques to map and classify coastal wetlands for the entire GLB. In addition, they identified adjacent land use for assessment as a potential wetland stressor. Danz et al. (2007) developed a cumulative stress index for the USA side of the GLB that integrates multiple anthropogenic stressors and can be used to identify vulnerable ecosystems and guide protection and mitigation efforts. Uzarski et al. (2017, 2019) presented standardized methods and indicators for assessing coastal wetland conditions across the GLB. This ecosystem approach uses indicators including fish, macroinvertebrates, water quality, and vegetation and therefore may be useful in its current or a modified form for assessing the condition of groundwater-dependent ecosystems specifically and their potential vulnerability. Condon & Maxwell (2019) used an integrated hydrological model that simulates the impacts of groundwater pumping and long-term storage declines on streamflow and evapotranspiration across a large part of the continental USA, including most of the USA and Canadian portions of the Great Lakes basin. Persaud et al. (2020) investigated the impact of future climatic forcing on groundwater and surface water in a Great Lakes basin. Kath et al. (2018) presented a conceptual framework for assessing the ecological responses associated with stressors that impact groundwater (e.g., water extraction or climate change). Impacts to groundwater-dependent habitats could be one of the ecosystem services assessed using this framework. Although the studies mentioned above are not necessarily focused on groundwater-dependent ecosystems, these databases and large-scale approaches are potentially useful for identifying and assessing groundwater-dependent ecosystems that are vulnerable to changes in groundwater quantity and/or quality or other anthropogenic stressors.

The influence of spatial patterns or patchiness of groundwater discharge to streams and nearshore environments on community structure and ecosystem function is not well known. While there is a fair amount known for groundwater influence on major fishery species, at both the whole stream and patch scale, there is less so for other aquatic species. Recent work on mussel species suggests that groundwater plays a role in their distribution (Rosenberry et al., 2016; Campbell & Prestegaard, 2016). Carlson Mazur et al. (2020) and Wilcox et al. (2020a,b) investigated how variation in hydrogeology and landform morphology affect plant community composition in two Great Lakes coastal wetland complexes.

In recent years, there has also been greater interest in better understanding the stream sediment as an important component of habitat in aquatic ecosystems. Sediments can potentially get exposure to groundwater and surface water contaminants. Peralta-Maraver et al. (2018) recently demonstrated that the hyporheos (subsurface groundwater transition zone) can be distinguished from the benthic as a discrete community with ecological integrity, but the boundary can vary with time based on dynamic hydrological conditions.

In addition to studies in the Great Lakes basin, there are studies done elsewhere in North America that have relevance with respect to understanding the ecology of groundwater-dependent ecosystems and assessing their vulnerability to stressors. Several studies have investigated the relationship between groundwater discharge and fish spawning habitat. For example, Briggs et al. (2018) examined a two km stretch of the Quashnet River, Massachusetts, and found that brook trout preferred to spawn in areas where the groundwater discharge resulted from relatively shallow flow paths and therefore avoided organic matter buried in the sediments. This oxygen-rich groundwater from localized groundwater flow paths was more critical in defining spawning habitat than more regional groundwater sources, although both types of groundwater may be important for maintaining the overall thermal characteristics of streams that make them suitable habitat for various fish assemblages. Larsen & Woelfle-Erskine (2018) also demonstrated that maintaining relatively high groundwater levels in coastal aquifers may be required to protect habitat in intermittent streams used by juvenile coho salmon.

In the Snake Valley of Utah, Grover (2019) examined the relationship between groundwater and surface water levels and the distribution and habitat of two cyprinid fishes in a groundwater spring complex. Groundwater levels were found to explain variations in surface water levels and, consequently, that long-term declines in groundwater levels of only 40cm would eliminate most of the spawning areas, illustrating the critical link between groundwater and aquatic habitat. Perkin et al. (2017) modelled the ecological consequences for stream fish assemblages associated with groundwater pumping from the US High Plains Aquifer. Their work illustrates the loss of streams associated with an increased depth to groundwater and the resulting loss of diversity through the homogenization of fish assemblages.

In the Prairie Pothole Region of the Midwest, Euliss et al. (2014) characterized groundwater flow patterns from discharge to recharge to flow-through. Resultant differences in salinity explained dramatic differences in aquatic macroinvertebrate communities across pothole types that previously had been observed by Euliss et al. (2004).

5.4 Updated priority science needs table

The science needs related to groundwater-dependent habitats in the Great Lakes Basin have some overlap with the science needs identified in other chapters of this report, particularly Chapter 2, *Groundwater-Surface Water Interaction*. For instance, former priority need 5A (Table 5.1) falls within the domain of Chapter 2 but will be valuable for guiding the identification of groundwater-dependent ecosystems as outlined in the former priority need 5B (Table 5.1). The updated science needs related to groundwater-dependent habitats (Table 5.2) have been reduced in number and are more strictly focused on the groundwater - habitat connection, leaving the continued requirement for the mapping of groundwater discharge to Chapter 2 of this updated report.

Table 5.2 Updated priority science needs related to aquatic habitats.

Priority Science Needs	**Related needs and information gaps**
5A. Groundwater models that allow characterization of spatial patterns and rates for groundwater recharge and discharge to surface waters.	• Compile and integrate monitoring data and modelling tools. • Use modeling capabilities to characterize and map groundwater recharge and discharge at regional and local scales.

5B. Integrate or align groundwater discharge models with models that control other groundwater-dependent ecosystem attributes.	● Integrated groundwater/surface water models toward a better understanding of groundwater dependent habitats at regional and local scales. ● Modelling needs include nearshore hydrodynamic models and hydrologic and thermal models for inland groundwater-dependent ecosystems (rivers, wetlands, lakes).
5C. Determine the influence of groundwater discharge (quantity and quality) on groundwater-dependent ecosystem attributes and species distributions.	● Build on existing, sub-regional knowledge of groundwater's influence on ecosystem attributes that impact habitat availability and suitability. ● Examine the role of groundwater in determining the effects of future climate change on biotic communities, especially wetlands. ● Improve understanding of the influence of nearshore groundwater discharge on Great Lakes coastal habitats and species distributions. ● Continued work on fish species, but expanded to other aquatic biota that have received less attention to date (e.g., freshwater mussels, vegetation).
5D. Classify and map groundwater-dependent ecosystems across the basin.	● Map and classify groundwater-dependent ecosystems across the basin. ● Classification system must be basin-wide, hierarchical, and aid in the assessment of groundwater-dependent ecosystem sensitivity. ● Assess sensitivity of groundwater-dependent ecosystems to groundwater variation due to climate change, land use change, and other stressors.

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6 URBAN GROUNDWATER ISSUES RELATED TO GREAT LAKES WATER QUALITY

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6.1 Introduction

This chapter is a follow-up and update to Chapter 6 in the previous Groundwater Annex "state of the science" report entitled "Effects of urban development on groundwater" (K. Warner et al., 2016). The main purpose of this chapter is to revisit the priority science needs identified in that chapter (Table 6.1) and to identify any new developments related to these science needs, based on new research published in scientific journals, or based upon initiatives/programs undertaken by water management agencies. The second purpose is to identify any other priority science needs that either were not mentioned in the 2016 report or have arisen as new priorities since that report.

Table 6.1 Priority science needs identified in 2016 report (Warner et al., 2016).

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

Priority Science Needs	Related needs and information gaps
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

Water management was mentioned twice in the list of priority science needs that Warner et al. (2016) compiled (Table 6.1), specifically management of groundwater (6A) and stormwater (6F). This emphasis was appropriate given that cities are places where water management needs are particularly evident and where resources dedicated to water management tend to be highly concentrated. Management of urban water is largely science- and engineering-based, so it naturally becomes a priority to identify science gaps directly related to water management practices and approaches and to address these needs with new research.

In urban areas the management of water is especially challenging because of the complex interactions between the various components of the urban water cycle, including precipitation, groundwater, surface water, and stormwater. In urban areas the water cycle has been modified by above- and at-ground infrastructure (buildings, paved surfaces, etc.) and subsurface infrastructure (foundations, tunnels, stormwater and sanitary sewers, water mains), as illustrated in Figures 6.1 and 6.2. With respect to Great Lakes water quality, the management of urban water, including groundwater, is particularly important because cities are focal, densely-populated areas (Figure 6.3) where various anthropogenic stressors affecting water quantity and quality loom especially large (Table 6.2), spotlighting related science needs. For example, most of the Areas of Concern identified under the Great Lakes Water Quality Agreement are in or near urban areas. Some of the largest cities in the Great Lakes Basin are located on shores of the Great Lakes (Figure 6.3), where groundwater discharges directly to and exchanges with shoreline areas. In other cities in the basin, groundwater can indirectly affect the water quality of the Great Lakes, for example by discharging to urban streams that flow to the Great Lakes.

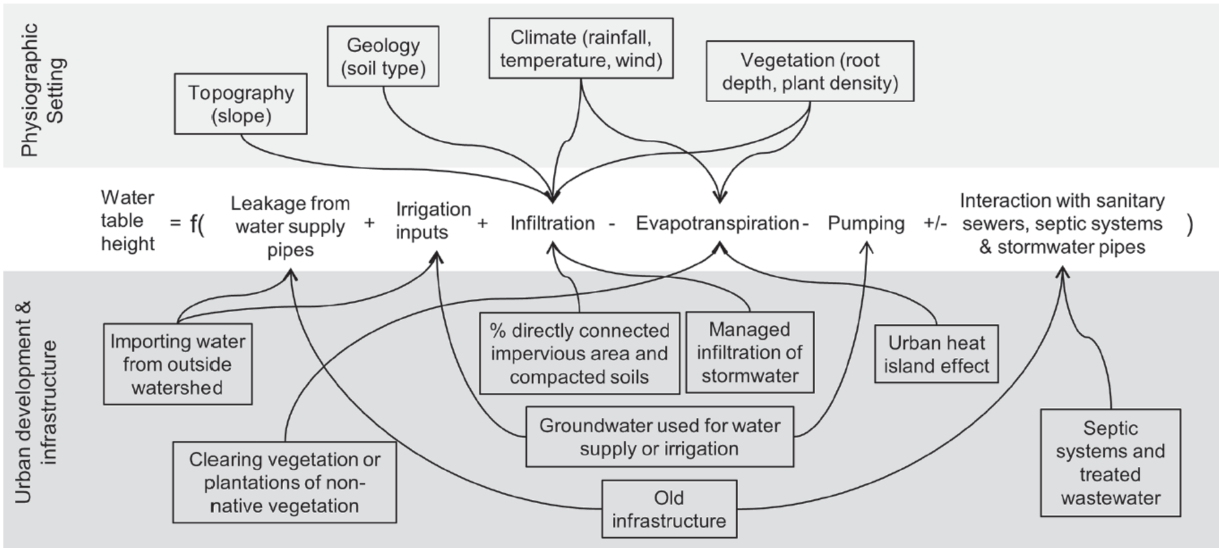

Figure 6.1 Urban water cycle (from Bhaskar et al., 2016).

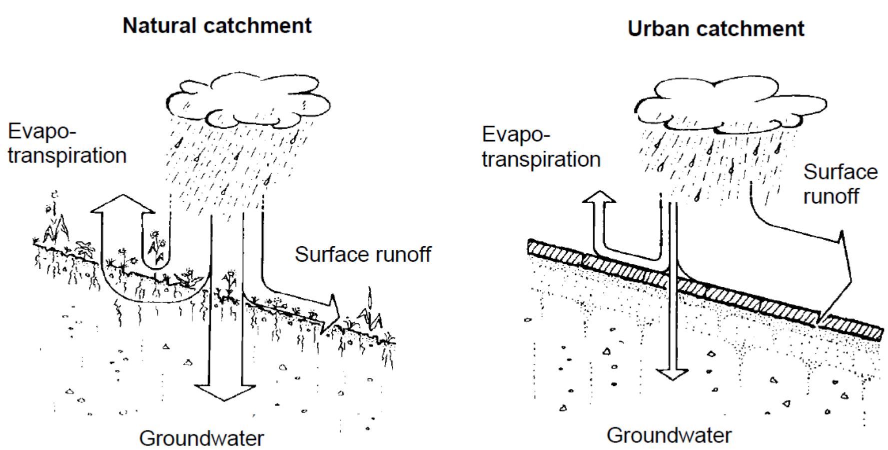

Figure 6.2 Illustration of water balance changes due to urbanization (from Sokac, 2019).

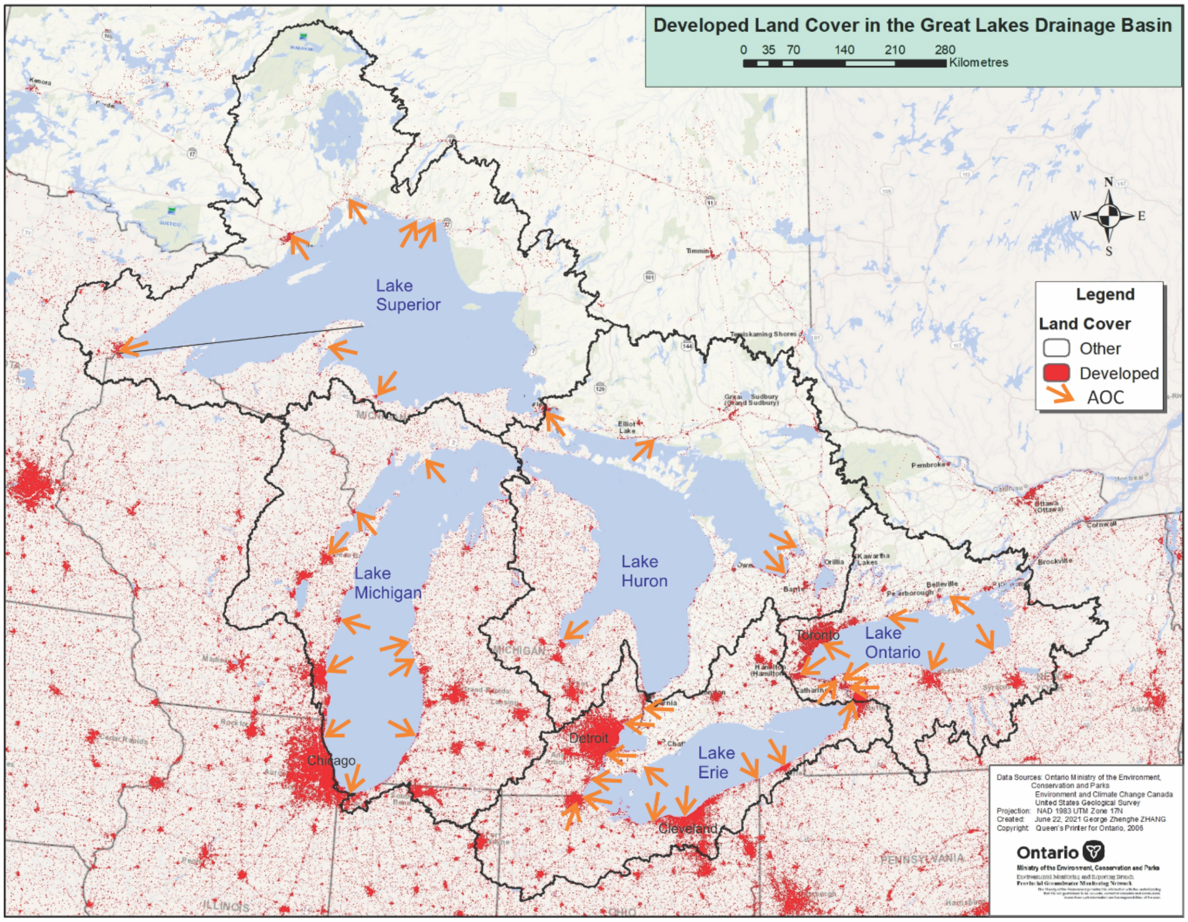

Figure 6.3 Developed areas in the Great Lakes Basin (largely urban). Note that many of the Areas of Concern occur in the developed areas.

Table 6.2 Examples of stressors related to groundwater that tend to be magnified in urban areas*.

Water cycle disrupted by changes to water fluxes: irrigation, sewer leakages, water line leakages, impervious surfaces, infiltration galleries, dewatering, etc.
Relatively high loading of contaminants to groundwater, such as road salt applications, industrial sites, spills, leaks from a variety of sources (Warner et al., 2016)
Relatively high nutrient loading by leaking sewers, fertilizers, etc.

Aquatic ecosystems / habitats (streams, wetlands, lakeshores) are severely disrupted / altered and sometimes completely changed or even removed in urban areas
Alteration of temperatures of streams due to changes/disruption of water cycle and by thermal pollution (heating of groundwater from geothermal systems, removal of streamside vegetative cover and other sources)

*especially relative to undeveloped areas, some of these are also magnified in rural areas (e.g., irrigation, nutrient loading)

6.2 Updated status on priority science needs

A common theme in recent studies of urban hydrology is how urban water, including groundwater, is affected by various urban infrastructure components: paved surfaces, water pipes, sewers, buildings, tunnels, stormwater systems, etc. (e.g., Figures 6.1, 6.2). In the context of urban hydrology, recent studies have often pointed to the interactive relations between urban groundwater, sanitary sewers, and stormwater systems. These relations are intertwined and relevant to all six of the Priority Science Needs identified in Table 6.1 (6A to 6F). Although not identified as a separate or new Priority Science Need, in Sections 6.2.1 and 6.2.2 we provide an update (post 2016 science developments: research, policies, etc.) on this overlapping urban-groundwater-infrastructure theme. It is important to note that although Sections 6.2.1 and 6.2.2 capture new developments that touch on many of the earlier identified Priority Science Needs, other science developments specifically related to the previously identified science needs 6A to 6E (from Table 6.1) are subsequently presented in Section 6.2.3. Science need 6F ("Monitoring and research on stormwater management and dewatering") is completely covered in the following overlapping-theme sections.

6.2.1 Gaps in understanding relationships between groundwater and urban infrastructure

Recent publications document a growing global awareness of a need to better understand urban groundwater. Some of the drivers are: (i) increased use of stormwater infiltration systems, which impact urban groundwater (Bhaskar et al., 2018; Bonneau et al., 2017; Pinasseau et al., 2020); (ii) increasing awareness about a need to understand urban groundwater in order to make decisions about subsurface infrastructure projects (Attard, Rossier, & Eisenlohr, 2016; Attard, Rossier, Winiarski, et al., 2016), (iii) needs to understand chronic or emerging problems such as region-wide flooding of basements (Shepley et al., 2020).

Science updates related to impacts of urbanization on Water Budgets/Hydrologic Cycle

A review of the international literature provided a summary of numerous urban impacts to the hydrologic cycle (McGrane, 2016). Specifically, the author noted studies quantifying both increases and decreases in infiltration due to green infrastructure and impervious surfaces. He also noted quantification of sewer network infiltration and exfiltration, which can change sewer flow by more than 50%. The spatial expanse, age and integrity of the sewer infrastructure are the primary factors determining the degree of subsurface exchange/flow to/from sewers (McGrane, 2016).

