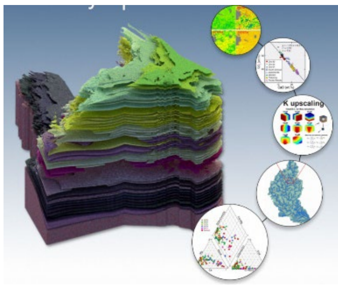
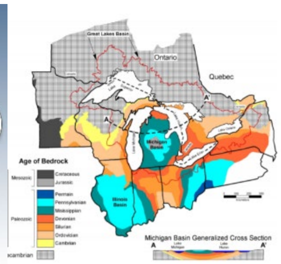
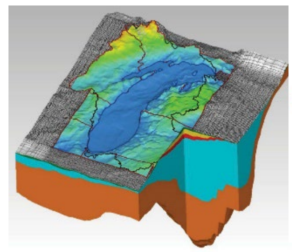
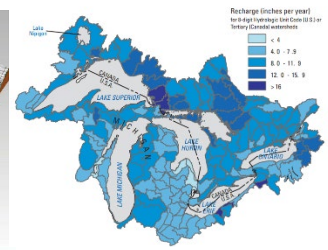
Development of a Great Lakes Groundwater and Surface Water Conceptual Framework









A report submitted to the International Joint Commission by the Great Lakes Science Advisory Board-Research Coordination Committee

March 2022

Prepared by:
LimnoTech, Ann Arbor, Michigan

In association with:
Envirings, Inc., Ontario
René Drolet Consulting Services, Ontario
nicholas-h2o, Michigan
Pedro Restrepo, Consulting Engineer, Minnesota

Foreword

The International Joint Commission Great Lakes Science Advisory Board-Research Coordination Committee adopted the following contractor report to complete its project: “Development of a Great Lakes Groundwater and Surface Water Conceptual Framework.”

In January 2019, the Committee published its 2018 phase one report: “Great Lakes Surface and Groundwater Model Integration Review.” [1] The phase one report helped address one of the science gaps identified by the Great Lakes Water Quality Agreement Annex 8 to support a coordinated effort in groundwater science and management actions. The phase one report summarized the results of a literature review of relevant government reports and peer-reviewed publications pertaining to groundwater modeling, surface water modeling, integrated surface and groundwater models, and select related modeling tools. The phase one report also synthesized the findings of a workshop involving 41 experts from Canadian and US government agencies and academia. The workshop participants discussed options for developing an integrated groundwater and surface water model for the Great Lakes basin. The phase one report recommended the development of a Great Lakes groundwater and surface water conceptual framework.

The Committee’s project “Development of a Great Lakes Groundwater and Surface Water Conceptual Framework” fulfills that recommendation. The following contractor report, adopted by the Committee, describes the scientific, technical and management elements of a conceptual framework for basinwide groundwater-surface water numerical models.

The intended audience for this report includes groundwater-surface water researchers, managers, research funders and those who use research products and tools, including regulators, water resources managers, and users of groundwater and surface water data. The framework primarily considers groundwater-surface water quantity models, but also includes water quality considerations.

The conceptual framework presented incorporates the needs and priorities of stakeholders in government, academia, the private sector, and interested nongovernmental organizations. The report elaborates on necessary management elements needed to implement the framework for a basin-scale model, including its principles, funding and approval needs, model development and intercomparison, and data management protocols.

[1] Accessible at: ijc.org/en/sab/great-lakes-surface-and-groundwater-model-integration-review-october-2018.

The conceptual framework proposed in this report provides detailed scientific and technical guidance for numerical model development, including: (1) two classes of physical and conceptual models, (2) three numerical model elements (equations, parameters and variables), (3) basinwide hydrology and data availability, and (4) model calibration.

The report finds that:

1. Better information is needed regarding water budgets for: high-use areas (such as for municipal supplies, quarries or agricultural irrigation areas); improved monitoring and understanding of water table elevations, pressure heads and baseflow; and better forecasts of future conditions.

2. There is a demonstrated need for increased strategic resource investment at the basin scale for integrated groundwater-surface water monitoring, modeling and research to better determine sustainable yields in withdrawal permitting and provide technical support for policy changes and program improvements.

3. For stakeholders and groundwater-surface water resources managers to answer specific questions, they need model outputs and tools with seasonal to annual resolution at the tributary watershed, local, and state/provincial scales.

The report recommends that:

- Groundwater-surface water modelers, funders of research and users of research products/tools should use this report's conceptual framework as a guide for basinwide modeling to answer specific and temporal questions.

