Groundwater Science Relevant to the Great Lakes Water Quality Agreement: A status report

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Executive Summary*

Prepared for the Great Lakes Executive Committee
by the Annex 8 Subcommittee

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Authors (alphabetical order): Cindy Chu,[1] Brewster Conant Jr.,[2] Paulin Coulibaly,[3] Serban Danielescu,[4,5] Matt Diebel,[6] Don Ford,[7] Rick Gerber,[8] Norm Grannemann,[9] Ken Howard,[1] Matt Mitro,[6] David Hyndman,[10] Scott MacRitchie,[11] Linda Nicks,[12] Jeff Patzke,[13] Cam Portt,[14] Howard Reeves,[8] Clare Robinson,[15] James W. Roy,[4] Gayle Soo Chan,[16] John Spoelstra,[4,2] Jon Sykes,[2] Dale Van Stempvoort,[4] Mary Ellen Vollbrecht,[5] Kelly Warner[8]

Report Editors: Norm Grannemann[8] and Dale Van Stempvoort[4]

[1]University of Toronto, [2]University of Waterloo, [3]McMaster University, [4]Environment and Climate Change Canada, [5]Agriculture and Agri-Food Canada, [6]Wisconsin Department of Natural Resources, [7]Toronto and Region Conservation Authority, [8]Conservation Authorities Moraine Coalition, [9]U.S. Geological Survey, [10]Michigan State University, [11]Ontario Ministry of the Environment and Climate Change, [12]Upper Thames River Conservation Authority, [13]Ohio Environmental Protection Agency, [14]Portt and Associates, [15]Western University, [16] Credit Valley Conservation Authority

Members of the Annex 8 subcommittee: Jon Allan, Michigan Office of the Great Lakes; Mike Baker, Ohio Environmental Protection Agency; Norm Grannemann, US Geological Survey (co-chair); Scott MacRitchie, Ontario Ministry of the Environment and Climate Change (alternate); Lisa Sealock, Environment and Climate Change Canada; Ian Smith, Ontario Ministry of the Environment and Climate Change; Gayle Soochan, Ontario Conservation Authority; Dale Van Stempvoort, Environment and Climate Change Canada (co-chair); Mary Ellen Vollbrecht, Wisconsin Department of Natural Resources

*For references, a glossary of terms and further details, please see the full report

1. Context, Scope and Purpose of This Report

Being underground and “out of sight” is one reason that the role of groundwater in the Great Lakes Basin has often been overlooked, although the volume of fresh groundwater in the basin is approximately equal to that of Lake Huron. For many years, groundwater science in the Great Lakes Basin was focused on finding drinking water. In the last several decades, however, efforts are being devoted to understanding groundwater as part of the overall water budget and ecosystems in the basin. Awareness is growing of the strong interaction between surface water and groundwater, and a better understanding of this interaction is required because essentially all groundwater is flowing towards and will eventually discharge into surface water if not extracted. This interaction and connection has implications for many Great Lakes water quality issues.

When the Great Lakes Water Quality Agreement (GLWQA) was signed in 1972 by the Governments of Canada and the United States (the “Parties”), the importance of groundwater was not recognized. When it was revised in 1978, Annex 16 was added to the GLWQA, to address “pollution from contaminated groundwater,” but no formal process for reporting was provided. In 1987, a modified Annex 16 called for progress reports. In 2012, a new Annex 8 was formed to address groundwater more holistically, and committed the Parties to coordinate groundwater science and management actions. The initial task is to “publish a report on the relevant and available groundwater science” (this report). The broader Annex mandate is to (1) “identify groundwater impacts on the chemical, physical and biological integrity of the Waters of the Great Lakes;” (2) “analyze contaminants, including nutrients in groundwater, derived from both point and non-point sources impacting the Waters of the Great Lakes;” (3) “assess information gaps and science needs related to groundwater to protect the quality of the Waters of the Great Lakes”; and (4) “analyze other factors, such as climate change, that individually or cumulatively affect groundwater’s impact on the quality of the Waters of the Great Lakes.”

This report describes how the natural flux of groundwater to the Great Lakes and their tributaries can enhance water quality and water quantity and provide essential habitats for Great Lakes ecosystems. This report also describes how groundwater can be a transmitter (vector) of contaminants and excessive loads of nutrients, which are derived from both non-point sources and point sources, to the Great Lakes. Contaminants are defined as substances that are released to the environment by human activity which have, or potentially may have, undesirable or harmful effects on human health or aquatic ecosystems. In addition to the direct flux of groundwater that transports contaminants and nutrients to the Great Lakes, the flux of groundwater to streams flowing into the Great Lakes also must be considered because the ecology and habitats of streams are interconnected with ecology of the Great Lakes (for example, fish spawning and migration).

2. Groundwater/Surface water Interaction

Groundwater is increasingly recognized as being important in the water budget of the Great Lakes and for maintaining chemical, physical, and biological integrity of the Great Lakes Basin. Direct and indirect discharges of groundwater are estimated to be as much as 2.7% and 42%, respectively, of inflows to the Great Lakes, and the groundwater component of streamflow averages approximately 70% of the flow in streams within the basin.