Recent research is showing the dominant role of relatively shallow and young groundwater contributing to baseflow in streams (Berghuijs & Kirchner, 2017; Jasechko et al., 2016), including urban streams (Grande et al., 2020). This tendency may be amplified in the subsurface of urban environments, given the presence of complex networks of drains, pipes, and tunnels that provide large permeable channels (commonly referred to as ‘urban karst’), which enhance the shallow, lateral flow of groundwater (Shepley et al., 2020; Warner et al., 2016). In support of this concept, using water $\delta^{18}O$ data, Bonneau et al. (2018) found evidence that the groundwater discharging to streams in an urban catchment had a shorter residence time in the subsurface compared to groundwater draining to streams in the adjacent forested catchment. Similarly, in a study of an urban catchment in the Great Lakes Basin (New York), Slosson et al. (2021) found evidence that increased “impervious” surface cover and “disconnection” of stream corridors from riparian groundwater by construction of “channelized, armored banks” resulted in delivery of chloride loads closer to de-icing salt application rates, and 50% higher compared to loads in “intact” reaches.

In a recent review, Bonneau et al. (2017) noted that, in spite of some recent progress, little is known about how infiltrated water travels along subsurface urban karst pathways. In a study in Mississauga, Ontario (near Toronto), Shepley et al. (2020) found that the surficial glacial till deposit acts as an aquitard, constraining shallow groundwater flow and storm sewer system exfiltration to permeable fill in the utility trenches. This severe urban karst effect resulted in unintended flow from “surcharged” storm sewer trenches into foundation drainage collector systems resulting in widespread basement flooding. In contrast, (Attard, Rossier, & Eisenlohr, 2016; Attard, Rossier, Winiarski, et al., 2016) observed that other structures that are installed in subsurface urban environments (e.g., foundations) do not enhance groundwater flow, but have the opposite effect, acting as hydraulic barriers. A take-away message from these studies is that, in addition to the natural complexity of the subsurface environment, anthropogenic elements add further complexity. As a result, research lessons learned in one urban area in the Great Lakes Basin may not be readily applied to other urban areas with different subsurface conditions. This indicates a need for studies and collection of localized subsurface data in each urban area. Several international studies have quantified subsurface flows in cities (Table 6.11). For example, in Brussels, Belgium, a study used a data-mining analysis of sewer infiltration patterns to determine seasonal characteristics of water seepage into main sewers, and seepage improvements after sewer repairs (de Ville et al., 2017). A case study of Hue, Vietnam, developed a water budget to quantify exfiltration and infiltration effects on sewage flow and quality, and found substantial flows and substantial seasonal differences (Watanabe & Harada, 2019). The City of Pezinok, Slovakia, a small urban area, was used for a case study to quantify a full water budget, including detailed data for infiltration and exfiltration associated with both water supply pipes and sewers to and from groundwater (Sokac, 2019). And finally, a study of a 40-year period of land use changes in Perth, Australia, was used to quantify the hydrologic impact of urbanization with extensive stormwater infiltration, using groundwater level observations from an urban catchment (Locatelli et al., 2017).

Table 6.3 Urban water cycle studies outside of the Great Lakes basin.

Focus of Study	Study location	Reference
Impacts of Development Pattern on Urban Groundwater Flow Regime	Baltimore County, Maryland, USA	(Barnes et al., 2018)
Will it rise or will it fall? Managing the complex effects of urbanization on base flow	Perth, Western Australia; Baltimore, Maryland, USA	(Bhaskar, Beesley, et al., 2016)
Evaluation of infiltration-based stormwater management to restore hydrological processes in urban headwater streams	Maryland, USA	(Fanelli et al., 2017)
Physically based modeling of stormwater pipe leakage in an urban catchment	A northern German city	(Peche et al., 2019); (Peche et al., 2019)
Using Remote Sensing Based Metrics to Quantify the Hydrological Response in a City	Brussels capital region, Belgium	(Wirion et al., 2019)

An earlier study in Basel, Switzerland (Epting et al., 2008), relied on comprehensive modelling within an urban setting to evaluate and mitigate potential impacts of road tunneling construction on the groundwater flow regime, both in the short term (e.g., construction dewatering) and in the longer term (e.g., emplacement of impervious subsurface facilities (e.g., cutoff walls, tunnels, etc. that lead to long standing groundwater flow diversions). With groundwater being utilized by many industries, the existing urban data available were supplemented with construction-related monitoring wells and pumping tests, to parameterize the model. The study demonstrated the successful use of numerical modelling in a complex, spatially and temporally variable urban setting, to push construction activities in specific directions to minimize negative construction impacts on groundwater resources.

Science updates related to groundwater and sewers

Recent studies of the relationship of urban groundwater and sewers are particularly relevant for Great Lakes cities given that most of the sewer systems are old and prone to significant leakage. For example, the American Society of Civil Engineers (ASCE) 2017 Infrastructure Report Card indicates that wastewater infrastructure (e.g., sewer pipes) is aging, in poor condition, and leaking. A 1989 exfiltration report by EPA showed a 30-50% flow loss at a time when ASCE rated the sewer infrastructure as “C” (mediocre) condition. The 2017 sewer infrastructure grade was decreased to “D+” (poor) by ASCE, indicating likely higher exfiltration rates. Wastewater grades for the Great Lakes states specifically ranged from C to D- (American Society of Civil Engineers, 2017).

Several recent field studies have documented substantial infiltration of groundwater to sanitary, combined or storm sewers (Table 6.4). An approach based on detailed monitoring of various components of the urban water cycle, including sewer flows, precipitation, and groundwater levels was recently applied in Denmark (Thorndahl et al., 2016). Others used tracers, dissolved silica (Maguire & Fulweiler, 2016), the artificial sweetener acesulfame, or the stable isotope composition ($\delta^{18}O$) of water (Penckwitt et al., 2016) to probe the influx of groundwater to storm sewers or combined sewers. Consistently, these studies found evidence for significant rates of infiltration of groundwater to sewers. Some authors inferred that large fractions of water in sewers were derived from groundwater (Table 6.4).

Table 6.4 Summary of recent studies on infiltration of groundwater to urban sewers.

Focus of study	Type of sewer*	Inferred fraction of groundwater	Location	Reference
Dissolved silica as a tracer of groundwater infiltration	CSS	39%	Boston, MA	(Maguire & Fulweiler, 2016)
Flow measurements, modeling of groundwater infiltration	SAS, CSS	Average 23-48%	Denmark	(Thorndahl et al., 2016)
Stable isotope ($\delta^{18}O$) of water as tracer of groundwater infiltration	SAS	Up to 41%	Germany	(Penckwitt et al., 2016)
Flow measurements that demonstrated groundwater infiltration	CSS	Not provided	Detroit, MI	(Hoard et al., 2020)
Dilution of artificial sweetener acesulfame as tracer of groundwater infiltration	SAS	Not provided	China	(Zhao et al., 2020)

*CSS = combined storm/sanitary sewers, SAS = sanitary sewers, STS = storm sewer

Hoard et al. (2020) found substantial water transfers in a full water-cycle monitoring study in a small sewershed in Detroit, Michigan. They inferred groundwater flow into a leaky combined sewer system based on detailed monitoring of sewer flows, precipitation, and groundwater levels. They found that full urban water-cycle monitoring (all surface and subsurface inputs and outflows) is crucial to understanding how stormwater control measures influence flows to receiving waters. For example, their study showed that change in groundwater storage can play a major role in increasing the dry-weather flow in sewer conveyances due to high groundwater tables relative to the elevation of these pipes, which allow a substantial amount of infiltration and exfiltration. Flows within the sewer indicate an unexpected exchange of water between the leaky sewer and the groundwater system, pathways through abandoned or failing residential infrastructure, or a combination of both.

Understanding the position of the sewer infrastructure relative to the saturated groundwater table is also key to elucidating which parts of the sewer network might be losing water to the groundwater system (i.e., those parts above the water table). Sewers below the water table can gain volume from groundwater infiltration into the system, increasing wastewater treatment volumes and costs (The Regional Municipality of York, 2020). Results from a study in Buffalo, New York, indicate that vacant lands citywide may cumulatively infiltrate 51–54% additional annual rainfall volume compared to pre-demolition state. The findings illustrate that vacant lots as purposeful landscapes can reduce water fluxes into aging wastewater infrastructure by increased recharge to groundwater (Kelleher et al., 2020).

While recent attention on groundwater-sewer relations has often focused on groundwater infiltration into sewers (above), some recent studies have probed the reverse process, exfiltration (leakage) from sewers to groundwater. The exfiltration process is particularly relevant to the contaminant-related mandate of this chapter, probing the relationship of urban groundwater and Great Lakes water quality.

Timely reviews have been provided on modeling of sewer exfiltration to urban groundwater (Nguyen et al. 2021) and prediction of sewer pipe condition (Mohammadi et al., 2018). Of particular relevance to this report, Nguyen et al. (2021) identified the following research needs: (a) better understanding of "core processes" of sewer exfiltration at the pipe scale and of "transport and transformation processes" of sewer leakage into subsurface geological units; (b) the need to advance modeling of the fate and behavior of a wide range of sewage-derived contaminants in groundwater; and (c) challenges in up-scaling models from pipe/local scale to city or sewer network scale. Earlier reviews of sewer exfiltration (Reynolds & Barrett, 2003; M. Rutsch et al., 2008; Mandy Rutsch et al., 2006) provide useful context, as do other more recent summaries of relevant information (Ali & Choi, 2019; Lauwo et al., 2012; Raney, 2020).

Various post-2016 publications have reported new methods to measure or model sewer exfiltration. Most of the studies have been conducted outside of the Great Lakes basin (Table 6.5). In a modeling study, Peche et al. (2019) demonstrated that defects in sanitary sewers can result in significant leakage: depending on local conditions, either infiltration of groundwater into the sewers, or exfiltration of sewage to groundwater. Researchers in California developed a model of sewer exfiltration probability based on sewer pipe attributes and groundwater elevation (Lee et al., 2015; Roehrdanz et al., 2017). They found that this model could predict the probable occurrence of various wastewater indicators (Table 6.5) in underlying shallow urban groundwater. The indicator concentrations in groundwater were generally less than 1% of the sewage concentrations (Lee et al., 2015), suggesting similar fractions of sewage contribution to the groundwater. Shepley et al. (2020) used monitoring wells and dye tracing to probe flow from storm sewers to groundwater. Ishii et al. (2021) reported that the artificial sweetener acesulfame was an excellent tracer for evaluating sewer exfiltration to groundwater. Analyses of tracers in groundwater in a city in Ukraine (Vystavna et al., 2018) showed that the impact of sewer leakage was highly variable from site to site, with sewage contributing up to 29% of the groundwater. Notably, 7 of the 17 samples indicated ≥13% sewage contribution to the groundwater. Results of a study in Germany (Nguyen and Venohr, 2021) estimated an average exfiltration rate of ~1 mm per m of sewer pipe per year, with highest rates of exfiltration in regions with older sewers (> 40 years). They estimated that sewer exfiltration accounted for 9.8% and 17.2% of nitrate and phosphate loads from urban systems emitted to the environment, and that these fractions would increase with ageing of sewers.

Table 6.5 Studies on exfiltration from sanitary sewers to groundwater.

Focus of study	Study location	Reference
Chemical tracers of sewer leakage to groundwater: artificial sweeteners, tryptophan-like fluorescent, bisphenol A, other organic compounds, dissolved organic matter, nitrate, stable isotope of water ($\delta^{18}O$)	California, USA	(Lee et al., 2015; Roehrdanz et al., 2017)
Tracers (stable isotopes of water, chloride) to estimate rates of leakage of municipal tap water and sewage to groundwater	Ukraine	(Vystavna et al., 2018)
Chemical tracer of sewer leakage to groundwater: artificial sweetener acesulfame	Japan	(Ishii et al., 2021)
An integrated assessment approach to prevent risk of sewer exfiltration	Edmonton, Canada	(Kaddouraa & Zayed, 2018)
Physically based modeling of stormwater pipe leakage in an urban catchment	Germany	(Peche et al., 2019); (Peche et al., 2019)
Assessment of nutrient pollution from urban systems including sewer exfiltration	Germany	(Nguyen and Venohr, 2021)
A review of modeling of sewer exfiltration	-	(Nguyen et al., 2021)

Recent relevant policy/program developments in Great Lakes Basin related to relationships between groundwater and sewers

In their "Guide for Estimating Infiltration and Inflow", the US EPA (2014) defined three major components of wastewater flow in a sanitary sewer system: "base sanitary (or wastewater) flow, groundwater infiltration and rainfall derived inflow and infiltration, more commonly referred to as inflow" (US EPA, 2014). Various municipalities in Ontario have recently developed policies and programs to reduce infiltration of groundwater and inflow (rainwater and snow melt) to sanitary sewers (e.g., The Regional Municipality of York., 2020). They have also supported efforts to develop "best practices" to manage this infiltration and inflow (Kesik, 2015). These programs have resulted in various activities, such as rehabilitation and replacement of sewers and sewer connections, and disconnection of downspouts, weeping tiles, sump pumps, and other structures from sanitary sewers, and establishment of localized (micro-basin) monitoring to support these infiltration reduction efforts (e.g., The Regional Municipality of York, 2020).

In this review, no information was found on recent (post 2016) policy, practice and program developments by the various levels of government (including municipalities) in the Great Lakes Basin directly related to quantifying leakage from municipal sanitary sewers, or to quantifying fluxes of contaminants from urban sources, such as stormwater and leaking sewers, to groundwater. Rather, leaks from sewers are addressed on a case by case basis when they are discovered.

Various levels of government in the Great Lakes Basin provide "guidance" or "standards" on leak testing of sewers (e.g., Michigan Department of Transportation, 2020; Ontario Ministry of the Environment, 2008; Pennsylvania Department of Environmental Protection, 2017; Wong & Kerkez, 2018). However, the testing that is described in such guidance documents is for one-time detection of leaks, not for quantifying ongoing rates of exfiltration from sewers to groundwater. Consequently, it appears that there are no government-based data on sewer leakage rates in the basin, either for older existing systems or newly constructed ones. Nor does there appear to have been any recent policy developments related to quantifying the frequency or risk of sanitary sewer exfiltration or examining factors contributing to exfiltration.

Related health risk impacts associated with groundwater quality

It is increasingly evident that sewer exfiltration poses a significant threat of rising levels of toxic substances and microbial pollution in urban groundwater (Nguyen et al., 2021). Urban modifications to the near-surface zone in particular, impact contaminant exposure pathways by potentially shortening travel distances and hydraulic retention times in shallow groundwater (Voisin et al., 2018; Zhang & Chui, 2019). Regional pipe networks, which are considered critical health infrastructure (Clarke et al., 2017), are the primary method of transporting water in urban centers in the Great Lakes Basin. The exchange of groundwater and sewer water along sewer corridors presents both chemical and biological hazards (Peche et al., 2017, 2019). Assessing shallow hydrologic changes due to sewer pipe presence and subsurface fill is critical for determining subsurface pollutant risk (McGrane, 2016). Improved understanding of shallow water table fluctuations is a practical means to infer subsurface flow patterns and will contribute to understanding subsurface pollutant movement (Yang et al., 2018).

Urban sewer lines represent an exposure pathway for vapor intrusion into buildings, which is often neglected in vapor intrusion conceptual site models (Eklund et al., 2012; Ma et al., 2020; McHugh et al., 2017). In addition to vapor transport directly through the headspace in a pipeline, McHugh et al. (2017) noted that leaking sewer pipes alongside basements or subfloors can transmit vapors across the entire length of the pipes. Due to the potential for vapor transport in the headspace of a pipe or through the fill material surrounding pipes, sewer lines that intersect the groundwater have a higher vapor intrusion risk. Sewer vapor testing is recommended as part of the conceptual site model at these higher-risk locations. Therefore, the proximity of the water table to a sewer line is a key variable in prioritizing vapor intrusion risk.

6.2.2 Groundwater–green infrastructure relations

Research on urban stormwater management and green infrastructure

Within the Great Lakes Watershed, the urban area of Cleveland, Ohio, has been an active region of green stormwater infrastructure (GSI) research. Several recent studies report on results in the West Creek watershed, a tributary to the Cuyahoga River, which discharges to Lake Erie. One study reported that GSI resulted in increased infiltration 7.6%, based on measurements and a model of the hydrologic cycle (Avellaneda et al., 2017). Another study documented that stormflow peaks and total discharge can be reduced by certain types of street retrofit with green infrastructure that promotes infiltration of stormwater (Jarden et al., 2016). Control measures that infiltrate stormwater, for example rain gardens, result in increased stream baseflow and decreased runoff (Avellaneda & Jefferson, 2020). Two intensively studied rain gardens showed substantial infiltration and evapotranspiration of stormwater (Shuster & Darner, 2018). The efficacy of a water balance model in an urban environment (DRAINMOD-Urban) has also been tested, and results illustrate hydrologic conditions where the model does and does not work well (Lisenbee et al., 2020). Full water cycle monitoring and a model of an unlined bioretention cell were used to quantify the 'recoupling' of the surface and subsurface hydrology (Stewart et al., 2017). A study of bioretention cells allowed quantification of runoff reduction and increased infiltration and evapotranspiration (Winston et al., 2016).

A study of permeable pavement and underground stormwater harvesting system in Huron, Ohio, illustrated significant peak stormwater volume and peak flow rate decreases (Winston et al., 2020). The performance of low impact development practices, specifically permeable pavement and an underdrain, were evaluated with measurements and models for a site in Ontario, Canada, and a site in Kitsap County, Washington. Measurable groundwater table fluctuations and flow in the underdrain resulted from rainfall events, and relations between rainfall magnitude and expected water table and flows were developed (Zhang & Chui, 2018); relations between rainfall, water table fluctuation, and underdrain flows varied with statistical analysis technique.

Some examples of GSI studies outside of the Great Lakes Basin are provided in Table 6.6, and a few examples are summarized here. A study of permeable pavement performance near Montreal, Canada, showed significant peak flow delays and runoff reductions (Vaillancourt et al., 2019). A stormwater management review paper noted that studies tend to focus on peak flows and flow volumes, but groundwater components (baseflow and recharge) receive less attention and quantification (Jefferson et al., 2017). The effect of stormwater infiltration at several scales was examined in the context of base flow, with authors concluding that the effect of infiltration on stream baseflow was ambiguous due to unknowns about subsurface water movement. Potential groundwater movement through urban karst described as the high-permeability channels and trenches that house underground utilities, creates challenges for linking catchment-scale stormwater infiltration to stream base flow (Bonneau et al., 2017). Evapotranspiration associated with green infrastructure vegetation is still poorly estimated (Thom et al., 2020).