- Federal and state/provincial governments should maintain and enhance their three-dimensional hydrogeological data collection, surveillance and monitoring programs in areas where groundwater-surface water conditions are rapidly changing. This includes developing and maintaining real-time sensor networks, data management systems and staffing.

- The lead government groundwater-surface water modeling agencies should develop a basinwide monitoring enterprise plan. This plan should be updated regularly to incorporate information on the current state of the network, data management and communication, and to suggest enhancements in supporting priority modeling, management needs and resource needs.

- The federal agencies with the strongest technical skills in groundwater-surface water modeling should lead an effort to compile a joint scoping document with terms of reference for the development of a binational numerical groundwater-surface water model for the Great Lakes basin. The document should include: a concept of operations; data and technical requirements; critical use cases; a detailed wiring diagram of model components and software/hardware; a development schedule; a list of management tools and products to be developed from models; operations and maintenance details; an estimate of financial and staffing needs; and a timeline. The document should also specify in as much detail as possible:
    - elements that would be conducted internally by the agencies themselves, and
    - components that would be outsourced to academic or private sector partners via competitive grants or contracts.

  The outsourcing document could be formatted as a draft scope of work or request for proposals.

- The IJC, in collaboration with the Great Lakes Water Quality Agreement Annex 8 Groundwater Subcommittee and the Great Lakes Commission should support a binational collaborative entity organized around the topic of Great Lakes groundwater-surface water modeling, management and policy. The entity would facilitate information exchange across disciplines and jurisdictions, and maintain listings of supporting projects, subject matter experts, representatives of key stakeholder constituencies and potential funders.

Sometimes called the "sixth Great Lake," groundwater resources, and their interactions with Great Lakes surface waters, are critical to better model and manage.

Chris Winslow
US Chair
IJC Great Lakes Science Advisory Board-
Research Coordination Committee

Gavin Christie
Canadian Chair
IJC Great Lakes Science Advisory Board
Research Coordination Committee

Acknowledgments

The consulting research team gratefully acknowledges the time and energy of the steering committee members and International Joint Commission staff who provided advice and guidance for this study and report, and the generous contributions of time and knowledge by stakeholders in interviews and in completing questionnaires.

Steering Committee Members

Sandra Eberts, US Geological Survey, IJC Great Lakes Science Advisory Board-Research Coordinating Committee (SAB-RCC) US co-chair
Réjean Couture, Natural Resources Canada, SAB-RCC Canadian co-chair
Jon Allan, University of Michigan
Lauren Fry, National Oceanic and Atmospheric Administration
Drew Gronewold, University of Michigan
Nicole Herman-Mercer, US Geological Survey
Howard Reeves, US Geological Survey
Ram Yerubandi, Environment and Climate Change Canada
Helen Zhang, Ontario Ministry of the Environment, Conservation and Parks

Lizhu Wang, IJC Great Lakes Regional Office, project manager
Victor Serveiss, IJC US Section Office
Robert Phillips, IJC Canadian Section Office

Consulting Team Authors

John Bratton, LimnoTech, project manager and lead US author
Mary P. Trudeau, Envirings, lead Canadian author
René Drolet, René Drolet Consulting Services, policy subject matter expert, Canada
Jim Nicholas, Nicholas-h2o, hydrogeology subject matter expert, United States
Pedro Restrepo, Consulting Engineer, hydrology subject matter expert, United States

Cover images from left to right: block diagram of modeled Paleozoic bedrock layers representing regional geological formations colored by age with additional geological images (cover of Russell and Kjarsgaard, 2020); bedrock geology of the Great Lakes basin (Bornhorst 2016); Lake Michigan basin topography, bathymetry, subsurface geology and model grid cells (Feinstein et al. 2010); map of annual estimated shallow groundwater recharge rates for tributary watersheds of the Great Lakes basin (Neff et al. 2005).

Table of Contents

List of Figures ... vi
List of Tables ... vii
List of Acronyms ... vii
Foreword ... i
Executive Summary ... viii
1.0 Introduction ... 1
- 1.1 Study background ... 1
- 1.2 Terminology ... 3
- 1.3 Study objectives ... 3
- 1.4 Study team ... 4
- 1.5 Organization of this document ... 4

2.0 Methodology ... 5
- 2.1 Developing management elements of the conceptual framework ... 5
- 2.2 Developing scientific elements of the conceptual framework ... 6

3.0 Management Elements of the Conceptual Framework ... 7
- 3.1 Stakeholders and roles ... 7
- 3.2 Key stakeholder advice ... 8
- 3.3 Broader stakeholder priorities ... 13
- 3.4 The central guiding theme for the conceptual framework development ... 18
- 3.5 Management elements of the conceptual framework ... 19