Groundwater exchanges with surface water bodies including streams, lakes, and wetlands. This interaction typically occurs as groundwater discharge, including base-flow contributions to streamflow, which maintain streamflow and inland lake levels, especially during droughts. Groundwater exchanges also may occur as groundwater recharge where surface water moves into the subsurface. These exchanges occur through transition zones: volumes of streambeds, lakebeds, wetlands, and adjacent geological materials where characteristics change from a groundwater dominated system to a surface water dominated system. The nature of groundwater/surface water exchange is governed by hydraulic properties, including gradients, which determine direction of flow, and conductivities of subsurface geological materials, which determine the ability of these materials to transmit water.

Surface water bodies can either gain or lose water in areas of groundwater/surface water exchange. A gaining stream receives groundwater discharge, and a losing stream recharges the subsurface. The exchanges are complex and variable on spatial scales ranging from centimeters to tens of kilometers. Regionally, groundwater discharge is controlled by topography, stream slopes, and underlying geology. In each stream reach, discharge varies as a function of sediment composition, streambed topography, meandering patterns, presence of fine-grained organic matter, and stream stage relative to the groundwater table. Stream water can penetrate streambed sediments, move laterally through them, potentially mix with groundwater, and then re-enter the stream farther downstream. Such transition zones (called hyporheic zones) have unique hydrological, biological, and geochemical characteristics, and also have the potential to attenuate contaminants (Sections 3, 4). Groundwater/surface water exchange also varies over time, with seasonal changes in precipitation and evapotranspiration that affect groundwater levels. Runoff from storms and snowmelt may increase river stages and cause reversals in hydraulic gradients and thereby reverse the nature of groundwater/surface water exchange. During peak streamflow, surface water moves into adjacent streambanks as bank storage, and then that stored water can subsequently discharge back to the stream when the stream stage declines; similar reversals occur along lakeshores where storm winds may change surface water levels.

Direct and indirect groundwater discharge to the Great Lakes

Groundwater contribution to a Great Lake is direct when it discharges through the lakebed and is indirect when groundwater discharges into streams or wetlands that flow into the Great Lakes. Most groundwater follows short (local-scale) flowpaths through shallow geological units, largely glacial deposits (deposited from ice or glacial meltwater). Estimates of direct groundwater discharge to each of the Great Lakes range from about 0.1% to 2.7% of total inflows, and discharge tends to be focused in nearshore areas. Based on numerical modeling of groundwater flow for the entire Lake Michigan drainage basin, an estimated 1.1% of the total lake inflow is from direct groundwater discharge. The dominant groundwater contribution to the Great Lakes is indirect discharge to tributary streams, which is estimated as 22% to 43% of total water influx to these lakes (excluding the flow between these lakes through connecting channels). Large uncertainties are associated with all of these estimates, and additional research is needed to better quantify direct and indirect groundwater discharge to the Great Lakes.

Relationship of groundwater discharge to water quality

Discharging groundwater may be relatively pristine and improve surface water quality, or groundwater may be contaminated and adversely affect surface water quality (see

Sections 3, 4, and 5). Adverse effects can be the result of either concentrations of contaminants in discharging groundwater or the total mass loading of substances from groundwater. To evaluate effects on the receiving body of water, the quality, quantity, and flowpaths of the discharging water and the role of potential attenuation processes in the transition zone (see Sections 3, 4) must be known. Discharge of groundwater commonly moderates surface water temperatures, thus providing suitable fish habitat (thermal refuge) and spawning areas (Section 4). Constituents in groundwater may moderate the pH of surface waters or provide nutrients that affect growth of macrophytes and other aquatic vegetation. Differential discharge patterns provide preferential habitats for benthic and hyporheic organisms and enhance biodiversity.

Human effects on groundwater/surface water exchanges in the Great Lakes Basin

Human activities affect groundwater/surface water exchange. Virtually all groundwater is moving towards and will eventually discharge into surface water, including contaminated groundwater, unless extracted. Groundwater withdrawals (e.g. pumping for water supply) may induce infiltration from surface water bodies, or reduce the flux of groundwater to surface water bodies, potentially lowering surface water levels, or drying them up. Urbanization and land-use changes alter groundwater recharge rates and surface water runoff in streams. Human-induced climate change alters precipitation patterns, recharge to groundwater, groundwater temperatures, and runoff (Section 7).

Priority science needs related to groundwater/surface water exchange

- Tools are needed to appropriately characterize spatial heterogeneity and temporal variability in groundwater/surface water exchanges on local scales to model and make predictions on a regional scale;
- Accurate quantification of groundwater discharges to surface water is needed;
- Identification of significant groundwater flowpaths to surface water and delineation of groundwater discharge zones are needed;
- Critical relationships between groundwater discharge and aquatic ecosystem health need to be determined; and
- Characterization and understanding of the role of transition zone processes on the quality of surface water is needed.