Table 6.6 Green infrastructure studies outside of the Great Lakes basin.

Focus of study	**Study location**	**Reference**
Hydrologic performance of permeable pavement	Montreal, Canada	(Vaillancourt et al., 2019)
Review of 100 stormwater management studies	Various, international	(Jefferson et al., 2017)
Review of stormwater infiltration in the urban environment	Various, international	(Bonneau et al., 2017)
Stormwater infiltration flow path	Melbourne, Australia	(Bonneau, Fletcher, et al., 2018)
Low impact development and base flow	Clarksburg, Maryland USA	(Bhaskar, Hogan, et al., 2016)
Review of low impact development modeling tools	Models, no location	(Kaykhosravi et al., 2018)
Tree transpiration and stormwater control measures	Melbourne, Australia	(Thom et al., 2020)
Potential for contamination of urban groundwater by a stormwater infiltration system	Minnesota, USA	(de Lambert et al., 2021)

Focus of study	Study location	Reference
Comparison of stormwater infiltration from drywells and infiltration basins	Models, no location	Sasidharan et al., 2021)

In their review, Bonneau et al. (2017) reported a knowledge gap related to the effects of stormwater infiltration on groundwater recharge and baseflow in urban streams. Bhaskar, Hogan, et al. (2016) found that new urban development in a watershed in Maryland, USA which included stormwater infiltration systems ('low impact development') had increased total streamflow and base flow compared with control (forest and agriculture) watersheds. This was likely the result of reduced evapotranspiration and increases in point sources of recharge, a water balance shift that was an "unintended consequence" of the 'low impact development' (Bhaskar, Hogan, et al., 2016). In a follow-up study, Bhaskar et al. (2018) looked at fluctuations in the water table in the same urbanized watershed, noting some increased water table levels downgradient of stormwater infiltration locations. They concluded, however, that it is not straightforward to connect infiltration-based stormwater management and groundwater recharge (Bhaskar et al., 2018). A holistic study of the subsurface movement of infiltrated stormwater illustrated the complexities and challenge to make prediction of base flow effects (Bonneau, Fletcher, et al., 2018). In contrast, a study in Clarksburg, Maryland, documented the influence of low-impact development (GSI) practices on base flow (Bhaskar, Hogan, et al., 2016). A review of 11 low impact development modeling tools illustrated deficiencies in available tools, noting that all of the reviewed models require improvement in water balance calculations, especially in accounting for evapotranspiration and infiltration (Kaykhosravi et al., 2018). In a study in Australia, Locatelli et al. (2017) found that urban development with stormwater infiltration resulted in an increase in groundwater recharge, a decrease in evapotranspiration, a rise in the water table, and an increased risk of groundwater seepage "above terrain."

de Lambert et al. (2021) investigated the potential for contamination of urban groundwater by a stormwater infiltration system. They found that the number and concentrations of contaminants (viruses, other pathogens, pharmaceuticals, personal care products, etc.) in the groundwater were greatly reduced compared to samples of stormwater and vadose water sampled beneath the infiltration gallery. A study in France (Lebon et al., 2021) found significant differences in dissolved organic carbon, nutrient concentrations, biofilm biomass, and bacterial community structures in groundwater sampled downgradient of stormwater infiltration systems compared to groundwater sampled upgradient of these systems. Increased microbial activities, bacterial richness, and diversity in groundwater biofilms were observed downgradient during a rainy period, but not during a dry period.

Other recent studies have indirectly examined the relations between stormwater and groundwater. For example, Masoner et al. (2019) collected samples of urban stormwater from 21 sites across the United States, including the Great Lakes region. They found that stormwater transports substantial quantities of mixtures of organic contaminants, including polycyclic aromatic hydrocarbons, pesticides, pharmaceuticals, and other chemicals, that potentially impact both groundwater and surface water. Similarly, Spahr et al. (2020) provided a review of the occurrence of hydrophilic trace organic contaminants (e.g., pesticides, plasticizers, flame retardants) in urban stormwater. Masoner et al. (2019) stated that their study highlighted the continuing need for studies of the fate, transport, and persistence of stormwater contaminants that are infiltrated to groundwater. Pinasseau et al. (2020) found higher concentrations of some organic chemicals (e.g., carbendazim, diuron) in groundwater influenced by stormwater infiltration; in contrast, some legacy contaminants (e.g., herbicides atrazine and simazine) in groundwater were diluted by the same stormwater infiltration. Bork et al. (2021) reported that stormwater infiltration systems pose a risk for pollution of urban groundwater by commonly used biocides.

Related impacts on water quality and health

Interest in implementing GSI has been increasing, but certain water quality and flooding concerns have been noted (Prudencio & Null, 2018). GSI allows stormwater to infiltrate over time but has the potential to introduce pollutants into the groundwater (Jalali & Rabotyagov, 2020). This concern is especially important for urban areas with shallow groundwater tables. Zhang & Chui (2018) provided a recommended distance to the water table of at least 1.5 to 3 meters below the bottom of bioretention cells to minimize the height of groundwater mounds formed. To understand the impact of GSI on groundwater dynamics, multiscale models are recommended (Zhang & Chui, 2018). Proper placement of GSI will help mitigate flooding within urban neighborhoods. Steis Thorsby et al. (2020) found that GSI placement at the upstream end of the storm sewer system generated the largest reduction in flooding into homes. GSI is an important tool in managing stormwater, but there is a need for understanding the tradeoffs of groundwater storage versus the public health concerns related to the potential for flooding and groundwater quality problems.

Relevant policy, practice and program developments by various levels of government

Green infrastructure can direct storm runoff into groundwater via enhanced infiltration or other methods. A 2018 review compared long-term control plans used by 25 U.S. cities to quantify the types of gray and green infrastructure (GSI) being used by communities to address various stormwater-related problems, including combined sewer overflow. Key factors for adopting green infrastructure included metrics related to the governance of stormwater management. Five “green leader” cities—those that dedicated >20% of the control plan budget to green infrastructure – were identified, and three of the green leader cities are in the Great Lakes Basin: Milwaukee, Wisconsin, Syracuse, New York, and Buffalo, New York. The study found that the most important factor was the ability to take advantage of a “policy window” to incorporate green infrastructure into stormwater plans. Over long periods of time, green leader cities have built momentum for green infrastructure through a series of phases. The phases have included experimentation, demonstration, and finally full transition to approaches to manage combined sewer overflow. (Hopkins et al., 2018).

An analysis of policies and data from Onondaga County, New York, (Syracuse area) illustrated that participatory governance with strong citizen influence and engagement can increase green infrastructure. Incentives combined with outreach policies can play an important role when regulatory instruments are absent (Lieberherr & Green, 2018). The "Gray to Green" (G2G) scenario planning tool provides a structure to facilitate conversations and actions to incorporate urban forest and green infrastructure planning into stormwater management. Two case studies (Milwaukee, Wisconsin, and Tampa, Florida) illustrate the application of the planning scenario tool, which quantified benefits of different stormwater management practices (Tsegaye et al., 2019).

In Canada, the water component (partnership of several Conservation Authorities in Ontario) of the Sustainable Technologies Evaluation Program (STEP, https://sustainabletechnologies.ca) has conducted various projects related to GSI. This has included various research, technology evaluation, and monitoring projects, and it has generated guidance documents, for example, the Low Impact Development Stormwater Management Planning and Design Guide (Credit Valley Conservation Authority, Toronto and Region Conservation Authority, 2011). Based on information posted on the STEP website, there are no current projects that focus specifically on understanding linkages between GSI and groundwater.

Although there have been numerous recent studies related to stormwater and green infrastructure, the focus has largely been on changes to surface water flows and their metrics, and surface water quality. Studies specifically quantifying groundwater quality or quantity changes are less common. The lack of groundwater information has implications for the Great Lakes basin: (1) quantification of groundwater flux is not a focus of current research, so this science need has not been met; and (2) myriad green infrastructure project studies infer the role of groundwater in mitigating a series of surface water problems. However there has been little investigation into the effect of additional infiltration of stormwater on groundwater quality – or into long-term effects on surface water quality, given that infiltrated stormwater slowly moves through the subsurface to discharge at locations in tributaries or into the Great Lakes directly.

6.3 Previous priority science needs

This section presents science updates for Priority Science Needs identified as 6A to 6E (from Table 6.1). These are presented in Sections 6.2.3.1 through 6.2.3.5; updates for science need 6F is completely covered in Sections 6.2.1 and 6.2.2.

6.3.1 Data Collection and analysis for urban groundwater resource management (6A)

A working group in Europe described the subsurface as being 'out of sight, out of mind' with respect to planning and management, which has resulted in a significant gap in critical knowledge (Mielby & Sandersen, 2017). Gogu et al. (2017) observed that cities struggle because of a lack of detailed, accurate knowledge of the subsurface environment and the interaction between urban infrastructure and urban groundwater. Barnes et al. (2018) pointed out the current lack of access to data on urban groundwater, noting a need for a national database to facilitate efficient and effective interpretative research. Dochartaigh et al. (2019) noted that urban groundwater is often poorly understood and thus overlooked and ineffectively managed, especially in cities with limited groundwater pumping because little groundwater data exist.

Recent publications also document a growing global awareness of a need to better understand urban groundwater (Table 6.7). Progress is particularly evident in Europe, where "Sub-Urban", a European Cooperation in Science and Technology Action was initiated in 2013 to improve the understanding and use of the subsurface urban environment (Campbell et al., 2017). A goal of Sub-Urban is to form relationships between urban subsurface geoscience experts (e.g., national geological agencies, university researchers et al.) and urban decision makers, planners, practitioners (private consultants and contractors), the developers they serve, and the wider research community. As of 2017, Sub-Urban had expanded to include a network of >150 researchers and 23 actively participating cities (Campbell et al., 2017).

Thinking comprehensively about the urban subsurface environment, von der Tann et al. (2018), noted that the subsurface environment offers many services to urban communities (e.g., stability for buildings; providing drinking water and materials; serving as a heat source or retention basin; accommodating infrastructure and development, etc.). They argued that decisions regarding the allocation and management of the urban subsurface, including groundwater, need to be made in a much more comprehensive, integrated manner than is the current widespread practice. Currently, within the Great Lakes Basin, decisions with implications to significantly alter and affect the subsurface environment are typically made on an ad-hoc, case-by-case basis as land-use change development proposals come forward for approval. Typically, subsurface planning is absent from current thinking and practice within the Great Lakes Basin.

These examples illustrate that these science gaps are still national and global issues, not restricted to the Great Lakes Basin (see Table 6.7).

Table 6.7 Examples of cities where research efforts to understand urban groundwater have recently expanded.

Great Lakes Basin	
Toronto and surrounding urban areas, Canada	(Holysh & Gerber, 2014)
Elsewhere	
Glasgow, United Kingdom	(Dochartaigh et al., 2019)
Berlin, Germany	(Frick et al., 2019; Kuhlemann et al., 2020)
Bucharest, Romania	(Gogu et al., 2019)
Milan, Italy	(De Caro et al., 2020)
Barcelona, Spain	(Tubau et al., 2017)
Odense City, Denmark	(Mielby & Sandersen, 2017)

As noted in Warner et al. (2016), most of the larger urban areas within the Great Lakes Basin do not rely upon groundwater as a source of drinking water. As a result, groundwater receives little attention within urban centers across the Great Lakes unless problems arise. Groundwater management within the urban areas of the Great Lakes Basin is largely reactive with very little active 'management' taking place. For example, in the Greater Toronto Area, consultants are retained on an as-needed basis to assist in solving specific urban groundwater problems, for example dewatering for large construction projects or contamination spills/incidents. However, typically, the data and interpretations gleaned from such studies are not synthesized to inform future water management activities. Rather, the reports are stand-alone documents, and the data and knowledge held within them eventually gets lost and forgotten. This lack of consistent groundwater-related monitoring data coupled with generally poor management of the information that does exist, is a common theme, noted in many papers that discuss urban hydrogeology (Dochartaigh et al., 2019; Tubau et al., 2017).

As a result of the reactive approach to groundwater management within the Great Lakes Basin, technical groundwater management staff, including those from provincial, state, and municipal levels, continue to struggle to obtain data with which to characterize, understand, and proactively manage groundwater conditions in urban areas within the Great Lakes Basin.

Given the existing data-poor situation, numerical modelling is likely to become an increasingly critical tool to assist managers to better explore and understand groundwater conditions in urban areas. Models, and the insights gained from them, always benefit from additional data to constrain model inputs. However, even in data-poor areas, with proper verification, validation, and calibration, numerical models can help improve the understanding of urban groundwater systems. Barnes et al. (2018), in their Baltimore, Maryland study, combined a sparse hydrogeological database with higher resolution topographic data (Lidar), land use, vegetation cover, and infrastructure data to explore the role of imperviousness in six different urban subwatersheds. One finding was that variability in subsurface storage was observed to decline as imperviousness within a catchment increased. The finding was attributed to a combination of decreased infiltration and evapotranspiration in the more urbanized catchments. Although the study allowed for the elucidation of broad hydrogeological characteristics, uncertainty in many of the assigned parameters prevents the model from being applied more generally and limits the exploration of more detailed urban groundwater conditions.

A study in Basel, Switzerland, also relied on comprehensive modelling within an urban setting to evaluate and mitigate potential impacts of road tunneling construction on the groundwater flow regime (Epting et al., 2008). The study looked both at short term practices (e.g., construction dewatering) and long term practices (e.g., emplacement of impervious subsurface facilities such as cutoff walls, tunnels, etc. that lead to long standing groundwater flow diversions). With groundwater being used by many industries, the existing available urban data were supplemented with construction-related monitoring wells and pumping tests to parameterize the model. The study demonstrated the successful use of numerical modelling in a complex, spatially, and temporally variable urban setting, to turn construction activities in specific directions to minimize negative impacts to groundwater resources.

On the Canadian side of the Great Lakes Basin, many regional-scale numerical models were completed across broad parts of Ontario, and encapsulate many urban centers (e.g., Toronto, Waterloo, Guelph, Barrie, Newmarket, Brampton, Milton, etc.). These comprehensive numerical modelling studies were undertaken between 2007 and 2015 through the Province's Source Water Protection (SWP) initiative. The studies were a response to the Walkerton tragedy of 2000, in which bacterial contamination from a manure source in one of the town's groundwater supply wells led to severe sickness in some 2000 residents and the death of six people. The SWP models were primarily used to delineate both quality and quantity related wellhead protection areas for municipal supply wells. Often municipal drinking water supply wells are located outside of urban areas, but even where wells are located within an urban area, the delineated wellhead protection area commonly extends outside of urban centers into adjacent rural areas. Although the models are parameterized with only sparse data in urban areas, the models nonetheless provide a regional scale comprehensive assembly of existing data. The models also are a synthesis of the data into an understanding of subsurface geological and hydrogeological conditions. Given the synthesis of regional geology/hydrogeology that has been built into the models, the models present a significant opportunity. If the models are maintained in working condition, then as future data are collected, the models can be refined and updated to shed light on a variety of hydrogeological issues (Marchildon et al., 2017). Some issues that could be further explored include the investigation of interaction between groundwater and sewer infrastructure or urban streams, groundwater quality, and how groundwater connectivity and interaction with the Great Lakes may change over time with climate change.

The numerical models, and the current insights that they have delivered, are already being used for other purposes. One example is the City of Barrie, in the context of their concern for how deep construction activities might affect groundwater quality at municipal supply wells. Using the existing knowledge built into their Source Water Protection Model (Bester, 2013), Barrie recently developed a risk management process to evaluate development proposals and their potential impact on groundwater resources (Martin, 2019).

The Oak Ridges Moraine Groundwater Program (ORMGP) is one innovative program that presents a potential template for how groundwater data can be more effectively managed and made accessible. The ORMGP covers an area of over 30,000 km^2 along the north shore of Lake Ontario, stretching northwards into the Georgian Bay/Lake Huron drainage basin. ORMGP is a joint initiative of 15 local government agencies (municipalities and watershed authorities) and has assembled an 80-gigabyte digital groundwater analysis system of water and geology related data. While much of the program's data, along with interpretive graphing and mapping tools, are available via a freely accessible website, the program also provides an alternative passworded section where technical users can download data directly, see interactive, up-to-date graphing tools (e.g., explore the interaction between climate events and groundwater response), access over 11,000 historical consulting reports, and access numerical groundwater modelling data, files, and insights (e.g., water budget analyses). A central mandate of the ORMGP is to effectively manage a water-related database, which underpins all the knowledge, insights, and understanding of flow systems that eventually lead to robust decision making.

With respect to urban groundwater-related decision making, it is also important to note that the ORMGP is focused not only on the management of data, but also more importantly on the accessibility and use of the data. It is through the use of data, for example in interpolating a regional water table surface, identifying potential groundwater discharge areas or in creating long term hydrographs, that errors in the database can be identified and corrected. Considerable effort is expended on assisting partner agencies with quickly accessing insights from data interpretation to provide input to decision makers (i.e., answering questions such as 'Will the second-floor parking garage require permanent dewatering'?).

Faced with a similar situation as is current practice within the Great Lakes Basin, that is, where groundwater related data are not purposefully nor effectively managed, California and New Mexico recently enacted new legislation to improve their water data management. In 2016 California passed the Open and Transparent Water Data Act (AB 1755, Dodd), which requires eight state agencies to create, operate, and maintain a statewide integrated water data platform and to develop protocols for making the data available to support decision making. New Mexico passed its Water Data Act (NMSA 1978, 72-4B) in 2019 with an aim of identifying and integrating key water data for both groundwater and surface water. In both states, it was recognized that a lack of data and information was limiting the ability to understand and manage water. If enacted within the Great Lakes Basin, similar legislation would advance the need for coordinated, accessible groundwater data.

6.3.2 Quantitative information about contaminant sources (6B)

This science need relates to quantifying sources that contaminate urban groundwater and, in turn, potentially impact Great Lakes water quality. Some recent studies related to this science need are presented above in Sections 6.2.1 and 6.2.2. Specifically, the focus of the few recent (post-2016) studies has been on quantifying exfiltration (leakage) from urban sanitary sewers, as discussed in Section 6.2.1.

A vast array of contaminant sources in urban areas include point sources (e.g., landfills, industrial sites, brownfield sites, spills) and diffuse sources (e.g., applications of de-icing salts, fertilizers, pesticides) (Warner et al., 2016; Burri et al., 2019; Gesels et al., 2021). In the Great Lakes Basin, quantitative information about these sources is generally in the form of tabulated data summaries that do not specifically quantify impacts on groundwater (see following section), and more detailed information is often not available to the public (e.g., consultant reports for the private sector). Research about groundwater contamination from these sources is usually site-specific, or focused on a single plume, and thus not incorporated into city-wide or catchment-scale assessments of contaminant sources. The lack of quantitative information about sources that contaminate groundwater in urban areas reflects not only the complexity of these environments and the large, confusing assemblage of known and potential sources (White et al., 2016; Burri et al., 2019; Gesels et al., 2021;

McCance et al., 2021), but also the difficulties (e.g., legal challenges) in the legalities around making accessible the data produced from such studies. This reality is reflected in a recent study of an aquifer beneath a city in the United Kingdom, in which many organic chemicals including atrazine, simazine and naphthalene, as well as elevated nitrate were detected (White et al., 2016). The authors observed that multiple tracers are often required to understand the contributions from sources and pathways of contaminants in urban groundwater because of the varied sources of urban contaminants.