3. Influence of Groundwater Contaminants on the Great Lakes

As noted in Section 2, groundwater/surface water exchanges can have positive effects on the water quality of surface waters in the Great Lakes Basin. Uncontaminated groundwater inputs can reduce concentrations of contaminated surface water through dilution. In such cases, groundwater discharge zones may be refuges for aquatic life. Also, contaminated surface water that enters streambeds and later returns to surface water may have reduced contaminant loads due to attenuation processes in the subsurface. Indeed, the hyporheic zone has been termed the “river’s liver.”

Groundwater also can transport contaminants to surface waters. The concern may be either concentrations of contaminants in discharging groundwater or total mass loading of substances from groundwater. Groundwater can become contaminated with various chemicals and other substances (including mixtures) including nutrients, salts (e.g., road/deicing salt), metals, petroleum hydrocarbons, chlorinated solvents and additives, radionuclides, pharmaceuticals and other emerging contaminants, pesticides, and pathogens. Groundwater contamination may occur as accidental releases or intentional applications, releases at one point (point source) or over broad areas (non-point source), single event or continuous releases, and the contaminants may be synthetic or naturally occurring substances that are released by human activities (e.g., road salt). The contaminants that are commonly found in groundwater are typically in widespread use or common in the environment, are soluble in water, and have chemical properties that allow them to travel unhindered through subsurface materials. Many contaminants also follow other pathways to surface water, which may obscure groundwater inputs. Urban groundwater commonly has complex mixtures of contaminants and pathways.

Incidents of groundwater contamination in the Great Lakes Basin are quite common and well known, with information residing in many government databases (including those generated by monitoring programs) and the published scientific literature. However, it is likely that much groundwater contamination goes undetected.

Contaminants transported by groundwater can potentially impair use of surface waters for water supplies or fish consumption (via contaminant bioaccumulation), or contribute to algal blooms that make these surface waters unsuitable for recreation. The risk that contaminants pose depends on the extent and distribution of contaminant sources, the fate and ease of their transport in the subsurface prior to reaching receptors, and their toxicity or other deleterious effects. The water quality and ecosystems of the Great Lakes may be affected by direct groundwater discharge through lakebeds and via indirect groundwater discharge to tributaries and connecting water bodies (Section 2). Groundwater may also serve as a long-term source of contaminants or nutrients that are essentially stored in the subsurface and delivered slowly to surface water. This potential long-term source of contaminants or nutrients warrants consideration when evaluating the expected effectiveness of management actions designed to improve surface water quality and may be the rate limiting factor with respect to achieving total restoration.

Shallow groundwater is more likely than deep groundwater to be impacted by contaminants. Contaminant attenuation mechanisms in groundwater include sorption onto solid surfaces, mineral precipitation, radiogenic decay, microbial degradation, abiotic reactions, volatilization, and uptake by organisms (including plants). Some of these processes may be enhanced in transition zones and groundwater discharge areas, but these zones also provide habitats for a large variety of benthic and interstitial organisms, which are thus susceptible to harm by contaminated groundwater. Organisms that reside in groundwater discharge zones can be exposed to high concentrations of groundwater contaminants before dilution by mixing with surface water. In contrast, those dwelling in hyporheic zones of streams or in wave swash zones of lakes may benefit from dilution by influxing surface water. Other exposures to groundwater-derived contaminants can occur within the surface water column, or from contact or ingestion of impacted sediment, detritus, or benthic organisms. Discharging plumes of contaminated groundwater commonly have low dissolved oxygen levels, which may adversely affect aquatic ecosystems. The unique nature of the biota and possible adverse exposure scenarios in transition zones has prompted the U.S. Environmental Protection Agency and Environment Canada to issue guidance for evaluating these zones in ecological risk assessments.

Few documents in the scientific literature or in government reports (e.g., as related to Areas of Concern) provide relevant information on contaminated groundwater discharge to surface water bodies of the Great Lakes Basin. Many of these involve localized contamination and focus on fate and transport processes; much less information is available on loadings and cumulative effects at larger scales. Thus, it is not known where the worst discharges of contaminated groundwater to surface water are occurring in the Great Lakes Basin and how these correlate to sensitive aquatic ecosystems, or to what extent contamination is accumulating in sediments in the basin due to groundwater inputs. In addition, it is not known how discharge of contaminated groundwater to surface water will change over time. The potential for groundwater contaminants to reach surface water can be estimated using groundwater data and conceptual or numerical models, but determining actual discharge locations (transition zone or water body) requires direct field measurements because of the uncertainties in attenuation processes and small-scale variations in groundwater flow patterns. Assessing effects of groundwater contaminant discharge by measuring increases in contaminant concentrations (or related tracers) in surface water bodies commonly is unsuccessful because of dilution or other attenuation processes. Commonly, it may be necessary to directly sample discharging groundwater in the sediments beneath the surface water body where maximum concentrations and exposures occur. Various sampling methods, when combined with measurements of groundwater discharge, can be used to assess contaminant fluxes to surface water.

Priority science needs related to the effects of contaminants in groundwater on Great Lakes water quality

- Compiling information on groundwater contaminant sources that threaten surface waters in the basin;
- Determining better methods for detection and assessment of groundwater contamination discharging into surface water bodies;
- Improving assessment of the remediation potential of the subsurface (especially the transition zone);
- Determining the sensitivity of transition zone organisms to variations in groundwater discharge and quality;
- Assessing the ecological effects of groundwater contaminants; and
- Determining regional-scale flux of contaminants from groundwater to the Great Lakes waters.

4. Groundwater and Nutrients in the Great Lakes

Excess nutrients degrade water quality in the Great Lakes Basin by stimulating excessive macrophyte and algal growth (eutrophication). This can result in destruction of fish and wildlife habitats, loss of species diversity, and negative effects on human water uses such as recreational activities, tourism, fisheries, and drinking water supply. Excessive phosphorus loading is implicated as a main factor causing eutrophication in the Great Lakes. Under certain conditions, excessive nitrogen, silica, and iron also stimulate algae growth in the Great Lakes.

Management of nutrient loading to the Great Lakes has focused primarily on controlling inputs from point sources (e.g., wastewater treatment plants), banning phosphate detergents, and implementing agricultural best management practices. Groundwater commonly is identified as a potential non-point nutrient source, but the role of groundwater remains poorly understood, in part because of the difficulty in quantifying groundwater nutrient loading to surface waters.

Both nitrogen and phosphorus undergo cycling in the environment, and occur in different forms as nutrients, which have different mobility in groundwater. Nitrate, which is very soluble and mobile in groundwater, is one of the most ubiquitous groundwater contaminants. The dominant attenuation process of nitrate is denitrification (reduction of nitrate to nitrogen gases). Denitrification occurs under anaerobic conditions, which commonly exist in transition zones near the interface between groundwater and surface waters, including riparian zones and hyporheic zones. Consequently, these transition zones can have a disproportionate effect on regulating fluxes of nitrogen from groundwater to surface water. Orthophosphate is the most important form of phosphorus in groundwater and may react with cations to form stable minerals, adsorb to sediment, or be taken up by plants and converted to organic phosphorus. Because of the tendency of phosphorus to accumulate in sediment, it is generally assumed that orthophosphate is not mobile in groundwater, and that surface runoff and sediment erosion dominate phosphorus loading to surface waters. However, increasing evidence indicates that under certain conditions, orthophosphate can be mobile in groundwater. Orthophosphate is more mobile in aquifers with high pH, high organic content, low metal oxide content, and anoxic conditions.

Nutrient concentrations in groundwater vary widely with land use practices, landscape characteristics, and subsurface conditions. Nitrate concentrations commonly are elevated in urban and agricultural areas; however, concentrations of phosphorus and other forms of nitrogen generally are not elevated in most areas. In riparian zones, geochemical processes generally decrease nitrate and increase phosphorus concentrations in groundwater before its discharge to surface waters; however, few monitoring wells are located in these areas to measure these effects. Therefore, existing monitoring data likely do not provide a complete picture of the nutrients that actually reach surface water.

Sources of nutrients in groundwater

With about 35% of land in the Great Lakes Basin being farmed, agricultural practices are a substantial source of nutrients to aquifers in the basin. Phosphorus fertilizer application rates have slightly decreased in recent years, but nitrogen fertilizer application rates continue to steadily increase. Confined livestock operations are of particular concern because of the large amount of manure produced and disposed of through land application. Many non-agricultural sources contribute nutrients; thus, nitrate concentrations in groundwater are sometimes higher in urban areas than in surrounding agricultural areas. Non-agricultural sources include septic systems, leaky underground sewer lines in urban areas (Section 6), non-agricultural fertilizer uses, and municipal and industrial landfills, particularly closed unlined landfills, many of which are located along the shores and tributaries of the Great Lakes.

Discharge of nutrients from groundwater to surface water

Shallow glacial deposits are most vulnerable to nutrient contamination (Section 2). Groundwater discharge can have beneficial or adverse effects on water quality in tributaries (Sections 2, 3). The effects are strongest during low flow periods when base flow is sustained mainly through groundwater discharge; however, the contribution of groundwater nutrient loading to water quality of streams of the Great Lakes Basin is not well understood. A substantial portion of nitrate in streams may be derived from groundwater. Phosphorus loading from groundwater may also be substantial, particularly in settings with coarse-grained soils and shallow confining layers, soils that are artificially drained, or where preferential flow is through fractures and macropores. Recognition is increasing that the ecological health of streams may be controlled by continuous phosphorus inputs, such as groundwater discharge, that dominate during periods when the biological demand is greatest (e.g., low flow periods during summer).

Evaluating groundwater nutrient loading to tributaries is extremely challenging. Groundwater discharge is particularly difficult to quantify due to high temporal and spatial variability (Section 2). Furthermore, the discharge of nutrients is also controlled by the specific nutrient sources and by the complex biogeochemical reactions and hydrological processes occurring as nutrients are transported from their source to a receiving surface water body. Nutrient loading from groundwater is commonly highly regulated by processes that occur in transition zones (e.g., hyporheic zones) and riparian zones. Riparian zones often remove nutrients in groundwater before their discharge to surface waters. Reactions occurring in hyporheic zones (see Section 2) can substantially modify the chemistry of discharging groundwater or infiltrating surface water. Reactions in the hyporheic zones can change the form of dissolved nitrogen compounds, and regulate phosphorus by providing temporary storage. The functioning of these zones is extremely complex and strongly affected by spatial heterogeneities, flowpath residence times, and events such as streambank flooding. Despite these complications, discharge of groundwater to streams may be an important pathway for nutrient delivery to the Great Lakes.