Some recent research has addressed the need to distinguish sources of contaminants in urban groundwater. For example, Kiefer et al. (2021) used a screening analysis approach (i.e., no intention to target specific compounds), together with targeted analyses of trace organic chemicals in urban groundwater samples, to try to distinguish urban and agricultural contaminant influences. Their un-targeted analyses detected some chemical pollutants that had previously not been reported in groundwater, and many compounds remained unidentified. Gesels et al. (2021) introduced indicators based on analyses of inorganic trace elements to quantify and distinguish the impact of diffuse pollution in urban and industrial areas from the influence of lithology (geology). Similarly, based on analyses of major ions, stable isotopes of nitrate and other parameters, Li et al. (2021) applied cluster analysis and other techniques to distinguish anthropogenic sources of groundwater contamination from “natural background levels”. Propp et al. (2021) found that analyses of artificial sweeteners and other contaminants of emerging concern may be helpful to trace contamination of urban groundwater from legacy landfills. Khazaei & Milne-Home (2017) found that analyses of trace amounts of artificial sweeteners were also helpful in discriminating septic effluent and road salt sources of chloride in shallow urban groundwater near Toronto, Ontario.

<u>Relevant policy, practice and program developments by various levels of government</u>

In this review, no information was found on recent (post 2016) Great Lakes Basin policy, practice, or program developments by the various levels of government (including municipalities) that directly related to quantifying the fluxes of contaminants from various sources to urban groundwater. Currently there are no programs in place to quantify leakage from municipal sanitary sewers, or to quantify fluxes of contaminants from urban sources, such as spills, stormwater and leaking sewers, to groundwater. Similarly, it appears that there are no government programs in place to estimate groundwater contaminant loads (and associated risks) in urban areas at city-wide or watershed scales, or changes in these loads in response to site-specific or larger-scale remediation efforts. Furthermore, Great Lakes Basin assessments are lacking with respect to fluxes of contaminants from urban groundwater to urban streams, wetlands and other water bodies. These comments apply both in general, and specifically to Areas of Concern that have been identified in the Great Lakes Basin, leaving open questions about the role of groundwater in Great Lakes water quality issues.

Some government programs do provide general information on releases of contaminants to the environment in the Great Lakes Basin. For example, on the U.S. side, the federal Toxics Release Inventory program requires facilities to report annually amounts of toxic chemicals released to the environment including water (surface water bodies) and land disposal (U.S. Environmental Protection Agency, 2019). Many of the facilities are in urban areas. Reporting is by chemical (767 in total), including some per- and poly-fluoroalkyl substances (PFAS), which were added in 2019. The "land disposal" data includes amounts disposed by deep well injection but does not provide any information on releases to shallow urban groundwater via such pathways such as stormwater infiltration and sewer leaks. On the Canadian side, Environment and Climate Change Canada provides the National Pollutant Release Inventory as an online database (Environment and Climate Change Canada, 2021) with general information on releases (spills, leaks, etc.) and disposals of over 320 pollutants in Canada, including Ontario, currently for the period 1994-2019. The data include the amount of each pollutant released, the site in which the release or disposal occurred, and whether this was to land, water, air, or a combination of these. There is no information about impacts on groundwater specifically. Similarly, a number of Ontario wide historical and more recent databases provide an indirect indication of how groundwater quality might be impacted (e.g., Environmental Compliance Reports which record incidences of contaminant releases into air, sewers, and water) and are available for download via the Province's Open Data Catalogue (https://data.ontario.ca/dataset/environmental-occurrences-and-spills). In summary however, none of these sources are adequate for contributing to the general knowledge about urban groundwater quality in the Great Lakes Basin.

6.3.3 Monitoring of groundwater quality and assessment of potential health risks (6C)

Understanding groundwater quality in urban areas presents many challenges, including the logistics of getting access to monitoring locations, and finding effective ways to inform communities about the importance of urban groundwater. A very limited number of urban centers in the Great Lakes Basin use groundwater for domestic supply. Thus, there is often an 'out of sight, out of mind' mentality for groundwater (Howard & Gerber, 2018). Oversight of groundwater, however, disregards the potential for contaminated groundwater in urban centers to negatively impact residents through vapor intrusion, subsurface seepage into homes, interconnection with sewer/water lines, and connection with surface water resources. To better understand potential health risks associated with urban groundwater, both monitoring and management are essential. A clear characterization of groundwater quality provides both an avenue for remediation and a basis for health risk evaluation. The primary findings related to this science need were presented in Sections 6.2.1 and 6.2.2.

Two studies in Detroit (Carmichael et al., 2019; Sampson et al., 2019) reviewed qualitative methods to understand both the environmental health and physiological health of residents due to flooding from groundwater infiltration (Carmichael et al., 2019; Sampson et al., 2019). The Sampson et al. (2019) study highlighted the importance of social inequity in contributing to long-term and ongoing inland flooding pollutant exposures. This type of narrative research provides an example of how communication and collaboration between communities and municipalities can lead to practical recommendations for reducing the risk of exposure.

Developing vulnerability models for groundwater to contamination, or health impacts from groundwater pathways, requires robust data-intensive approaches, which are challenging. The most commonly used groundwater vulnerability model is DRASTIC (Aller et al., 1987). In a review of DRASTIC-like models, three approaches were used for estimated groundwater vulnerability. These include index-based methods, statistical approaches like regression models, and the use of simulations to forecast groundwater contaminant movement (Barbulescu, 2020). Alternative models to the DRASTIC and DRASTIC-like models are presented in Table 6.8. While these models are useful tools, they are often based on sparse field data, which can be critical for understanding heterogeneous urban settings.

Table 6.8 Summary of urban groundwater risks and vulnerability modeling papers.

Title	**Summary**	**Citation**
Assessing Groundwater Vulnerability: DRASTIC and DRASTIC-Like Methods: A Review	Review of DRASTIC-like methods for groundwater vulnerability.	Barbulescu, (2020)
A critical review of integrated urban water modelling, Urban drainage and beyond; Impact of Hybrid Water Supply on the Centralized Water System	Urban Biophysical Environments and Technologies Simulator (Urban-BEATS) models are a multiscale model for modeling urban city-wide catchment to individual lots.	Bach et al., 2014; Sitzenfrei, 2017
Analysis of Potential Risks Associated with Urban Stormwater Quality for Managed Aquifer Recharge	Managed aquifer recharge (MAR) is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit.	Song et al. (2019)
Developing a multi-scale modeling system for resilience assessment of green-grey drainage infrastructures under climate change and sea-level rise impact	Interconnected Channel and Pond Routing Model, which integrated green infrastructure and storm sewers as part of a resilience strategy for urban drainage infrastructure.	Joyce et al., (2017)
Quantifying cumulative effectiveness of green	Classification of aquifer vulnerability using K-means cluster analysis.	Jalali and Rabotyagov (2020)

Title	Summary	Citation
stormwater infrastructure in improving water quality		

6.3.4 Base data acquisition and monitoring of urban water balances (6D)

This science need pertains to quantifying how urban areas change the water balance and introduce new water balance components. The water balance in urban areas can change substantially due to increased imperviousness, engineered areas of focused recharge, irrigation, and other anthropogenic changes to the land- and sub-surface (Figures 6.1 and 6.2). The primary findings related to this science need were presented in Sections 6.2.1 and 6.2.2.

There are relatively few new studies related to the priority science need of base data acquisition and monitoring of urban water budgets at different spatial scales. Published studies within the Great Lakes Basin are especially lacking. There is, however, active EPA-funded research underway in the United States through its Great Lakes Restoration Initiative. Active research sites are located in Fond du Lac, Wisconsin, Buffalo, New York, Detroit, Michigan, and Gary, Indiana, (U.S. Geological Survey, 2017; Baker et al., 2022)

Understanding the position of the sewer infrastructure relative to the saturated groundwater table is key to elucidating which parts of the sewer network might be losing water to the groundwater system (i.e., those parts above the water table). Sewers below the water table can gain volume from groundwater infiltration into the system, thereby significantly changing the water balance by altering natural groundwater flow paths. This also leads to increased wastewater treatment volumes and costs (The Regional Municipality of York, 2020). Results from a study in Buffalo, New York, indicate that vacant lands citywide may cumulatively infiltrate 51–54% additional annual rainfall volume compared to pre-demolition state. The findings illustrate that vacant lots as landscape features can reduce water fluxes into aging wastewater infrastructure by increased recharge to groundwater (Kelleher et al., 2020).

6.3.5 Research on urban groundwater movement and contaminant fate (6E)

Research on urban groundwater movement

A current lack of data is driving a generally poor understanding about movement of groundwater in urban areas in the Great Lakes Basin (see 2.3.1). As discussed in section 6.2.1, this situation is made worse because of the complex ways in which urban infrastructure affects the urban water cycle, for example by creating urban karst which may serve as pathways of groundwater flow.

Beyond local scale (single facility, site) investigations, recent published studies on urban groundwater movement (e.g., flow systems) are rare. A few recent studies have looked at urban groundwater flow systems at neighborhood to regional scale (Moeck et al., 2021; Newman et al., 2021; Teimoori et al., 2021). In Detroit, Michigan, shallow urban groundwater flow was evaluated on a regional scale encompassing four major watersheds and at a local scale containing several city blocks (Teimoori et al., 2021). A local urban water budget was developed with subsequent groundwater simulation to evaluate the effect of urban settings on groundwater flow. In Basel, Switzerland, a groundwater flow system was investigated by using apparent groundwater ages based on helium analyses, together with hydrochemical data, water isotopes and perchloroethylene concentrations (Moeck et al. (2021). This study found evidence for inter-aquifer mixing and preferential flow paths. Working with similar techniques, Newman et al. (2021) investigated residence times and groundwater–surface water interactions in an urban aquifer in Colorado. They also found evidence for mixing, including "young" and "old" groundwater. The analyses and techniques used in these studies may be widely applicable to groundwater studies in other urban areas.

Research on contaminant fate in urban groundwater: de-icing salts

Warner et al. (2016) noted that the use of sodium chloride as de-icing (road) salt is a serious and growing contaminant issue in most urban areas of the Great Lakes Basin. Since 2016, many studies on urban groundwater quality in the Great Lakes Basin and the surrounding region have focused on chloride as both a pollutant and a tracer (Table 6.9). Some studies probed de-icing salt versus other sources of chloride (Khazaei & Milne-Home, 2017; Oberhelman & Peterson, 2020). Other studies looked at related chloride concentrations and trends in urban streams (Gutchess et al., 2018; Oberhelman & Peterson, 2020). In terms of significant advances in the science, some recent studies have begun to look at wider impacts of the transport of de-icing salts by groundwater and stormwater to other urban waters, including lakes, streams and wetlands (Helmueller et al., 2020; Kelly et al., 2019; Minnesota Ground Water Association, 2020; Roy, 2019; Wyman & Koretsky, 2018).

In a recent study in Maryland, Snodgrass et al. (2017) looked at how modern stormwater management practices affect road salt movement through urban watersheds. They observed that plumes of chloride and sodium from road salt in urban groundwater discharged to streams throughout the year (indicating storage of these ions in groundwater), concluding that modern stormwater management practices are not protecting surface water bodies from road salt contamination.

Table 6.9 Studies in the Great Lakes Basin and the surrounding region that focused on chloride as a pollutant and/or a tracer.

Focus of study	Location	Reference
Chloride concentrations and trends in urban streams	central New York	Gutchess et al., 2018

Focus of study	Location	Reference
Impacts of the transport of de-icing salt on an urban wetland	Madison, Wisconsin	Helmueller et al., 2020
Impacts of de-icing salts on urban watersheds including pond, wetlands	Minnesota	Herb et al., 2017
Distinguishing de-icing salt, septic and agricultural sources of chloride	Near Toronto, Ontario	Khazaei & Milne-Home, 2017
Relationship between de-icing salt application rate and residence time of chloride in shallow aquifers	Illinois	Ludwikowski & Peterson, 2018
Mobilization of radium and radon by deicing salt in urban groundwater	Connecticut	McNaboe et al., 2017
Impact of de-icing salt on an urban lake	Kalamazoo, Michigan	Wyman & Koretsky, 2018
De-icing salt versus agricultural sources of chloride; chloride concentrations and trends in urban streams	Illinois	Oberhelman & Peterson, 2020;
Impact of chloride in discharging groundwater on endobenthic organisms in urban streams	various sites in Canada, including Ontario	Roy, 2019;
Impacts of stormwater infiltration on chloride in groundwater	Minnesota	Minnesota Ground Water Association, 2020

Some researchers have concluded that historic storage of de-icing salts in the subsurface, including in groundwater, is now a serious legacy problem (Kelly et al., 2019; Warner et al., 2016); reductions in use of de-icing salts may not be reflected in improved stream water quality for decades (Kelly et al., 2019). In contrast, Ledford et al. (2016) inferred much shorter residence times for storage of road salt in a surficial aquifer within the riparian zone of an urban stream at Syracuse, New York (within the Great Lakes Basin), and concluded that this temporary groundwater storage buffered the surface water concentrations after periods of road salting.

A key implication of the road salt studies is that there is a need to look at ways to rethink and reduce the use of de-icing salt in urban areas (Kelly et al., 2019; Ludwikowski & Peterson, 2018; Snodgrass et al., 2017). However, recent research in support of such initiatives are sparse (e.g., Haake & Knouft, 2019; Kelly et al., 2019; Lembcke et al., 2017).

Recent relevant policy/program developments in Great Lakes Basin related to groundwater contamination by de-icing salts

A working group that included Conservation Ontario, the Province of Ontario, and the Government of Canada recently released a guidance document intended to serve as a resource on environmental best management practices for road salt use in winter for maintenance purposes (Ontario Good Roads Association, Conservation Ontario, 2018). In Ontario, the water component of the Sustainable Technologies Evaluation Program (STEP) has included various projects that address management and use of de-icing salts. For example, The Toronto and Region Conservation Authority (2019) has recently released a procurement guidance document for parking lot snow and ice management. This document, developed for educational purposes, provides guidance on such topics as accurate salt delivery, low chloride alternatives, and reducing salt application rates.

The Minnesota Pollution Control Agency has recently (2015) released a revised "Winter Parking Lot and Sidewalk Maintenance Manual." This document provides guidelines on such topics as salt storage and application rates. It also includes documented cases of reductions in salt use based on interviews of people who had had training about the guidelines.

Research on contaminant fate in urban groundwater: other contaminants

Other recent studies that have looked at contaminants in urban groundwater are listed in Table 6.10. Most of these studies have focused on trace organic compounds, including those of emerging concern for human health and aquatic ecosystems. Some have looked at observed or potential fluxes of these contaminants from discharging groundwater to urban streams (e.g., Parajulee et al., 2017; Lemaire et al., 2020; Balbarini et al., 2020).

Volatile organic compounds are common urban groundwater contaminants that pose vapor intrusion risks. Vapor intrusion is considered the pathway with the greatest potential to result in human exposure at sites impacted by volatile organic compounds in groundwater (Ma et al., 2020). Contaminated groundwater provides an opportunity for subsurface intrusion of hazardous compounds into commercial and residential buildings (C. J. Miller et al., 2020). Subsurface intrusion is now considered on the U.S. Hazardous Ranking System for Superfund designations (USEPA, 2017). Modifications to the near-surface zone alter contaminant exposure pathways by potentially shortening travel distances and hydraulic retention times in shallow groundwater (Voisin et al., 2018; Zhang & Chui, 2019).

Table 6.10 Examples of recent studies of contaminants in urban groundwater.

Focus of study	Location	Reference
Array of organic contaminants in urban groundwater	United Kingdom	(White et al., 2016)
Groundwater transport mentioned as potential pathway for benzotriazoles in urban streams	Canada	(Parajulee et al., 2017)
PFAs in groundwater as tracers of landfills	Australia	(Hepburn, Madden, et al., 2019; Hepburn, Northway, et al., 2019)
Sources of heavy metals in urban groundwater	Australia	(Hepburn et al., 2018)
Anthropogenic micropollutants as tracers in groundwater	Global (review)	(W. Warner et al., 2019)
Sulfonamides and metabolites in urban groundwater	Spain	(Jurado et al., 2020)
Non-steroidal anti-inflammatory drugs and their metabolites in an urban aquifer	Spain	(Jurado et al., 2021)
Neonicotinoid insecticides in surface water, groundwater, wastewater	Minnesota	(Berens et al., 2021)
Chlorinated ethenes in urban groundwater	Italy Denmark Switzerland	(Pollicino et al., 2019) (Lemaire et al., 2020) (Moeck et al., 2021)
Pharmaceuticals in groundwater discharging to a stream	Denmark	(Balbarini et al., 2020)
Conceptual model for vapor intrusion from groundwater through sewer lines	United States	(Beckley & McHugh, 2020)

6.4 Critical/Emerging science needs and opportunities

Based on this review, there is growing awareness about several science needs. As described below, there are new and expanding opportunities to address some of these emerging priority science gaps.

6.4.1 Need for data collection, transmission, storage and visualization

Data Management

Within our urban environments, there is a significant ongoing need for improvements to data management and data access with respect to water resources, including groundwater. This will grow ever larger as more data are collected in real time with smarter technologies . New emerging methods and technologies (e.g. big data analytics, Internet of Things, edge computing, and machine learning) have the power to rapidly change the way water data are handled, transformed, and analyzed. However, they first require a robust data management infrastructure before their power can be harnessed for decision making.

Data processing

Data management is only a first step in transitioning to improved urban water management decision-making. Data processing techniques and visualization tools, whereby insights can be teased out from big data sets to quickly assess temporal, spatial and depth related trends is a necessary follow up to data management. The Internet of Things facilitates connecting physical objects in the field to sensors, software, and other technologies over the internet. New water monitoring devices often utilize Internet of Things technology for monitoring sewer systems (Salam, 2020a, 2020b), combined sewer overflows (Zhang & Chui, 2018), and surface water (Shafi et al., 2018). The recent growth in Internet of Things use has prompted additional needs for processing. Edge computing is one relatively new computing paradigm that allows sensors to communicate with a distributed computing system (Erol-Kantarci & Sukhmani, 2018; Satyanarayanan, 2017; Shi et al., 2016; Shi & Dustdar, 2016). Edge computing allows real-time data processing on edge servers located closer to mobile devices, sensors, or end users, thus reducing the reliance on cloud computing. While these technologies offer opportunities for smart water solutions, it is important to realize their limits and to assess the risks of data mismanagement (Moy de Vitry et al., 2019).

Successful examples include the big data analytics approach to managing groundwater in the Southern African Development Community region of Africa (Gaffoor et al., 2020) and for large regional groundwater sampling programs (Kang et al., 2020; Latchmore et al., 2020). Combining real time groundwater data with other relevant data can support decision making for sustainable groundwater management. Examples include decision support systems like AquaVar DDS in France (Ma 2020) and the proposed Water4Cities platform (Rizou 2018). In addition, computational tools that can evaluate groundwater quality and exposure routes are critical for establishing healthy urban environments. With lifestyle changes leading to more remote work after the COVID-19 pandemic, subsurface intrusion into households from groundwater through flooding or vapor intrusion is one pathway of increased concern (Miller et al., 2020). Additionally, using Internet of Things technology to monitor virus presence in groundwater is another area of increased interest (for example Salem et al., 2021).

Sensor Use

Recent advances in sensor availability and affordability will enable their greater use in groundwater monitoring. Combining information and communications technology with sensor technology can enhance effective management of field data thereby facilitating quicker and improved decision making (Park et al., 2020). This combination of information and communications technology can enable greater spatial and temporal resolution of water quality in hard-to-reach urban locations. Additionally, sensors provide a potential cost saving tool by reducing response time and minimizing impact when leaks or water quality issues occur. An example of this approach is the proposed Water4Cities program/initiative (Chen & Han, 2018; Rizou et al., 2018). Water4Cities is a proposed information and communications technology platform that approaches urban water availability, quantify, and quality at a city-wide scale through using sensor monitoring infrastructure and robust data visualization tools.

Open Data Resources

Open data resources enable easier assessment of the competing and interdependent water needs of urban cities. In addition to data access, providing tools and easy to use visualization is a critical way to enhance equitable open data resources. Recently, the Michigan Department of Environment, Great Lakes, and Energy released their new Maps and Data web portal which contains all public maps and data from Michigan Department of Transportation, and Michigan Department of Natural Resources (Michigan Department of Environment Great Lakes and Energy, 2021). The universal platform is an open data site that does not require any special computer program or formal Geographic Information System (GIS) education to access the files or tools. The USGS National Water Information System has provided online access to USGS surface water, groundwater, and water quality data for decades. A multi-year, multi-million-dollar effort is underway to update and upgrade the infrastructure and interface. Modernization will include improving user access and support, standardizing data formats, and enhancing linkages between time-series and discrete data for surface water, groundwater, water quality, and water use datasets (https://help.waterdata.usgs.gov/news/Feb-12-2019).

For an overview of national and international databases, the Consortium of Universities for the Advancement of Hydrologic Science hosts a list of open data ports developed by the Global Water Information Interest Group of the Research Data Alliance.

While not a complete list, the resources in Table 6.11offer a starting point in evaluating both local Great Lakes Basin and international open data sources, and they offer examples for entities considering creating or upgrading data availability resources.

Table 6.11 Examples of open data sources.

Group	Name	Location	Owner
Consortium of Universities for the Advancement of Hydrologic Science	Open Water Data Initiative (OWDI)	https://www.cuahsi.org/data-models/portals	Federal Geographic Data Committee
Consortium of Universities for the Advancement of Hydrologic Science	Data portals list	https://www.cuahsi.org/data-models/portals	Global Water Information Interest Group
Internet of Water	IoW Water Data Hubs	https://internetofwater.org/resources/hubs/	User defined.
Great Lakes Observing System	Data portals list	https://www.glos.us/	Integrated Ocean Observing System
Oak Ridges Water	Oak Ridges Moraine Groundwater Program	Oakridgeswater.ca	Oak Ridges Moraine Groundwater Program

6.4.2 Need for multidisciplinary science in support of holistic management of the urban subsurface

Optimistically, future management of Great Lakes cities and their urban environments will transition towards more holistic approaches that include management of the subsurface. These could include comprehensive management of urban water, including groundwater.

Though such approaches have been lacking, there are promising recent developments. For example, as already mentioned above, "Sub-Urban" is a recent initiative intended to improve understanding and use of the urban subsurface, and to promote cooperation between urban subsurface experts and researchers, urban decision makers, planners, practitioners, and developers (Campbell et al., 2017). There is some evidence of the emergence of more holistic approaches to manage urban water in the Great Lakes Basin. For example, Tovilla & Webb (2017) found evidence for slow but steady knowledge transfer by municipalities in Ontario from their use of management system standards for protection of municipal drinking water (as required by the Province) to their wastewater and stormwater sectors. Twelve Ontario municipal utilities have either recently adopted environmental management systems for their wastewater and stormwater systems or are in the process of adopting such systems, and most of these municipalities lie within the Great Lakes Basin (Tovilla, 2020).

Emergence of holistic approaches to manage the urban subsurface will require the support of more comprehensive, multidisciplinary science programs. Such programs could include cooperative efforts by experts in geoscience, hydrology, hydrogeology, civil/geotechnical engineering, chemistry, microbiology, ecology, and other relevant fields.

6.4.3 Need for understanding influence of green stormwater infrastructure (GSI) on groundwater

Properly-designed and situated GSI can provide sustainable solutions for stormwater management through promoting infiltration, however the impact of adding stormwater into neighborhood groundwater is typically not measured (Masoner et al, 2019; Selbig & Banerman, 2007; Burant et al, 2018; Spahr et al, 2020). Understanding the impacts of introducing additional water, perhaps of degraded quality, to the groundwater system through GSI installations presents a knowledge gap in urban water budgets. In addition, there is a gap in understanding of the influence of stormwater on groundwater quality, and how it might relate to urban health concerns, especially since most waterborne disease outbreaks in the United States come from exposure to untreated groundwater with floodwaters (Andrade et al., 2018; Ashbolt, 2019). Urban groundwater monitoring would address groundwater quantity and quality uncertainties/challenges related to GSI. Currently, researchers are evaluating GSI impact to groundwater in Detroit through a US EPA funded program called GSI-Informed Urban Groundwater Monitoring Networks (Miller et al., 2021). This program is designed to develop low-cost community solutions for evaluating GSI impact on both groundwater flow and quality in urban neighborhoods.

6.5 Updated priority science needs table

Although there have been incremental steps to better characterize groundwater quality and flow in urban areas in the Great Lakes basins, challenges remain. Table 6.12 reflects the updated science needs specific to adequately assess urban groundwater quality and the urban hydrologic cycle that includes groundwater.

Table 6.12 Updated Priority Science Needs, with reference to the 2016 list (Table 6.1).

Updated 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 modeling tools supported by sufficient data to allow verification, validation, and calibration; - ongoing model maintenance and updating ('living models'); - creation and population of long term, urban wide comprehensive (e.g. water quality, extraction, water levels, geology, infrastructure) subsurface databases that incorporate site-specific project data; - increased data access (online preferable); - urban water table mapping (including seasonal variability) to better understand exfiltration from water pipes/sewers and infiltration into sewers; - depth of water/sewer pipe infrastructure mapping; - monitoring and quantification of urban water balances - quantification of water/sewer pipe exfiltration and infiltration rates, including septic systems; - quantification of transfers to groundwater system from GIS and /or stormwater facilities
6B. Quantitative data, information, and web-based maps of urban groundwater quality including contaminant sources, transfers, fate**	-- Chemical audits, base data acquisition and monitoring - Increased online availability of point source and site monitoring data; - background urban groundwater monitoring to establish levels and variability in non-point sources (e.g. road salt, lawn fertilizers, etc.)
6C. Assessment of potential health risks associated with degraded urban groundwater quality	- Improved understanding of human exposure to degraded urban groundwater and potential health risks/disease; - Improved understanding of subsurface intrusion exposure routes from shallow groundwater.

Updated Priority Science Needs	Related needs and information gaps
6D. Holistic monitoring and research on urban groundwater flow at multiple scales that captures interplay with urban infrastructure including stormwater, sewage, green infrastructure, municipal water systems, buildings, tunnels, streams, lakes and wetlands	- improved understanding of the cumulative role of urban infrastructure on groundwater flow; - Monitoring and management of dewatering; - improved understanding of groundwater migration mechanisms through 'urban karst' infrastructure corridors; - Knowledge and monitoring related to stormwater/GIS releases (both quantity and quality) to groundwater systems; - quantification of the influence of urbanization on the water budget.

* The text added here incorporates the former priority need 6D (Table 6.1): "Base data acquisition and monitoring of urban water balances"

**The text added here incorporates the former priority need 6E (Table 6.1): "Research on urban groundwater movement and contaminant fate"

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Common overapplication of road salt to sidewalks and roads can lead to groundwater contamination, which can then discharge to nearby streams (and wetlands and lakes), leading to elevated concentrations of salt during base flow periods, even during summer.

Photo credit: James Roy, Environment and Climate Change Canada

7 CLIMATE CHANGE EFFECTS ON GROUNDWATER

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7.1 Introduction

Climate change has the potential to alter the physical and chemical properties of water in the Great Lakes Basin (GLB) and their ecological functions. This chapter synthesizes existing research associated with the potential effects of a changing climate on the quality (including temperature) and quantity of groundwater in the Great Lakes Basin. It includes analysis of realized and predicted future impacts.

Research shows large spatial and temporal (i.e., seasonal) variability in groundwater response to climate change between regions. Most studies combine field observations with modelling. Many have focused only on small/medium basins. At these small scales, groundwater systems in this region are projected to be fairly resilient to climate change impacts, although research is limited. Modelling studies of larger basins (e.g., Grand River, Saginaw Bay, Maumee River) predict an increase in groundwater storage, but groundwater sensitivity to climate change may depend strongly on local physiographic features. Uncertainty in model simulations, particularly from climate models used to force hydrological models, is a major challenge. There have been too few studies to date that investigate the interplay of climate change and groundwater quality in the Great Lakes Basin to draw conclusions about future groundwater quality and ecohydrology.

This synthesis focuses on what is known about the effects of a changing climate in the GLB on (1) groundwater recharge, (2) groundwater storage, (3) groundwater discharge and GW-SW interaction, (4) exacerbating future urban development impacts on groundwater, (5) groundwater quality, and (6) ecohydrology (including SW water quality). Key findings are summarized, followed by a more in-depth review of the literature. A summary of methods, models, and technology that have been used to examine this topic in the GLB is also provided. Model uncertainty has become an increasingly important topic and is also discussed. The report concludes with a synthesizes of the main science needs to better understand the impacts of climate change on groundwater resources in the GLB.

7.2 Summary (Key Findings)

Groundwater Recharge: Most studies on groundwater recharge and impacts of climate change in the Great Lakes basin are examined at small/medium basin scales. Simulation results show large spatial and temporal (i.e., seasonal) variations between the study areas.

While some studies have reported a general increase in annual recharge, they also noted substantial seasonal variabilities (i.e., significant increase in winters and slight decrease in summers). Other studies at these small scales have predicted either overall increases or decreases in infiltration and recharge. One of the key studies at a large watershed scale found that local physiographic features strongly affected the magnitude of climate change impacts on groundwater, with regions with deeper water tables revealing a higher sensitivity. Furthermore, the largest changes in groundwater levels, recharge, and soil moisture typically occurred in such regions, suggesting compounding impacts. Substantial snowmelt hydrology shifts between historical "warm" and "cool" years have also been linked to considerable seasonal changes in streamflow and groundwater recharge dynamics. For the first time, a fully integrated SW-GW hydrologic model has been set up for Continental Canada to quantify the impact of climate change on groundwater flow systems. However, climate modelling has become a main source of uncertainty, and the July 7, 2021 use of ensembles of climate models and scenarios to force hydrological simulations is a key recommendation highlighted in many studies.

Groundwater Quantity (Storage Changes):

Field data and models have been used to study the impact of climate change on groundwater storage across a wide range of spatial scales (from field to continental scale) and geographical locations. However, many of the studies were carried out on field or small/medium basin scales. Although there is variability in the results reported at these scales, many studies concluded that groundwater systems were expected to be fairly resilient to climate change impacts. However, some studies focused only on recharge or discharge and did not directly address storage changes. Model uncertainty and spatial variability in the compound effect of climate change and intensification of groundwater abstraction for agriculture use have been reported at regional scales. However, studies tended to predict a potential local increase in baseflow that depends on factors such as the aquifer type (confined vs. unconfined). Studies of large basins (e.g., Grand River, Saginaw Bay, Maumee River) generally predicted an increase in groundwater storage, but groundwater sensitivity to climate change depends strongly on local physiographic features, and uncertainty with model simulations has been frequently emphasized. Model projections at continental scales are rare, still in the early stages, and uncertain in Canada, particularly concerning implications for the Great Lakes. One model was able to capture surface drainage well across most of Canada, but model performances deteriorated in both the Arctic and Great Lakes regions, which was attributed to uncertainty in observed precipitation - they recommended improved observational climatology in these regions. Historical data has also been frequently used to examine the response of hydrological systems to changes in climate conditions. For example, an analysis based on ground monitoring and remote sensing data found that the increase in terrestrial water storage over the past decade has been primarily due to changes in shallow subsurface waters (i.e., vadose zone and unconfined aquifers).

Groundwater Discharge and GW-SW Interaction:

Similar to the previous studies on recharge and storage, recent studies on groundwater discharge and GW-SW interaction highlight the importance of quantifying and reducing uncertainties associated with climate and hydrological simulations. While some studies indicated a potentially significant discharge reduction and no substantial change in groundwater head or net exchange flux by mid-century, others predicted a considerable increase in hydraulic heads and stream discharges during winters and a slight decrease in summer by the end of the century. However, those studying subsurface drainage discharge provided conflicting predictions (i.e., significant reduction or significant increase) by the end of the century.

Exacerbating the Impacts of Future Urban Development on Groundwater:

Studies on the impact of urban development on groundwater quality and quality are scarce. A study about climate change vulnerability assessment of drinking water sources (surface and groundwater) in Canada indicated high exposure to climate change across the seasonal and annual periods for all case studies, but the uncertainty of the exposure assessment was also considered high due to the use of modelled data. A study in the Greater Chicago Area emphasized that an increase in water demand led to unsustainable groundwater extraction from the Lake Michigan basin and an induced increase in baseflow, which attenuated the reduction of infiltration and baseflow by impervious surfaces. Stormwater management facilities and flooding mitigation measures were able to mitigate impacts across different spatial scales.

Groundwater Quality:

Climate change can impact groundwater quality through a variety of mechanisms related to modifications in hydrological processes such as recharge, storage, and discharge, as well as water temperature variations and shifting anthropogenic practices. There have been too few studies to date that investigate the interplay of climate change and groundwater quality in the Great Lakes Basin to draw conclusions about future groundwater quality. Thus this topic needs much further investigation in this region. Emphasis should be placed on examining various contaminant types (e.g., both point and non-point sources, both anthropogenic and geogenic origin). Integrated modelling studies, as well as vulnerability assessments, are useful to examine future groundwater contaminant concentrations and risk to support improved land and water management.

Ecohydrology (including SW Water Quality):

Groundwater dependent ecosystems (GDEs) are expected to be impacted by climate change through anticipated changes to the water balance (e.g., droughts impacting groundwater heads, discharge quantity and timing) and water quality (e.g., new/varied contaminant sources; modified contaminant transport and geochemical transformations; temperature changes). Very few studies have focused on ecohydrology related to groundwater systems and climate change in the Great Lakes Basin. Moving forward, a multidisciplinary approach is required. Ecosystem-scale ecological, hydrological and geomorphological data should be collected to supplement typical hydrological monitoring programs. Furthermore, fully-integrated models that explicitly represent groundwater flow and contaminant transport and groundwater-surface water interactions are needed, and they must be employed at a spatial and temporal scale fine enough to be meaningful for ecohydrological processes. Detailed technical understanding of potential issues is required to aid the development of land use regulations to protect GDEs under a changing climate.

Model Uncertainty:

The issue with model uncertainty is highlighted in nearly every reviewed study that involved modelling. Some studies have averaged results from multiple Global Circulation Models (GCMs) that had been statistically downscaled to provide a more robust projection than the use of a single GCM. Other studies demonstrated the importance of Regional Climate Model (RCM) lake model coupling for capturing the regional influence on spring and summer water balance. The climate forcing linked to GCM and IPCC climate emission scenarios is generally recognized as the primary source of uncertainty, but the representation of heterogeneity in hydrologic models is also viewed as a major challenge. Under-representation of seasonal soil freezing and thawing processes is also considered a key problem in many models. The importance of more and longer-term monitoring data to characterize all climate and hydrologic components and soil temperature profiles has been echoed in many studies. There are also not enough studies that have been conducted using a similar or consistent approach to easily or meaningfully compare the simulation results.

7.3 Literature Review

7.3.1. Groundwater Recharge

Recent studies on future climate change impacts on groundwater recharge are primarily at field or watershed scales. Fewer studies of larger basins (or continental scales) tend to focus more on understanding the overall response of hydrological systems to observed climate patterns.

Field Scale and Small/Medium Basins (< 500 km^2)

Most of the studies of small- and medium-size basins have concentrated on the southwestern Ontario region (e.g. Brouwers, 2008; Larocque et al., 2019; Motiee and McBean, 2017; Sultana and Coulibaly, 2011). The climate variables used in these studies were generally obtained through GCMs and statistically downscaled regional models for different future periods until the end of the 21st century. These climate variables were then used to force coupled hydrologic models, such as SWAT-MODFLOW model (Larocque et al., 2019), HELP3-HydroGeoSphere (Brouwers, 2008), Mike SHE-Mike 11 (Sultana and Coulibaly, 2011), or sometimes to a single infiltration model like Visual- HELP (Jyrkama and Sykes, 2007), depending on the objectives of the studies.

The simulation results demonstrated distinctive spatial and temporal (i.e., seasonal) variations among study areas. For a sub-catchment of Lower Whitemans Creek, Larocque et al. (2019) predicted that the overall groundwater system would be fairly resilient (i.e. no drastic changes in groundwater elevations) to climate change impacts in the future, especially with more recharge, streamflow, baseflow and higher groundwater elevation during winter and fall. Meanwhile, groundwater recharge and streamflow were expected to decrease during the growing season. Similarly, Motiee and McBean (2017) predicted an increase in infiltration and recharge during winter due to more frequent and pronounced freeze/thaw effects, as well as the reversed effect (decrease in infiltration and recharge) in summer owing to evaporation in the Guelph region of the Grand River watershed. Brouwers (2008) identified a strong climate impact upon the timing of hydrologic processes in the Alder Creek area. Shifting the spring snowmelt to earlier in the year can lead to an overall decrease in runoff and an increase in infiltration for both drier and wetter future climate scenarios. However, the changes were expected to be more pronounced in the surface water system than in the groundwater. Results also suggested increased evapotranspiration (ET), especially in the summer months, increased recharge (from 0.36 to 4.12 mm), and a small increase in the average water table elevation.