Although direct groundwater discharge is only estimated to be a small component in the Great Lakes water balances (Section 2), this direct discharge may play a disproportionately important role in delivering nutrients to the lakes. In particular, nutrient loading via direct groundwater discharge may be considerable where shallow aquifers in shoreline areas have high nutrient concentrations.

Priority science needs related to the impacts of nutrients in groundwater on Great Lakes water quality

- Determining linkages among land-use, land management, and groundwater nutrient loading;
- Defining the role of transition zones and other zones in regulating groundwater nutrient fluxes to surface waters;
- Upscaling local scientific understanding to regional scale assessments; and
- Assessing the availability and of groundwater quality data.

5. Groundwater and Aquatic Habitats in the Great Lakes

Groundwater affects the water budgets and availability of suitable habitat for organisms within the Great Lakes, coastal wetlands, and the inland lakes, streams, and wetlands within the Great Lakes Basin. Groundwater fluxes into and out of aquatic ecosystems affect the hydrological, thermal, and chemical characteristics, and consequently affect the quantity, quality, and types of habitats available to biota. The natural chemistry of groundwater is beneficial, even essential to some aquatic ecosystems (e.g., calcareous or rich fens). The chemistry of groundwater that affects aquatic habitats can be influenced by the surrounding geology and human activities in the watershed (e.g., contaminants, see Sections 2, 3, and 4).

Effects of groundwater in Great Lakes nearshore habitats, tributaries, and wetlands

Nearshore areas of the Great Lakes provide diverse, essential habitats and link the terrestrial watershed and open water. The nearshore areas are the focal areas for water quantity, water quality and natural resource issues in the Great Lakes because these areas are most affected by human stressors. In general, direct groundwater discharge to the Great Lakes is highest in nearshore areas, but its spatial heterogeneity (due to differences in hydraulic properties of geologic materials and other factors, see Section 2) affects the quantity, quality, and types of habitats available to biota. Groundwater temperatures are relatively constant so groundwater discharges can moderate surface water temperatures and affect habitats. Studies demonstrating the effects of temperature on nearshore biota or habitat are abundant, but studies linking the effects on both habitat and biota are lacking. Comparative analyses of nearshore habitat conditions and communities in high versus low groundwater discharge conditions are also lacking.

Compared to nearshore areas, groundwater inputs to streams may have a relatively greater effect on the chemical and thermal characteristics because most of the water in some streams may be derived directly from groundwater (Section 2). Streams that supply water to the Great Lakes provide habitat for riparian and riverine flora and fauna, and are the principal spawning and nursery habitats for one-third of the fishes in the Great Lakes. Much of the water flowing in tributaries is derived from the discharge of groundwater (Section 2), exposing the riverine biota to groundwater-transported nutrients and contaminants (Sections 3, 4). The thermal characteristics of streams are determined by the relative effects of groundwater, stream morphometry, and climate and watershed characteristics. The magnitude, timing, and spatial variability of discharge can affect the thermal regimes, affecting the structures of stream communities. In winter, groundwater seeps provide overwintering habitat free of subsurface ice; in summer, groundwater provides cool stream temperatures, and refuges for species near their upper thermal limits. Stream benthic invertebrate abundance, taxonomic richness, and periphyton respiration can also be enhanced by a high rate of groundwater discharge.

Coastal and inland wetlands are some of the most ecologically diverse and biologically productive systems in the Great Lakes region, and have an important role in attenuating human impacts (e.g., nutrients, sediments) on water resources. Ninety percent of the wetlands in Great Lakes coastal areas are marshes; other major types include swamps, bogs, and fens. Two types of groundwater-dependent coastal wetlands along the Great Lakes have been distinguished: rich coastal fens and rich conifer swamps. Groundwater interaction with these wetlands is dependent in part on the geology. The groundwater provides a stable influx of water and nutrients, and may also contribute contaminants. Linkages between water budget components and wetlands are not well known, due largely to poor understanding of how groundwater flows into and out of wetlands. Few studies are available for groundwater effects on thermal conditions of habitats of these fens and swamps.

Priority science needs related to the role of groundwater on Great Lakes habitats

- Mapping of groundwater recharge and discharge because this information is essential for understanding its effects on habitat;
- Integrating groundwater models with other ecosystem models, such as nearshore hydrodynamic, tributary and wetland thermal and hydrological models to determine ecological relationships between individual species, populations, or communities and groundwater discharge;
- Evaluating the importance of groundwater discharge on species distributions and ecosystem attributes;
- Evaluating the importance of spatial patterns in groundwater discharge on ecosystem attributes; and
- Identifying ecosystems that are vulnerable to changes in groundwater discharge.

6. Effects of Urban Development on Groundwater

The Great Lakes Basin hosts some of North America's most populous cities, and urbanization is increasing. Groundwater can be an important source of supply for sprawling city suburbs and smaller, rural towns; however, most large cities in the basin draw most of their water from the Great Lakes meaning that urban groundwater attracts little attention until problems arise. Problems include water quality impacts on receiving water bodies and sensitive aquatic ecosystems, and rising groundwater levels.

Quantity and quality issues

Although urbanization may reduce direct recharge to groundwater, urbanization also radically alters the entire water cycle, introducing new sources of recharge that may more than offset any losses of direct recharge. These sources include infiltration from septic systems, leaking sewers and water mains, excessive urban irrigation, and runoff either naturally as indirect recharge or intentionally as a consequence of stormwater management schemes. Over time, excess recharge can lead to rising groundwater levels and an upward flushing of salts and contaminants that had previously accumulated in the shallow unsaturated zone. These rising groundwater levels can cause flooding of streets, cellars, sewers, septic systems, utility ducts, and transport tunnels; reduce the bearing capacity of structures; and affect amenity space by water-logging sports fields and killing trees. "Urban karst" (e.g. cracks in the impermeable pavement, permeable zones associated with fill material, presence of underground pipe networks) together with green infrastructure, strongly affects urban recharge and shallow groundwater flow. Dewatering for construction may affect adjacent surface water bodies such as rivers and lakes, and may have profound effects on nearshore water temperature, clarity, nutrient, and ion chemistry, thereby affecting habitat quality.

In cities throughout the Great Lakes Basin, urban groundwater commonly is contaminated by many different urban-sourced pollutants, such as nutrients (especially nitrate), salt, chlorinated and petroleum hydrocarbons, metals and a broad range of synthetic chemicals (Sections 3, 4). In many urban areas, a high density of sources effectively merges to create a distributed source. Most of this contaminated groundwater will enter the Great Lakes, directly as lakeshore discharge or indirectly via drains, streams, and tunnels. Many of the contaminants in urban groundwater are a legacy of past practices (e.g. brownfield sites in industrialized ports). Road salt, leaking sewers, and closed, unlined landfills represent some of the threats to urban groundwater. About one-half of the salt applied to roads and other areas in urban areas enters the subsurface, causing a gradual long-term increase in the salinity of groundwater and receiving streams. Urban streams in the Great Lakes Basin already have base-flow chloride concentrations considered chronically toxic for many freshwater species. Urban growth and industrial development throughout the basin has occurred near the lakes and streams such that residence times for polluted groundwater often tend to be short (e.g., less than 1 year). This poses a considerable threat to fish-spawning grounds and similarly sensitive groundwater-dependent ecosystems.

Some issues in large urban areas in the Great Lakes Basin

During the mid- to late 1900s, westward expansion of the Chicago suburbs increased the demand for groundwater causing a lowering of regional water levels in the shallow aquifers. The drilling of deep wells raised concerns that deep saline water and/or radium would be drawn into shallow aquifers, which were already showing evidence of degradation by urban pollutants. Continuation of urban sprawl in the Greater Toronto Area has led to seriously contaminated groundwater in the form of polluted urban springs.

Priority science needs related to the impacts of urbanization on groundwater in the Great Lakes Basin

- Increased groundwater monitoring, collection of water use data, and development of models for urban water management and risk assessment;
- Collation of information on subsurface infrastructure and research on “urban karst;” and
- Research to advance understanding for improved stormwater management and for mitigation of impacts of dewatering.

7. Climate Change Impacts on Groundwater

The impact of climate change on the quality and quantity of groundwater in the Great Lakes Basin is poorly understood. Climate change has the potential to alter the physical and chemical properties of waters of the Great Lakes Basin and ecological functions of those waters. Increases in seasonal temperatures and changes in amounts and distribution of precipitation that are projected to occur could lead to fundamental changes to the water cycle and how water is managed. Changes will likely include timing and amount of water that recharges the groundwater system. The quality and quantity of groundwater available for drinking water and ecosystems such as cold water fish in streams will also likely be affected.

Instrumental observations show that land and sea surface temperatures have increased over the last 100 years, and global average temperatures are projected to rise another 2 to 4.7°C by the end of the century with even larger changes projected over land masses. This will affect water resources through changes in precipitation, wind speed, relative humidity, and the resulting evapotranspiration. Projected increases in cold season temperatures across the Great Lakes Basin would decrease the length of the freezing season, affecting runoff and infiltration; however, soil temperatures during the winter are decreasing, perhaps because of thinner, less-insulating snowpacks, illustrating the complex responses of natural systems to slow atmospheric warming. Few studies in the Great Lakes Basin have estimated how groundwater recharge varies in both space and time. These estimates are sensitive to soil temperature, snow accumulation, and snowmelt. Groundwater has a more complex relationship with climate than surface water. A modeling study of the Muskegon River in Michigan indicated that increased air temperatures increased evapotranspiration, but increasing precipitation in the winter months led to increases in groundwater recharge and increased streamflows.