Sultana and Coulibaly (2011) in Spencer Creek, Ontario, showed decreases in annual snow storage (by 1–5%) and groundwater recharge (by 0.5–6%), and increases in annual ET (by 1–10%) and stream flows (by 10–25%), which 3 were attributed to increased annual mean precipitation (by 14–17%) and annual mean maximum and minimum temperatures (by 2–3 oC) predicted by the climate model.

Large basins (>500 km^2)

Changes in water budget components and storage due to climate variables have been evaluated for the Grand River and Saginaw Bay watersheds in the State of Michigan (Niu et al., 2014). No climate models were used, but climate observations between 2000 and 2012 were used to force the process-based hydrologic model PAWS (Shen and Phanikumar, 2010) to simulate different hydrologic components that include groundwater. Vegetation growth dynamics were considered by coupling PAWS to the land surface model CLM (Lawrence et al., 2019). Trend analysis indicated that storage has increased in both watersheds over the past decade, driven mainly by changes in water in the vadose zone and the unconfined aquifer, and not by surface water or water in the confined aquifer. However, it should be noted that this model was set up with a highly simplified hydrostratigraphic based on 2 layers, a sequence that has been represented by others with 17 layers (Feinstein et al., 2010).

Reducing the uncertainties associated with climate modelling has become one of the key considerations in recent studies. This is mainly addressed by using ensembles of climate models and scenarios to force hydrological simulations (Colautti, 2010; Erler et al., 2019b; Paradis et al., 2016). For example, Erler et al. (2019b) found that RCM configurations employing different moist physics schemes generated considerably different simulation results, with the primary uncertainty associated with future summer precipitation. Shifts in the summer patterns are predicted to affect the seasonal and annual hydrological cycle. In the drier climate scenario, groundwater levels and recharge may decline, while in the wetter scenario, groundwater levels rise and recharge are likely to remain unchanged by the end of the century.

Both Erler et al. (2019b,a) and Colautti (2010) applied HydroGeoSphere (HGS, Therrien et al., 2010) a fully integrated hydrologic model to the Grand River watershed (6800 km^2) in southern Ontario. Erler et al. (2019b,a) coupled dynamically downscaled climate projections with the HGS model to assess climate change impacts on groundwater and soil moisture under monthly normal climatology, which is viewed as the first of its kind in the Great Lakes region where the local climate is heavily affected by major surface water bodies. In their study, Weather Research and Forecasting (WRF) models with two different moist physics configurations (WRF-T - drier and WRF-G - wetter) were used at 10 km resolution to force a sub-kilometer scale SW-GW integrated model. Results showed that local physiographic features strongly affected the magnitude of climate change impacts on groundwater. Regions with deep groundwater tables (i.e., below 2 m) had a higher sensitivity to changes in climate, with the largest variations occurring in groundwater levels, recharge, and soil moisture, potentially indicating compounding impacts. Colautti (2010) predicted changes in recharge could ranging between -5% to 22% and no increase in ET by the mid-century. Their simulations were purely synthetic and limited to steady-state conditions.

Groundwater recharge response to historical climate conditions has also been evaluated for the State of Michigan (Ford et al., 2020). The study categorized recent years (2003–2017) as “warm” or “cool” based on multiple metrics calculated from combined model-data reanalysis and observations from several sources for precipitation, temperature, daily snowpack SWE and melt rates. They found that both lower and earlier spring peak flows in streams occurring in warm years were associated with a decrease in the net groundwater recharge in the northern regions. Shifts between “warm” and “cool” years resulted in differences in stream flow and groundwater recharge dynamics, but no direct effect on groundwater storage has been established.

Continental Scale

The study area of Chen et al. (2020) spans the Canadian Continental Basin (10.5 million km^2) from the Pacific to the Atlantic Ocean, and from the northern parts of the contiguous United States to the Arctic Ocean and Alaska. A physics-based, three-dimensional, fully integrated hydrologic model was constructed with the HGS simulation platform. The hydrologic model was forced by an observed (1981-2010) gridded climate data set and compared lake water level and streamflow observations. On average, groundwater recharge across continental Canada was calculated at 201 mm/year, which was 36% of the total precipitation, and indicated a baseflow index of 0.7. This estimation is on the high end of values published from regional-scale studies in Canada but is consistent with those at the continental scale. The study found that large-scale groundwater flow systems were playing an important role in freshwater availability in Canada, and that potential climate change impacts on these regional-scale flows could have real implications on both groundwater and surface water availability.

7.3.2. Groundwater Quantity (Storage Changes)

Field data and models have been combined to study the impact of climate change on groundwater storage across a wide range of geographical locations and spatial scales. This includes field scale or small/medium basin studies (Larocque et al., 2019; Persaud et al., 2020; Brouwers, 2008; Saleem et al., 2020; Motiee and McBean, 2017; Sultana and Coulibaly, 2011; Pease et al., 2017), provinces/states studies (Borchardt, 2019; Mehan et al., 2019; Croley II and Luukkonen, 2003; Ford et al., 2020), and modelling studies for large basins (Erler et al., 2019b; Niu et al., 2014; Colautti, 2010; Kujawa et al., 2020) and continental Canada (Chen et al., 2020).

Field Scale and Small/Medium Basins (< 500 km^2)

Most of the studies report results at the field or small/medium basin scales. Although there is variability in the results, many studies at these scales concluded that groundwater systems are expected to be fairly resilient to climate change impacts (Larocque et al., 2019; Persaud et al., 2020; Brouwers, 2008). However, some studies focused only on recharge or discharge and did not directly address storage changes (e.g., Motiee and McBean, 2017; Sultana and Coulibaly, 2011; Pease et al., 2017). Larocque et al. (2019) simulated a 65 km^{2}sub-basin of the Lower Whitemans Creek, within the Lake Erie Basin, southwestern Ontario using three scenarios (GCMs; CMIP5) derived from a cluster analysis of 22 available scenarios (RCP4.5 and RCP8.5). They used SWAT-MODFLOW for integrated GWSW simulations for both historical (1970-2000) and future (2040-2070) periods. They concluded that the groundwater system is expected to be fairly resilient to climate change impacts. They argued that there are several opportunities for water use (such as increased pumping for irrigation) based on overall increased water availability in the future. However, for watersheds already under pressure for irrigation such as this one, challenges may occur due to the timing of future water availability in relation to critical timing for agricultural production. They predicted that more water will be available (recharge, streamflow, baseflow, groundwater elevation) in the watershed in winter and fall seasons, but less recharge and streamflow during the summer, which is a critical period for crops. They recommended long-term monitoring of all hydrologic components to help better understand stressed watersheds and how they may be impacted by climate change.

Persaud et al. (2020) examined the Upper Parkhill watershed (130 km^2) in southwestern Ontario within the Lake Huron Basin using HGS (integrated GW-SW flow simulation). Three RCMs (RegCM4; RCP 8.5), two ensembles of WRF, a synthetic scenario based on IPCC 5th assessment report predictions and temporal analogues based on historical climate conditions were used. The historical reference period was between 1986 and 2005, and the future period was 2040 and 2059. They predicted variability in both direction and magnitude of predicted hydrologic change; thus, they adopted a probabilistic interpretation of the results to help account for climate projection uncertainty. While a significant reduction in mid-century discharge was identified with a higher likelihood, a less significant change in groundwater head or net exchange flux was simulated. Brouwers (2008) combined HELP3 for simulation of surface and vadose zone processes with HydroGeoSphere for simulation of saturated groundwater flow in the Alder Creek basin (80 km^2) within the Lake Erie Basin in southwestern Ontario. Scaling factors derived from the second generation Canadian General Circulation Model (CGCM2) were applied to baseline precipitation, temperature and incoming solar radiation values to evaluate climate change effects. The reference period was 1960-2000, and the future period was 2020–2080. They predicted a small increase in future water table elevation despite earlier spring snowmelt, and decreasing runoff and increasing infiltration for both the drier and wetter scenarios, and increased evapotranspiration in the summer. However, a study at the Lynn River watershed (155 km^2) within the Lake Erie Basin in southwestern Ontario showed that lower river flows and groundwater elevations are anticipated in the future, indicating a decrease in water availability (Saleem et al., 2020).

Provincial studies

Some research carried out at regional scales shows uncertainty and spatial variability in the compound effect of climate change and intensification of groundwater abstraction for agriculture. However, potential local increase in baseflow that depends on factors such as the aquifer type (confined vs. unconfined) has been identified. For example, Croley II and Luukkonen (2003) looked at historical and future aquifer storage dynamics in the Saginaw aquifer in the Lansing, Michigan, area by applying the Great Lakes Environmental Research Laboratory's hydrologic modelling system with meteorology estimates for 1961 through 1990 (as a reference condition) and for the 20 years centered on 2030 (as a changed climate condition). Two meteorology estimates were used, one from the Canadian Climate 5 Centre and the other from the Hadley Centre. Results showed contradicting effects of future climate depending on the meteorological forcing. Groundwater levels declined using the Canadian predictions but increased using those from Hadley. It should be noted that the tremendous progress in the understanding of the climate dynamics in the GLB region over the last 18 years was not available at the time of this particular research.

Large basins (>500 km^2)

Studies of large watersheds (e.g., Grand River, Saginaw Bay, Maumee River) seem to suggest an increase in groundwater storage, but groundwater sensitivity to climate change depends strongly on local physiographic features and uncertainty in the model simulations has also been highlighted.

Erler et al. (2019b) developed the sub-kilometre scale HGS model for the Grand River Watershed (6800 km^2) mentioned in Section 7.3.1. They predicted that groundwater levels may decline in the drier climate scenario and rise in the wetter scenario, particularly in regions with deeper groundwater tables (below 2 m; 15% of the area). Niu et al. (2014) examined water budget components and storage changes in the Grand River and the Saginaw Bay basins between 1995 and 2007, combining remotely sensed data (GRACE for watershed water storage changes and MODIS for evapotranspiration) and the process-based hydrologic PAWS model. Their results indicate that storage increased in both watersheds. This change was attributed primarily to subsurface water components, particularly in the vadose zone and unconfined aquifer. Surface water and confined aquifers did not contribute much to these storage changes. The sensitivity of GRACE-derived estimates of groundwater-level changes in southern Ontario has been examined by (Hachborn et al., 2017).

Colautti (2010) simulated the Grand River basin (6800 km^2) using HGS and five mid-century synthetic scenarios developed from modifying the 1960-1999 precipitation record [-5% to +20%] and bounded by GCM-based climate scenarios. Results showed an increase in water table elevation (increase between 0.36 and 1.08 m) for most future scenarios, except when the precipitation was allowed to decrease by 5%, which lead to a water table decrease of 0.48 m. Kujawa et al. (2020) examined the uncertainty of existing models for the Maumee River Watershed, which is the largest watershed draining to the Great Lakes. They combined five independent SWAT models, with six climate models drawn from CMIP5 (i.e., CanESM, CSIRO-r6,CSIRO-r4, CSIRO-r10, MPI-ESM, NorESM) to look at both historical (1996–2015) and future projections (2046–2065). They did not observe clear changes in mid-century water quantity and quality. However, it should be noted that SWAT has limited groundwater simulation capacity.

Continental scale

Model projections at continental scales are in the early stages and still rare and uncertain in Canada, particularly concerning implications for the Great Lakes. Chen et al. (2020) developed one of the first large-scale hydrological modelling studies for Continental Canada using HGS that offers full GW-SW integration. They used the model to provide regional groundwater flow analysis for western Canada and a water balance analysis for the Great Lakes. The model was able to capture surface drainage well across most of Canada despite the highly simplified hydrostratigraphic representation and coarse mesh resolution. Model performances deteriorated in both the Arctic and Great Lakes regions, which was attributed to uncertainty in observed precipitation. They recommended improved observational climatology in these regions. Their study highlighted important large-scale groundwater flow systems that affect freshwater availability across the country, which could be affected by climate change and impact groundwater availability.

7.3.3. Groundwater Discharge and GW-SW Interaction

Subsurface drainage (i.e., tile drains) is a critical component of the hydrologic system that affects groundwater discharge and GW-SW dynamics at typical agricultural fields in the Great Lakes basin. However, studies in this area are limited and results appear to vary significantly. The impacts of future climate change on subsurface hydrology and the performance of controlled drainage at a field site in the headwaters of the Western Lake Erie Basin were evaluated by Pease et al. (2017). Subsurface drainage discharge was monitored at the site between 2013 and 2015. Eighty-three climate projections were used to drive a field-scale process-based hydrologic model, DRAINMOD (Skaggs et al., 2012) to simulate the water balance for high water table and artificially drained soils. By the end of the century, subsurface drainage discharge was projected to decrease (-14.5% to -23.7%) with the greatest decline during autumn due to increased temperature and evapotranspiration. The authors recognized differences in the projected discharge 6 from some other studies, and attributed it to different soil freezing conditions and future climate projects between Ohio and other higher-latitude areas. Results suggested that the role of controlled drainage to potentially retain more crop available water in the soil profile could become critically important under future climate conditions. A study by Mehan et al. (2019) in the Matson

Ditch Watershed in Northeastern Indiana used predictions from CMIP 5 (RCP 4.5 and 8.5) to force a SWAT model (Arnold et al., 1998). They predicted that annual subsurface drain flow totals could increase by 70% by the end of the 21st century.

Persaud et al. (2020) in the Upper Parkhill watershed indicateed a greater likelihood for a significant reduction in mid-century discharge, but no significant change in groundwater head or net exchange flux. Cochand et al. (2019) studied climate change impacts on hydrological systems at a Saint-Charles River catchment in Quebec where winter processes play a significant role. The average of multiple GCM forecasts and three different emission scenarios was used as the climatic input. An HGS model was modified to include snow accumulation and melting effects. Simulations suggested that surface and subsurface flow dynamics, especially in the winter, will be significantly affected by climate change. They predicted that winter hydraulic heads and stream discharges will increase significantly due to warmer temperature by the end of the century, with more liquid precipitation and snowmelt. However, summer hydraulic heads and stream discharges were predicted to fall, to a lesser degree, due to an increase in evapotranspiration. Sulis et al. (2012) applied the surface water-groundwater CATHY model (Camporese et al., 2010) to the 690 km^2des Anglais catchment, also in Quebec, Canada. The results showed high uncertainty to climate data, but seemed to suggest that changing patterns in rainy days have a significant impact on surface-groundwater interactions and recharge fluxes, with longer dry spells effecting soil moisture spatial variability.

Borchardt (2019) studied the correlation among climate variability, baseflow discharges and groundwater takings in Wisconsin between 1984 and 2014. A simple model, RORA (USGS 2017), was used as a preliminary study tool for evaluating the effects of high capacity wells on baseflow changes. They identified a strong correlation between groundwater withdrawals and baseflow discharge to surface waters. In some areas, as the number of wells withdrawing from the confined aquifer decreased, the declining baseflow rate trend (-15%) associated with climate variables alone was found to be mitigated or reversed (+67%). However, in areas where the number of wells withdrawing from an unconfined aquifer increased, the declining baseflow rate trend intensified (-18% to -28%).

7.3.4. Groundwater Quality

Climate change can impact groundwater quality through a variety of mechanisms related to modifications in hydrological processes such as recharge, storage and discharge (e.g., Bondu et al., 2016), as well as water temperature variations (Burri et al., 2019; Riedel, 2019). Shifting anthropogenic practices, such as increased pumping, additional irrigation or changing land use (e.g., different crops; different road de-icing needs) induced by climate change, can also impact groundwater quality (Li and Merchant, 2013; Paradis et al., 2016). Amanambu et al. (2020) provide a short review of worldwide groundwater quality concerns related to climate change. In the Great Lakes Basin, there are few studies thus far that address groundwater contamination under a changing climate. This topic needs further investigation in this region, and also more broadly across Canada (Larocque et al., 2019). Work completed thus far in the Great Lakes Basin includes integrated modelling (Saleem et al., 2020) and vulnerability/risk assessment (Milner et al., 2020; Persaud and Levison, 2021).

Integrated Modelling

In the Lynn River watershed (155 km^2) in the Lake Erie basin, Saleem et al. (2020) developed an integrated flow and contaminant transport model (HGS coupled with RZWQM2 for the root zone) to simulate nutrient (nitrate) transport to groundwater under agricultural fields (cash crops). In combination with using three RCMs for future climatic forcing (reference period: 1986-2005; future period 2040-2059) they simulated three potential future crop rotations (corn-soybean rotation, continuous corn, corn-soybean-winter wheat-red clover rotation) compared to the current corn-soybean rotation practice. The simulated nitrate concentrations are anticipated to be lower during the future period. The continuous corn scenario yielded higher nitrate concentrations than the corn-soybean rotation. The best management practice (BMP) scenario (corn-soybean-winter wheat-red clover rotation) produced significantly lower groundwater nitrate concentrations. Thus, it was recommended that BMPs should be adopted, especially in vulnerable hydrogeological settings, to reduce potential negative impacts of climate change on groundwater quality.

Outside of the Great Lakes basin, the impact of climate change on groundwater nitrate concentrations and the compound effects of agricultural practices has also been simulated for Prince Edward Island in eastern Canada (Paradis 7 et al., 2016). Groundwater recharge was simulated by an infiltration model HELP, which was forced by an ensemble of climate scenarios. The model predicts an increase in groundwater nitrate concentration by 25 to 32%, accentuated by a decreased in groundwater recharge (-2.1 to -12.4%) by the mid-century relative to the historic period (1970-2001). This was attributed to an increase in nitrate leaching from legacy loading and the agricultural intensification induced by climate change.

Vulnerability Assessments

Milner et al. (2020) developed a Microsoft Excel-based climate change vulnerability assessment tool for drinking water source quality, for both surface water and groundwater in Ontario. The purpose of the tool is to offer sciencebased guidance to municipalities and source protection authorities/committees about how to carry out a climate change vulnerability assessment for drinking water source quality. Ultimately, the climate change exposure (degree to which an area, well or surface water intake is exposed to climate variations) is assessed, and a rating is developed, incorporating historical and future climate change trends. Various climate change scenarios can be chosen. A pilot study was developed for the Seaforth Well Supply System, comprising three municipal wells that serve 2900 people. The system is located in southwestern Ontario in the Lake Huron basin (Maitland Valley watershed, 3266 km^2). The assessment tool results indicated that the area has a moderate-to-high exposure to climate change (for both seasonal and annual periods), with half of the assessed area-level (e.g., geology, land use) and well-level (e.g., depth to water table, historical issues, etc.) attributes being highly sensitive to climate change. The final overall impact rating for the area was evaluated as ”medium” (5.7/9), which suggests that source water quality may be moderately affected by climate change.