Non-climate factors will continue to affect the supply and demand of water under a changing climate. Few studies of the cumulative effects of climate change and human activities on groundwater resources are available. Modeling of the effect of human activities and land use on regional climate of the Great Lakes Basin indicates different responses, such as local increases or decreases in both evapotranspiration and runoff.

Climate, groundwater and projections: assessment of impacts

The assumption that the water cycle varies within a known range based on past observations of temperature, precipitation, and streamflow is no longer valid because of changing climate. For effective management, potential changes to the water cycle can be investigated using the projections from the Global Circulation Models (GCMs). However, these projections are based on a grid size of about 200 km, which is too coarse for the regional scale at which water resources management occurs, including the Great Lakes Basin. To provide the required information at a regional scale, two down-scaling techniques have been developed: statistical downscaling and Regional Climate Models (RCMs); however, GCM uncertainty is generally larger than downscaling uncertainty, and both are consistently greater than uncertainty from hydrological modelling or natural variability.

The ensemble approach, using projections from multiple GCMs and RCMs, is used to address this uncertainty; however, dissatisfaction with the remaining uncertainty associated with this "top-down" approach to downscaling-modeling has resulted in the development of an alternative approach: decision-scaling, a "bottom-up" approach. Potential vulnerabilities are defined by stakeholders and experts as thresholds (coping zones) for specific parameters of interest such as groundwater level or lake level. A climate domain is then constructed that contains the climate states required to cause the parameter of interest to exceed thresholds, using multiple climate simulations with specific or tailored projections based on past climate extremes. The "plausibility" of the climate state is then evaluated, as demonstrated in the International Upper Great Lakes Study.

Effects on groundwater quality and quantity

Few studies have investigated the effect of climate change on groundwater quality in the Great Lakes Basin. There continues to be uncertainty about the magnitude and even the direction of changes to groundwater recharge or levels in the Great Lakes Basin, demonstrating that we do not currently have the ability to quantitatively predict the magnitude or direction of the effects of climate change on groundwater resources with confidence.

Priority science needs related to the impacts of climate change on groundwater in the Great Lakes Basin

- Development of methods for uncertainty analysis for each step of the down-scaling modeling approach;
- Development of methods to identify and assess changing frequency and intensity of extreme events;
- Development and application of integrated models for climate, surface water, and groundwater;
- Development and application of future land and water use scenarios to model effects on groundwater; and
- Integrated hydrological monitoring, including groundwater.

8. Conclusions and Summary of Major Science Needs

A key question that is addressed by this report can be summarized as follows: Does groundwater improve or adversely impact Great Lakes water quality? As discussed in the previous sections, the flow of groundwater to streams in the Great Lakes Basin or directly to the Great Lakes can either improve or degrade water quality, and in some areas may simultaneously contribute both negative and positive effects. Thus, this report provides a range of responses to the above question, which can be summarized in the following five points:

1. Groundwater enhances water quality of the Great Lakes

The discharge of groundwater to streams flowing into the Great Lakes, and directly to the Great Lakes, contributes significantly to the replenishment of the water supply of the lakes. The discharge of groundwater, notably from pristine areas, to streams flowing into the Great Lakes, or directly to the Great Lakes, helps maintain the water quality of the lakes. This groundwater plays a crucial role in maintaining water quantity, quality, and temperature of habitats, some of which (perennial streams, coastal fens) are groundwater-dependent ecosystems.

2. Contaminated groundwater adversely affects Great Lakes water quality

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

3. Groundwater provides a treatment or storage zone that can protect Great Lakes water quality

Processes occurring in the subsurface can naturally attenuate, immobilize, or remove many contaminants. These processes commonly are enhanced in “transition zones” where exchange of surface water and groundwater occur. However, science gaps remain regarding the fate of contaminants in groundwater. For example, the available laboratory tests on which our current understanding of the fate of contaminants is based commonly do not pertain directly to groundwater conditions. Even when contaminants are not degraded or removed in the subsurface, groundwater can act as a zone of temporary or long-term storage (e.g., chloride trapped in clay-rich deposits), providing some protection of the water quality of streams in the Great Lakes Basin and of the Great Lakes.

4. Groundwater provides a long-term source of contaminants negatively affecting Great Lakes water quality

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

5. There are gaps in our understanding of how groundwater affects Great Lakes water quality

New approaches that provide more comprehensive tracking and accounting for the flow of contaminants in the Great Lakes Basin, including fluxes from groundwater to surface water, and the reverse (e.g., bank storage), are needed. As described in the following section, more comprehensive assessment and reporting on the effect of groundwater on water quality of the Great Lakes will require science advancements in eight different areas. These science activities are linked. For example, new interpretations (models, insights) often lead directly to rethinking what is required for monitoring, which may result in the design and implementation of new field measurement tools.

Major areas of science needs

The information gaps and science needs identified in this report can be summarized as the following major areas, in terms of science activities that could be undertaken to address the mandate of Annex 8 of the GLWQA:

- **Major Science Need 1: Advance assessment of regional-scale groundwater discharge (quantity) to surface water in the Basin.** Understanding how groundwater is affecting Great Lakes water quality will require more accurate local- to basinwide-scale accounting for the flux of groundwater to streams and to the Great Lakes.

- **Major Science Need 2: Establish science-based priorities to advance the assessment of the geographic distribution of known and potential sources of groundwater contaminants relevant to Great Lakes water quality, and the efficacy of mitigation efforts.** Understanding of how groundwater is improving or adversely affecting Great Lakes water quality will require compilation and assessment of locations of known or suspected sources of groundwater contamination that are considered to have potential or direct effects on the water quality in nearshore areas of the Great Lakes, and in streams flowing to the Great Lakes. An emphasis could be placed on identifying priority contaminants because of their widespread occurrence, persistence, mobility and/or adverse impacts. This assessment also could include an evaluation of the efficacy of mitigation efforts, including changes in regulations, practices, remediation prevention and containment approaches, and introduction of beneficial management approaches, with respect to groundwater contamination at these locations.

- **Major Science Need 3: Advance monitoring and surveillance of groundwater quality in the Great Lakes Basin.** Understanding of how groundwater is improving or adversely affecting Great Lakes water quality will also require compilation and assessment of the available groundwater quality data in the basin. The existing monitoring networks likely have significant gaps with respect to information about both non-point and point-source contamination. It is possible that these networks can be augmented by enhanced local-scale (e.g., site specific) groundwater surveillance or monitoring in urban and industrial areas. Consideration should be given to unconventional approaches, such as sampling shallow groundwater by temporary drive points in urban riparian zones and along urban shores, as demonstrated in some recent studies. Monitoring and surveillance should be expanded, in terms of the range of contaminants analyzed, to include “emerging concern” chemicals. It may be possible to incorporate or access information from existing, privately-owned or non-government organization (NGO)-operated monitoring wells in such areas, rather than requiring new, expensive installations. This information may be directly relevant to Areas of Concern in the Great Lakes (Annex 1 of the GLWQA) and Lakewide Management (Annex 2 of the GLWQA).

- **Major Science Need 4: Advance research on local-scale assessment of interaction between groundwater and surface water.** A more detailed understanding of groundwater/surface water interaction is needed in order to adequately assess the effect of groundwater on water quality and aquatic habitats in the Great Lakes. This effort would include local-scale field studies that consider the quantity of groundwater discharge, fluxes of contaminants between groundwater and surface water, and processes that attenuate these contaminants. This new field-based research could focus on riparian zones along streams and nearshore areas of the Great Lakes, including coastal wetlands, beaches, and developed urban shorelines, to directly assess the interaction of groundwater and surface water, and the effect of these exchanges on aquatic habitats. The goal of these local-scale studies would be to develop better conceptual and numerical models of the interaction of groundwater with surface water in different hydrogeological and land use settings in the Great Lakes Basin, water quality aspects of this interaction, and effects on aquatic habitats. Some of the local-scale studies could directly address information gaps and uncertainties associated with land use and infrastructure, especially in urban areas, but also in rural areas (e.g., tile drains), and also could assess how spatial and temporal variations in stream chemistry along their reaches are related to groundwater discharge.

- **Major Science Need 5: Develop better tools for monitoring, surveillance and local-scale assessment of groundwater – surface water interaction.** Development of better tools and protocols for inexpensive, relatively nonintrusive studies of groundwater/surface water interaction at the local (reach) scale is needed to support the monitoring, surveillance and research outlined above (Major Science Needs 2,3).

- **Major Science Need 6: Advance research on the role of groundwater in aquatic habitats.** Detailed site specific studies are needed on groundwater effects (including dependency) on aquatic communities, particularly benthic communities, and groundwater-dependent communities in streams and coastal wetlands. Investigations on how different ecological and microbial communities respond to the chemical constituents of shallow groundwater, including contaminants, would provide important information on the role of groundwater in aquatic habitats.

- **Major Science Need 7: Improve the understanding of effects of urban development on groundwater.** Quantitative data are lacking on the complex water cycle in urban areas of the Great Lakes Basin, about how groundwater participates in this cycle, and about how urban groundwater is affected by urban infrastructure and extraction. Quantitative information is also lacking about fluxes of contaminants from discharging groundwater to streams and lakes in urban areas. Addressing these science gaps by implementing new monitoring and research activities would greatly improve understanding of effects of urban groundwater on receiving water bodies and on aquatic ecosystems. Comprehensive groundwater modelling tools are needed to provide guidance on urban groundwater management and risk assessment.

- **Major Science Need 8: Develop scale-up models of the regional effects of groundwater on Great Lakes water quality.** Another vital link of an improved, integrated science approach would be to develop and revise regional-scale numerical models that incorporate the above, regional-scale discharge assessments, monitoring and surveillance data, and local-scale research activities. The challenge would be to upscale the enhanced understanding of local-scale processes (based on the local-scale studies) in order to assess regional-scale time-averaged efflux of groundwater (quantity and contaminants) to the Great Lakes, either directly or indirectly through the tributaries. This type of modeling will provide a very useful assessment of the regional-scale effects of groundwater on Great Lakes water quality and aquatic habitats.

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