Persaud and Levison (2021) modified a vulnerability index method (DRASTIC-LU) to better understand how groundwater contamination risk can change by mid-century (2050), while also considering the influence of land use scheme complexity. The method was applied in southwestern Ontario in the Upper Parkhill watershed (130 km^2; Lake Huron basin), using an empirical approach to obtain climate forcing values for mid-century (2050s) (reference period: 1979-2060; future period: 2045-2060). Several future land use scenarios were developed using the TerrSet Land Change Modeler (clarklabs.org/terrset/land-change-modeler), incorporating various crop rotations and tile drainage. For the case study area, all predictive scenarios had a statistically significant increase in mean DRASTIC-LU index values compared to the reference period (i.e., higher contamination risk predicted for the future). Key recommendations include that: 1) more detailed agricultural land use representation (inclusion of crop rotation and tile drainage data), has the potential to improve model predictions; and 2) land use representation in the model can influence future predicted changes in groundwater contamination risk. Persaud and Levison (2021) provided a valuable screening tool to understand the potential for changing groundwater contamination risk in rural regions.

7.3.5. Exacerbating the Impacts of Future Urban Development on Groundwater

Studies on the impact of urban development on groundwater quality and quality are scarce. Rougé and Cai (2014) used cross-statistical analysis, involving the Mann–Kendall trend test and the Pettitt change-point test, to look at crossing-scale hydrological impacts of urbanization and climate variability in the Greater Chicago Area. They used hydrological records in Northeastern Illinois that included daily streamflow data from 29 streamflow gauging stations for the 1953-2007 period and at 36 stations for 1969-2007. The results suggest that urban expansion has increased most streamflow metrics (e.g., average and different percentile streamflow across different seasons), except for spring flows and particular peak flow indicators. Large basins (> 200 km^2) observed more homogeneous streamflow changes than smaller ones (< 100 km^2). The impervious surface area was related to an increase in flooding, but stormwater management facilities and flooding mitigation measures were able to mitigate impacts across different spatial scales. An increase in water demand led to unsustainable groundwater extraction from Lake Michigan and an increase in baseflow, which attenuated the reduction of infiltration and baseflow by impervious surfaces. The authors highlighted that statistical analysis of direct anthropogenic inferences is difficult due to spatiotemporal climate variability.

The climate change vulnerability assessment tool for drinking water sources developed by Milner et al. (2020) (mentioned also in Section 7.3.4) provides a science-based method for local water resources managers by combining statistical methods with a multi-model ensemble created from existing model simulations from multiple climate modelling centres, RCPs (2.6, 4.5, 6.0, 8.5). A pilot study applied the tool to (1) the Burlington Drinking Water Intakes in Lake Ontario, (2) the Seaforth Groundwater Well Supply, and the (3) Mattagami River Drinking Water Intake. Both historical data (1970-2013, 1960-2008, and 1970-2013 period, respectively) and RCP 8.5 future climate projections 8 (2014-2050, 2020-2050, 2014-2050 periods, respectively) were used. The results indicated relatively high exposure to climate change across the seasonal and annual periods for all case studies, but the uncertainty of the exposure assessment was also considered high due to the use of modelled data.

7.3.6. Ecohydrology (including SW Water Quality)

There have been very few studies that have focused on ecohydrology related to groundwater systems and climate change specifically in the Great Lakes Basin. Kløve et al. (2014) present a comprehensive review about the impacts of climate change on groundwater dependent ecosystems (GDEs). Ecohydrology may be severely influenced by climate as well as land use change since inflows of groundwater to surface water receptors can modify physicochemical properties of the entire ecosystems (Hunt et al., 2016). GDEs are impacted by anticipated changes in water availability that modifies groundwater elevations and discharge quantity and timing (e.g., spring flow: Levison et al. (2014); stream flow: Saha et al. (2017); wetland dynamics: Levison et al. (2013); water quality degradation Lipczynska-Kochany (2018); Conant et al. (2019); and temperature increases Kurylyk et al. (2014); Riedel (2019). This is a topic that needs much further research to better understand how climate change may impact groundwater-dependent ecosystems.

In the Matson Ditch Watershed (4610 ha, northeastern Indiana, western Lake Erie basin), Mehan et al. (2019) examined the impact of climate change (two RCPs: 4.5 and 8.5) on nutrient loadings in tile drained agricultural areas, using SWAT. They predicted that by the end of the 21st century, subsurface drainage flows could increase by 70% and soluble phosphorous yield could decrease by 30 to 60%. Kujawa et al. (2020) used six climate projections (2046- 2065) and five independently developed hydrological models (SWAT) to examine nutrient loadings and hydrology in the Maumee River Watershed. This cash crop-dominated watershed is located in northwest Ohio and in portions of Indiana and Michigan, and is a priority watershed for reducing the occurrence of algal blooms in the western Lake Erie basin. For the simulated scenarios and various SWAT models (which have limited groundwater simulation capability), there was not a clear agreement on the direction of change in future discharge or nutrient loadings. For subsurface tile flows specifically, the change in discharge was from an 18% decrease to a 64% increase (ensemble average of an 18% increase), which was related to changes in surface runoff generation. For predicted future nutrient loadings, there was not a clear agreement on the direction of change. In southern Ontario, Chu et al. (2008) studied how air temperature and groundwater discharge influence the thermal diversity of stream fish communities in 43 quaternary watersheds. The applied climate change scenarios indicated that watersheds with higher groundwater discharge (i.e., more thermal diversity of fish) are less sensitive to climate change than those with lower discharge. Importantly, they emphasized that groundwater resources conservation will be important to limit impacts of climate change on the thermal habitat, and consequently thermal diversity of stream fishes.

As described previously, Milner et al. (2020) developed a Microsoft Excel-based climate change vulnerability assessment tool for drinking water source quality for both surface water and groundwater in Ontario. This tool could potentially be used to support the understanding of climate change-induced water quality vulnerability of various water sources for eco-hydrological applications. Although not a climate changed-focused study specifically, Carlson Mazur et al. (2014) developed a water-level fluctuation approach for estimating sub-daily ET and groundwater flow rates for dynamic, non-riparian wetlands and applied the method along the western shore of Lake Huron in the Negwegon State Park, Michigan. The approach sheds light on the evapotranspirative demand of plants for various climate and hydrological conditions.

Clearly, the impact of climate change on ecohydrology in the GLB needs much more consideration moving forward, using a multidisciplinary approach and fully-integrated models that explicitly represent groundwater processes and groundwater-surface water interactions. Collection of small-scale (ecosystem-scale) ecological, hydrological and geomorphological data, in addition to typical monitoring programs (i.e., river flows and groundwater elevations), is required for a comprehensive understanding of GDEs and how they may be impacted by climate and land-use changes (Kløve et al., 2014). Modelling must also be done at a scale fine enough to be meaningful and useful for eco-hydrological processes (e.g., Girard et al., 2015). Detailed technical understanding of potential issues is required to aid the development of land use regulations to protect GDEs under a changing climate.

7.4 Methods, Technology, and Uncertainty

A variety of approaches have been used to examine climate change impacts on groundwater resources in the GLB. Table 1 summarizes the models/methods for simulation or analysis, stemming from database, index and statistical approaches, to recharge models, groundwater models and fully integrated groundwater-surface water models. Table 2 summarizes the climate forcing scenarios/data.

Reducing uncertainties associated with climate modelling is a key challenge highlighted in recent studies. The use of ensembles of climate models and scenarios to force the hydrological simulations has been recommended. The need to improve observational climatology, the representation of land-surface processes and surface water flow, and the inclusion of periodic and transient processes has also been stressed. It has been recognized now that GCM data, or statistically downscaled GCM data, is not providing a full account of how climate change may influence hydroclimatology in the GLB because lake influences, and particularly lake-ice and projected changes in lake ice, are not accounted for. The current state-of-the-art work uses dynamically downscaled climate projections produced with regional climate models coupled to lake-ice models (e.g., Gula and Peltier, 2012; Notaro et al., 2012; Peltier et al., 2018).

The different hydrological models used have strengths and weaknesses pertaining to their ability to simulate groundwater flow processes. The level of detail in the subsurface will influence the integrity of any GW-focused results, and should be considered when interpreting and comparing the results from different studies. Representation of spatial heterogeneity involved in integrated hydrologic modelling also contributes to uncertainties. Some also argued that uncertainty also arises from the underrepresentation of seasonal soil freezing and thawing (Cochand et al., 2019), which has a direct impact on winter water dynamics.

Different models, hypothesis, modelers and experience can lead to large uncertainties in the assessments which can result in difficulties in comparing one individual study in one region to another one in a different area using a different approach. Thus, some level of standardization of methods may be needed over the GLB to allow assessing the relative influence of climate change on groundwater resources.

Table 7.1 Summary of models used in the reviewed studies located in the GLB.

Model (or Approach)	**Description**	**Studies using this model/approach**
DRAINMOD (Skaggs et al., 2012)	Process-based, distributed, field-scale model focusing on describing the hydrology of poorly drained or artificially drained soils. Used to determine recharge.	Pease et al. (2017)
DRASTIC-LU (Alam et al., 2014)	GIS-based method that incorporates land use and subsurface data to examine pollutant loading and aquifer vulnerability	Persaud and Levison (2021)
HydroGeoSphere (Therrien et al., 2010; Brunner and Simmons, 2012)	Integrated groundwater-surface water flow (and transport) model	Chen et al. (2020) Colautti (2010) Erler et al. (2019b) Erler et al. (2019a) Persaud et al. (2020) Saleem et al. (2020)
HELP3 and Visual HELP (often used with groundwater models) (Schroeder et al., 1994)	Hydrological modeling for designing landfills, predicting leachate mounding and leachate seepage to the water table. Used to determine recharge.	Brouwers (2008)
MikeSHE/Mike 11 (DHI Software 2007)	Integrated groundwater-surface water flow (and transport) model	Sultana and Coulibaly (2011)
MODFLOW Harbaugh (2005)	Groundwater flow model	Croley II and Luukkonen (2003)
Process-based Adaptive Watershed Simulator (PAWS)	Solves physically-based conservative laws for major processes of the hydrologic cycle	Niu et al. (2014)

(Shen and Phanikumar, 2010)		
RORA (USGS 2017)	Estimating groundwater recharge from streamflow record analysis	Barlow et al. (2015)
RZWQM2 (Ma et al., 2012) (coupled with HydroGeoSphere)	1D vadose zone crop model (used for nitrate leaching to groundwater)	Saleem et al. (2020) Borchardt (2019)
Soil & Water Assessment Tool (SWAT) Arnold et al. (1998)	Distributed parameter watershed to river basin-scale model to simulate water flow, nutrient mass transport and sediment mass transport (with an emphasis on surface processes)	Kujawa et al. (2020) Mehan et al. (2019)
SWAT-MODFLOW (Kim et al., 2008)	Integrated hydrological (SWAT for land surface processes and MODFLOW for spatially-explicit groundwater flow)	Larocque et al. (2019)
Climate Change Vulnerability Assessment Tool for Drinking Water Source Quality (using Microsoft Excel)	Combines statistical methods with a multi-model ensemble created from existing model simulations (for forcing scenarios)	Milner et al. (2020)
Remotely sensed data (e.g., GRACE for watershed water storage changes and MODIS for evapotranspiration)	GRACE: detailed measurements of Earth's gravity field anomalies MODIS: provides high radiometric sensitivity in 36 spectral bands	Niu et al. (2014)
Detecting Gradual and Abrupt Changes in Hydrological Record (using a statistical approach)	Combining the rank correlations of Mann–Kendall and Pettitt statistics. An indicator is extracted that determines whether an observed shift in a given time series is gradual or abrupt.	Rougé and Cai (2014)
Regression models or other statistical approaches	e.g., A statistical approach to determine relationships between	Chu et al. (2008) Ford et al. (2020)

	a dependent variable and one (or more) independent variables	

Table 7.2 Summary of climate forcing models/approaches used in the reviewed studies in the GLB.

Model (or Approach)	Description
CGCM2	Second generation of the Coupled Global Climate Model from the from the Canadian Centre for Climate Modelling and Analysis (CCCma)
CGCM3.1	Third generation of the Coupled Global Climate Model from the Canadian Centre for Climate Modelling and Analysis (CCCma)
CMIP5 (e.g., CanESM, CSIROr6, CSIRO-r4, CSIRO-r10, MPIESM, NorESM) and Representative Concentration Pathway (RCP)	Coupled Model Intercomparison Project (a database of coupled GCMm [Global coupled ocean-atmosphere general circulation models] simulations under standardized boundary conditions)
Empirical approach to obtain values for mid-century (2050s)	Predicting future net recharge and changing water table depth, in locations that are data-poor
GCM-GFDL	Global Climate Model from the Geophysical Fluid Dynamics Laboratory (NOAA)
GCM-GISS	Global Climate Model from NASA Goddard Institute for Space Studies (GISS)
HadCM3 - Hadley Centre Coupled Model 3	Hadley Centre Coupled Model version 3 (General Circulation Model)
Observed data and model-data reanalysis	Multiple metrics (precipitation, temperature, daily snowpack snow water equivalent (SWE), and melt rates) used to categorize recent years as ”warm” or ”cool” to examine di_erences on snowmelt regimes
RegCM4	Regional Climate Model system, originally developed at the National Center for Atmospheric Research (NCAR), maintained in the Earth System Physics

	(ESP) section of the International Centre for Theoretical Physics
Synthetic scenarios	Based on IPCC 5th assessment report predictions and temporal analogues based on historical climate conditions
Weather Research and Forecasting (WRF) Model	A numerical weather prediction system for atmospheric research and operational forecasting needs (National Centre for Atmospheric Research)

7.5 Science Needs

Table 7.3 summarizes the science needs highlighted in the reviewed studies.

Table 7.3 Summary of science needs highlighted in the reviewed studies in the GLB.

Science Needs	**Related needs and information gaps**
Further characterize and reduce uncertainties associated with climate projection	• Need to recognize that climate projections (i.e., meteorological forcing) of different climate scenarios and models can vary significantly, and are sometimes even contradictory, which leads to highly variable hydrological responses and nutrient dynamics. • Ensemble modelling reduces climate prediction uncertainties by averaging multiple emission scenarios and representations. • Dynamically downscaled RCMs can capture regional influence (e.g., lake effects) on seasonal water balance. • Climate variability across time and space remains an issue for the statistical analysis of direct anthropogenic inferences.
Further characterize and reduce uncertainties associated with hydrological modeling	• Need to recognize the effects of local physiographic features on hydrological system responses to climate change. • Need to evaluate the sensitivity of different hydraulic components or the potential compounding effects of multiple hydraulic components in responding to climate change. • Necessary to improve the representation of land-surface processes and surface water flow, and to include periodic and transient processes in order to quantify seasonal hydrologic changes and its potential impacts throughout the entire hydraulic year.

	• Fully integrated models that explicitly represent groundwater flow and contaminant transport and GW-SW interactions are needed, and they must be employed at a scale fine enough to be meaningful for ecohydrological processes. • Necessary to explore new ways to address increasingly complex and computationally demanding models (that include, e.g., coupled groundwater processes, chemical transport, and temperature), which often leads to the need for a tradeoff between model complexity and representativeness.
Further understand the compound impact of climate change, land use changes and urban development on the hydrological system, and on the associated management, adaptation, mitigation options.	• Need to recognize the compound impact of climate change and urban development on groundwater quantity and quality, as well as vulnerability of drinking water sources. • More information about anthropogenic stressors and their future projections E.g., details about tile drainage in agricultural systems, what types of future crops might be grown in the region in 50-100 years? • Better understand the spatial extent and impact of high capacity well on groundwater quality and quantity compounded by climate change effects.
Better characterize hydraulic systems and improve observational data (More data, long-term monitoring).	• Long-term monitoring of all hydrologic components and soil temperatures to help better understand stressed watersheds and how they may be impacted by climate change, especially the snow melting and soil freeze/thaw effects. • More geological data, better hydrogeologic characterization across the region. • Small-scale ecological, hydrological and geomorphological data to better understand ecohydrological impacts.
Further understand climate change impact on water quality (field and modelling).	• Emphasis should be placed on examining various contaminant types (e.g., both point and non-point sources, both anthropogenic and geogenic origin).
Develop practical models to support implementation and climate change adaptation.	• Current modeling techniques are time-consuming and require large quantities of data. User-friendly tools would benefit implementation by local governments for climate change adaptation purposes.

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8 CONCLUSIONS

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8.1 Introduction

Under the Great Lakes Water Quality Agreement protocol, Annex 8 commits Canada and the United States to publish an initial report on the relevant and available groundwater science, and update this report at least once every six years, with the intent to highlight significant and relevant advancements, new issues, or constraints related to the impact of groundwater on environmental quality within the Great Lakes Basin. The initial report, *2016 Groundwater Science Relevant to the Great Lakes Water Quality Agreement: A Status Report* (*2016 Report*), provided an exhaustive review of these issues. The report was divided into six topic areas and identified the science needs relating to each of those topics. This primary report thus serves as background and context for policy makers at all levels of government within the Great Lakes Basin, as well as watershed managers and scientists more generally. The current report provides an update to the 2016 report, describing progress made and knowledge gaps that warrant addressing, as well as identifying emerging or previously unknown issues. This update is not meant to provide comprehensive details of incremental scientific progress, which are beyond the scope of this work. Updates on progress to science needs and major gaps, continued areas of concerns, and constraints are highlighted below.

The overarching conclusions of the 2016 Report were: groundwater can provide a treatment or storage zone that can protect and even improve Great Lakes water quality and aquatic ecosystem health; at the same time, the groundwater system may provide a long-term source of contaminants, which pose a threat to water quality and aquatic organisms in receiving surface waters; and finally, that there are important gaps in understanding of how groundwater affects habitat availability on the Great Lakes Basin, which impacts the ability to effectively manage this resource.

8.2 Updates and progress to Scientific Gaps and Needs from the 2016 Groundwater science relevant to the Great Lakes Water Quality Agreement

Major data gaps and science needs to improve the understanding of groundwater issues in the Great Lakes Basin were identified in the 2016 status report. The gaps and scientific needs are listed below (*in italics*), and advancements made on these issues since the previous report are described:

Advance assessment of regional scale groundwater discharge to surface waters in the Basin.

The assessment of regional scale groundwater discharge to surface waters in the Great Lakes Basin requires monitoring of hydrologic conditions and modeling of the water balance. Recent work on developing a coupled groundwater/surface-water model for the basin provides insight on the relative dynamics of the coupled system and long-term average seasonal exchange of water between the groundwater and surface-water systems (Chapter 2). Various modeling and tracer-based approaches are being developed to yield estimates of contaminant loads to receiving waters, from both point and distributed contaminant sources. Quantifying regional scale contaminant loads is an asset for effects assessment (Chapter 3); however, updated methods would be helpful, as they would complement contaminant source data with more-detailed hydrological modeling. Some advancements in relation to nutrients have been made by integrating nutrient databases with GIS information to upscale modeling (Chapter 4). In addition, recent progress has been made in terms of understanding landscape controls on nutrient fluxes to groundwater (Chapter 4). An integrated groundwater/surface water model for the Great Lakes Basin was recently published and can serve as a testbed for how such regional models can help answer questions on the role of groundwater in the system (Chapter 2).

Assessing regional scale groundwater discharge to surface water is also necessary to evaluate potential climate change impacts to groundwater. Climate change may affect timing and magnitude of rainfall events, air temperature, and the temperature of precipitation. How quickly these changes will propagate to parts of the Great Lakes Basin may depend on how they interact with the groundwater system. A better understanding of the dynamics of groundwater in the regional system may help reduce uncertainties associated with climate modeling. Understanding the dynamics of the coupled groundwater/surface-water system is mainly addressed by using ensembles of climate models and scenarios to force hydrological simulations (Chapter 7).

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.

The *2016 Report* identified quantifying sources of contaminants to groundwater as a scientific need. To date, research has mainly focused on agriculture-sourced nutrients, petroleum hydrocarbons, and road salt, with limited work addressing other contaminants, including those deemed contaminants of emerging concern. Some advancement has been made in understanding sources of the emerging contaminants known as per- and poly-fluoroalkyl substances (PFAS), whose persistence and potential toxicity at low concentrations make them a threat to Great Lakes water quality (Chapter 3). Understanding groundwater contamination in urban areas is a challenge given the high density of both modern and historical point and diffuse sources of groundwater contaminants that often are unknown (Chapter 6). Linking contaminants detected in the environment to their source is challenging because many chemicals have multiple sources and also travel long distances; this is especially complicated in urban settings (Chapter 6). Several techniques are being developed to help identify and quantify these contaminants and their sources, including a screening analysis approach, indicators based on inorganic trace elements, or major ions or stable isotopes, and cluster analysis techniques to distinguish natural background levels from areas of anthropogenic sources. New and emerging contaminants of concern, such as artificial sweeteners, have also been used as tracers/indicators (Chapter 3). Guidelines have been developed for measuring groundwater contamination, and a reaction significance factor has been created to predict nutrient removal efficiency from hyporheic zones (Chapter 3).

Advance monitoring and surveillance of groundwater quality in the Great Lakes Basin.
The *2016 Report* identified a lack of data collection and monitoring programs. This lack of information impedes decision making by governments and policy makers and impairs the ability of groundwater scientists and modellers to accurately assess and simulate changes to groundwater. For models and simulations to be effective, the monitoring data must be temporally and spatially detailed enough to reduce model uncertainty. Robust monitoring data from various locations are also needed to upscale models and predictions from local scale to regional scale. Other non-Great Lakes Basin jurisdictions are making legislative efforts to increase collection, coordination, and use of groundwater data to support decision making. Similar legislation in the Great Lakes Basin would advance the goal of coordinated accessible groundwater data. Specialists have identified the creation of a robust open-source database as an important tool for the development of geological frameworks, hydrogeological regimes, groundwater models and eventually enhanced decision making.

Advance research on local scale assessment of interaction between groundwater and surface water.
Groundwater carrying contaminants or nutrients and discharging to streams and lakes has been the focus of several field studies across the Great Lakes Basin. These studies have advanced knowledge of how discharge and cycling within the hyporheic zone can influence biogeochemical cycling and attenuation of contaminants. Several studies measured the discharge of nutrients, phosphorus and nitrate, to surface water to help assess the importance of groundwater transport to chronic (Chapter 4). Research also includes methods development to improve sampling strategies and support the upscaling of local measurements to provide regional understanding (Chapter 2).

Develop better tools for monitoring, surveillance, and local assessment of groundwater-surface water interaction.
Measuring groundwater-surface water interactions is challenging, and new methods are required to increase and improve monitoring and surveillance. There have been advancements in sensor technologies and affordability that will enhance groundwater monitoring. Information from advanced sensors would be best used by integrating these

new sensors with information and communication technology, as it would enhance effective management of field data to facilitate timely decision making. Minor gains have been made in methods development for assessing contamination impacts on groundwater, including the development of a streambed velocity probe, which can aid in flow measurement in contaminant discharge zones, as well as using novel tracers such as artificial sweeteners to measure their movement from groundwater to surface water (Chapter 3). For nutrient assessment, a novel method has been developed that estimates the timing and magnitude of nitrogen flux to surface waters (Chapter 4). For assessment of groundwater-dependent ecosystems (Chapter 5), remote sensing techniques have been developed to map and classify coastal wetlands for the entire Great Lakes Basin. For the On the U.S. part of the basin, a cumulative stress index is being developed that integrates multiple anthropogenic stressors, standardized methods and indicators (e.g., fish) for assessing coastal wetland conditions across the entire basin, with modifications that may be useful for assessing the condition of groundwater-dependent ecosystems (Chapter 5). New measuring and modeling methods have been developed to identify the link between defects in sanitary sewers and leakage and determine sewer exfiltration probability (Chapter 6).

Advance research on the role of groundwater in aquatic habitats in the Great Lakes Basin

One of the top science needs identified to better understand the impact of natural and anthropogenic changes to groundwater-dependent ecosystems is the development and application of groundwater models that can simulate recharge, flow and discharge to surface waters (Chapter 5). While such integrated models exist, to date their application for understanding aquatic habitats is limited. Progress has been made in developing inventories of the coastal wetlands of the Great Lakes. The concept of groundwater affecting stream temperature and thus habitat suitability was advanced with the creation of a river size-temperature classification system for the United States drainage, and potentially for the entire Great Lakes Basin (Chapter 5). Proposals have also been made to develop a river ecosystem mapper and classification system, which includes classification of thermal regimes related to base flow index. Advancements have been made in predicting impacts to groundwater-dependent ecosystems and assessing vulnerability, using groundwater-surface water models integrated with other ecosystem tools. A conceptual framework for assessing the ecological responses associated with stressors that impact groundwater has been developed. A recent study on the hyporheic zone has demonstrated that this transition zone can be distinguished from the benthic zone as a discrete ecological community with varying boundaries, depending on hydrological conditions (Chapter 5).

Improve the understanding of effects of urban development on groundwater.

There is a growing need to better understand urban groundwater, specifically related to stormwater infiltration systems and subsurface infrastructure projects (Chapter 6). Recent research demonstrates that urban streams are influenced by subsurface development, which provides large permeable channels that can either enhance or slow the shallow, lateral flow of groundwater, depending on other factors (Chapter 6). These anthropogenic activities in the already complex natural subsurface environment add further complexity, and while some aspects will be broadly applicable, further studies are required in order to fully comprehend how specific sites/conditions are affected.

The relationship of urban groundwater and sewers is a topic of concern; much of the sewer system infrastructure in urban areas is old and leaks. The elevation of this infrastructure relative to the saturated groundwater table controls areas of potential infiltration (groundwater entering sewers) and exfiltration (contamination of groundwater with sewer wastewater). Recent studies using tracers and other methods have consistently found substantial rates of infiltration of groundwater to sewers. While modeling exfiltration, researchers identified a need for better understanding of the exfiltration process at the pipe scale and transport of sewer leakage (Chapter 6). This knowledge would advance modeling of the fate of contaminants (Chapter 3) and meet challenges of up-scaling models from the local pipe scale to city or network scale (Chapter 6). New measuring and modeling methods have been developed to identify the link between defects in sanitary sewers and leakage and determine sewer exfiltration probability. Recent studies have directly examined the relation between stormwater and groundwater, providing greater insight into the different concentrations of contaminants (i.e., viruses, pathogens, pharmaceuticals, and personal care products) that are found in stormwater systems (Chapter 6).

Recent developments in policy and municipal programming have focused on sewer and groundwater issues. These include new policies and best practices to reduce infiltration of groundwater and inflow to sanitary sewers, which have led to upgrades and improvements in some localized sewer systems. Despite such improvements, it is likely that large areas with infiltration or exfiltration of groundwater are yet to be identified. Research on urban stormwater management has revealed that green infrastructure improvements generally increase recharge to groundwater, decrease runoff and increase stream base flow. A potential unintended consequence of green infrastructure, however, may be increased loading of contaminants to the urban groundwater system. An analysis of policies and related data illustrated that participatory governance with strong citizen influence and engagement can increase use of green infrastructure, which can, in turn, play an important role when regulatory instruments are absent (Chapter 6).

Develop scaled-up models of regional effects of groundwater on Greats Lakes Water quality.

Due to challenges of sampling groundwater quality and quantity, modeling is an important tool to increase spatial scale of assessment and prediction. There is a need to take research at small site-specific areas and upscale to stream, watershed and Great Lakes Basin scales. Advancements in this area include modeling techniques integrating nutrient/contaminant databases with GIS information systems. To aid in upscale modeling, recent progress has been made in terms of understanding landscape controls on nutrient fluxes to groundwater (Chapter 4).

When addressing the potential for predicting climate change impacts on groundwater within the Great Lakes Basin, improvements to modeling are crucial. Field data and models have been combined to study the impact of climate change on groundwater storage across a wide range of geographical locations and spatial scales. Currently, most studies report results at the field or small/medium basin scales. Although there is variability in the results, many studies at these scales concluded that groundwater systems are expected to be fairly resilient to climate change impacts (Chapter 7). Research carried out at regional scales shows uncertainty and spatial variability in the compound effect of climate change and intensification of groundwater extraction for agriculture. However, groundwater level sensitivity to climate change depends strongly on local physiographic features and uncertainty in the model simulations. Model projections at continental scales are in the early stages and still rare and uncertain in Canada, particularly concerning implications for the Great Lakes (Chapter 7). One of the first large-scale hydrological modeling studies was developed for Continental Canada using HydroGeoSphere that offers full groundwater/surface-water integration (Chapters 2 and 7). The model provided regional groundwater flow analysis for western Canada and a water balance analysis for the Great Lakes. The model was able to simulate surface drainage across most of Canada despite the highly simplified hydrostratigraphic representation and coarse mesh resolution. This study highlighted important large-scale groundwater flow systems that affect freshwater availability across the country, which could be affected by climate change and impact groundwater availability (Chapter 7).

8.3 Emerging Issues

The *2016 Report* was a comprehensive review of the state of the groundwater issues within the Great Lakes Basin. Most issues of importance were covered in that review, however there are a few issues that have emerged since that time.

There are several "new" contaminants that have increased in concern since the *2016 Report*. Per and poly-fluoroalkyl substances are a group of chemicals that are used to make heat and stain resistant products, including firefighting foams. They have become an environmental concern because of their persistence and potential toxicity at low concentrations. Other compounds not mentioned in the *2016 Report*, which need to be considered as groundwater contaminants of significant concern, include phytoestrogens (estrogen mimics), agricultural crop-derived products, and neonicotinoid pesticides (e.g., Imidacloprid). Microplastics are also a "new" concern to groundwater because they have the potential to adsorb other contaminants and have the potential to travel substantially in karst and fractured-rock environments (Chapter 3).

Groundwater ecosystems were not originally part of the *2016 Report*; however, they are starting to receive some attention. Recent progress in understanding this ecosystem has been made, but not in the Great Lakes Basin. These new research studies have included genomic assessments, investigation of impairments from toxic contaminants and from land use changes, and assessment of how groundwater-dependent organisms may influence or be influenced by hydraulic properties of groundwater flow systems (Chapter 5).

Open data resources enable easier assessment of the competing and interdependent water needs of urban cities. In addition to data access, providing tools and easy-to-use visualizations are critical ways to enhance equitable open data resources. Jurisdictions could consider incorporating universal open-data platforms, as these open datasets would advance the ability to conduct analyses and thus provide a better comprehension of the urban water system as a whole.

8.4 Major Gaps, Scientific Needs and Constraints – Updated

Although advancements have been made related to the scientific issues raised in the *2016 Report* (See 8.2), some issues have not been addressed or need more work, and some are constrained for different reasons. Below is a description of these continued gaps and needs, categorized by what is needed.

More information (data/monitoring)

By far, the most common gap/need identified in this report is more data and baseline monitoring. This knowledge is essential in developing policies and guidelines, quantifying loadings, and improving modeling accuracy and reducing uncertainty. Baseline data might also be used to assess conditions and track progress of already implemented guidelines and policies. Technologies are advancing to allow for the collection of high-frequency and, in some cases, telemetered real-time data. These technologies have the potential to reveal patterns and processes in groundwater at a much finer spatial and temporal scale than previously possible, which would better support management, decision-making, and planning related to groundwater quality. However, to capitalize on these advances, infrastructure and support must be in place to collect, process, integrate, store, visualize, manipulate, and provide access to these large datasets.

A related challenge is that information from various agencies across the Great Lakes Basin can be difficult to assemble and synthesize. Contaminated sites, for example, fall under various regulatory frameworks, leading to differences in the amount and type of information available. A national database containing all the different types of data would facilitate both management and research efforts (Chapter 6). Other aspects of contaminant groundwater research in the Great Lakes Basin also need more effort. Quantifying regional scale loads for some contaminants would be an asset for effects assessments; however, updated methods are needed to couple contaminant source data with hydrological modeling (Chapter 3).

Regarding groundwater-dependent ecosystems, more work is necessary to identify local groundwater discharges associated with critical habitats, requiring coordinated effort by various stakeholders to collect and share local knowledge. The influence of spatial patterns or patchiness of groundwater discharge to streams and nearshore environments on community structure and ecosystem function is not well understood for aquatic species that are not perceived to have commercial/recreational value (Chapter 5).

In urban areas, there is a growing need to better understand groundwater, specifically related to stormwater infiltration systems, subsurface infrastructure projects, and addressing groundwater problems such as regional flooding of basements. Properly designed and situated green stormwater infrastructure can potentially provide sustainable stormwater management by enhancing recharge. However, the impact of the stormwater on the receiving groundwater is typically not measured. Understanding of the impacts of introducing additional water, perhaps of degraded quality, to the groundwater system through green stormwater infrastructure installations presents a knowledge gap in urban water budgets. In addition, there is a need to improve understanding of the influence of stormwater on groundwater quality, and how it might relate to human and environmental health concerns in urban areas. Recent studies on stormwater and green stormwater infrastructure focused on changes to surface water flows and their metrics, and surface water quality. Even so, little is known about the impact of groundwater discharge further downstream, on urban streams and lakes. There is even less focus on quantifying groundwater quality or quantity changes caused by stormwater (Chapter 6).

To further understand the compounding impacts of climate change, land use, and urban development on the hydrological system, there is a need for more information about how anthropogenic stressors impact groundwater quality and quantity. There is also a need for long-term monitoring of all hydrologic components and soil temperatures to help better understand stressed watersheds and how they may be impacted by climate change, especially from snow melting and soil freeze/thaw effects (Chapter 7). More geological data are needed to improve hydrogeologic characterization across the basin. In addition, there is a need for more small-scale ecological, hydrological, and geomorphological data to better understand ecohydrological impacts.

Research

For some aspects of groundwater science, baseline data on their own will not address the issues, and specific research is needed to better understand the inherent dynamics and complexities. For example, to better understand contaminants in groundwater, research is needed on acute and chronic effects on susceptible organisms, specifically for endobenthic populations (Chapter 5), and more documentation is needed on the ecological effects of groundwater contamination, particularly for mixtures of contaminants (Chapter 3).

The highest priority need for new policies and programs is assessing urban effects on groundwater with a holistic approach to urban water. With the high density of construction projects requiring substantial subsurface infrastructure, guidelines and policies are needed to retain integrity of groundwater quality and quantity (Chapter 6).

Exfiltration from storm-sewer infrastructure poses a risk for toxic substance and microbial pollution release. In particular, modifications to the near-surface groundwater zone can shorten travel distance of contaminants, leading to less attenuation and increasing exposure. This review found no policies or programs in the Great Lakes Basin related to quantifying leakage from municipal sanitary sewers to groundwater, or to quantifying fluxes of contaminants from urban sources to groundwater, which in turn would allow for estimates of groundwater contaminant loads (and associated risks) in urban areas and downstream at the watershed level. Therefore, future research is needed on assessing hydrologic changes created by sewer infrastructure and how this affects subsurface pollutant risk (Chapter 6). Although recent studies have directly examined the relation between stormwater and groundwater contaminants, more research is needed on the fate, transport and persistence of stormwater contaminants that infiltrate groundwater (Chapter 3).

For predicting and modeling impacts of climate change on groundwater in the Great Lakes Basin, there is a need to recognize how local physiographic features affect the hydrological system responses to climate change. The compound impact of climate change (Chapter 7) and urban development (Chapter 6) on groundwater quantity and quality, and the vulnerability of drinking water sources may be important to consider. To further understand the impact of climate change on water quality (field and modeling), more research could be directed toward examining various contaminant types (i.e., both point and diffuse sources, of both anthropogenic and geogenic origins) (Chapter 7).

Improved Modeling

Because of the challenges of data collection in the groundwater environment, modeling is an important tool, especially for predicting the impacts of climate change.
Quantifying regional-scale contaminant loads would be an asset for assessing the effects of contaminants in groundwater; however, novel methods are needed to update contaminant source data with hydrological modeling (Chapter 3).

In urban environments, concern from sewer exfiltration is not only limited to groundwater, but also to vapor transport from sewage pipes into buildings. Sewer vapor testing could be considered as part of the conceptual site model at these higher-risk locations. In addition, improvements are needed for existing models in water balance calculations to better account for evapotranspiration and infiltration. To get a better understanding of green stormwater infrastructure and its impact on groundwater, multiscale models are recommended (Chapter 6).

There is a need to reduce uncertainties associated with modelled climate projections, as different climate scenarios and models can vary significantly, and are sometimes even contradictory, which leads to highly variable hydrological responses and nutrient dynamics. Increasing the use of ensemble modeling reduces climate prediction uncertainties by averaging multiple emission scenarios and representations. Further characterization and reduction of uncertainty associated with hydrological modeling is needed. Thus, there is a need to evaluate the sensitivity of different hydraulic components or the potential compounding effects of multiple hydraulic components in responding to climate change. Fully integrated models that explicitly represent groundwater flow, contaminant transport and groundwater-surface water interactions are needed, and they must be employed at a scale fine enough to be meaningful for ecohydrological processes. New methods are needed to address increasingly complex and computationally demanding models, which often lead to the need for a trade-off between model complexity and representativeness (Chapter 7).

To further understand climate change impacts on water quality (field and modeling), there is a need for practical models to support implementation and climate change adaptation. Current modeling techniques are time-consuming and require large quantities of data. User friendly tools would benefit implementation by local governments for climate change adaptation purposes (Chapter 7).

Integration of New Technology

Since the *2016 Report*, there were advancements in sensor technology, availability, and affordability, which will enhance groundwater monitoring. To make best use of this information, it would be beneficial to work towards integrating these new sensors with information and communication technology to enhance effective management of field data to facilitate timely decision making.