4.0 Scientific and Technical Elements of the Conceptual Framework for a Basin-Scale Model ... 23
- 4.1 Design objectives for the conceptual framework ... 24
- 4.2 Scientific and technical considerations in numerical model development ... 25
- 4.3 Great Lakes hydrogeology and data availability ... 37
- 4.4. Considerations for model calibration ... 49

5.0 Findings, Gaps and Recommendations ... 50
6.0 Glossary ... 53
7.0 References ... 56
8.0 Appendices ... 61
- Appendix A.1 Model intercomparison experience in the Great Lakes basin ... 61
- Appendix A.2 Interviewee questions ... 64
- Appendix B Interview and questionnaire/registry participants ... 65
- Appendix C Information submitted through the stakeholder questionnaire ... 69
- Appendix D Expanded description of scientific elements of the conceptual framework ... 120

List of Figures

Figure 1. Organizational roles of survey respondents 14
Figure 2. Spatial scale preferences of survey respondents. 16
Figure 3. Temporal scale preferences of survey respondents. 17
Figure 4. Schematic diagram of the phases and key process management elements of a conceptual framework for a GW-SW modeling program for the Great Lakes basin ..19
Figure 5. Map showing the Great Lakes basin boundary and major tributaries developed from Great Lakes Aquatic Habitat Framework geospatial data. 24
Figure 6. Schematic representation of the primary atmospheric, surface water and groundwater fluxes that constitute the scientific elements of the Great Lakes GW-SW conceptual framework..28
Figure 7. Simplified diagram of the natural (blue or green) and human-influenced (yellow) scientific or physical elements of the conceptual framework 29
Figure 8. Schematic diagram of technical elements of the conceptual framework of the numerical model arranged sequentially 30
Figure 9. Annual recharge of shallow groundwater in the Great Lakes basin (Neff et al. 2005). 38
Figure 10. Map of normalized baseflow index showing greater baseflow in the northern parts of the basin (Neff et al. 2005) 39
Figure 11. Simplified bedrock geology of the Great Lakes basin, harmonized across the international border; modified from Great Lakes Aquatic Habitat Framework data...40
Figure 12. Binational data set for quaternary geology compiled and harmonized by GLAHF, based on USGS and Ontario Ministry of Northern Development and Mines datasets 46
Figure 13. Current land use in the Great Lakes basin shows agricultural and urban development in the south and forested areas in the north 47
Figure 14. Harmonized binational soil classification by drainage properties compiled by GLAHF using US Natural Resources Conservation Service and Agriculture and Agri-Food Canada databases 48

List of Tables

Table 1: Scientific elements of the conceptual framework and supporting data 6
Table 2. Summary of stakeholder groups and roles...7
Table 3. Management elements of the conceptual framework for a GW-SW model...................20
Table 4. Typical temporal discretization as a function of the planning horizon...........................31
Table 5. Characteristic times for hydrologic processes in the Great Lakes basin. 32
Table 6. Summary of available data. 44

List of Acronyms

ECCC	Environment and Climate Change Canada
GIN	Groundwater Information Network
GLAHF	Great Lakes Aquatic Habitat Framework
GSI	groundwater-surface water interactions
GW-SW	groundwater-surface water
HGS	HydroGeoSphere (an integrated groundwater-surface water model by Aquanty)
HRU	Hydrologic Response Unit
IJC	International Joint Commission
NDMNRF	Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry
NRCan	Natural Resources Canada
NOAA	National Oceanic and Atmospheric Administration (United States)
NWS	National Weather Service (United States)
SAB-RCC	(IJC) Great Lakes Science Advisory Board-Research Coordination Committee
USGS	US Geological Survey

Executive Summary

The Great Lakes basin is experiencing growing demands for groundwater resources from agricultural, residential and industrial users that are creating more competition and stressing aquatic ecosystems. This is compounded by climate change, which is leading to growing agricultural withdrawals to offset greater rainfall variability and more intense droughts, among other impacts. The technical tools to support decisions about sustainable aquifer pumping are inadequate to address many situations, and investments in this area have not been a priority. Legal disputes, transboundary tensions, regulatory uncertainty and water shortages have been the results. Where groundwater flows to streams are impacted, summer water depths drop and temperatures rise, stressing fish, mussels and other aquatic organisms. Strategic investments in the technical infrastructure to improve groundwater management are needed across the Great Lakes basin (the basin). A basin-scale model will provide the foundation on which management questions can be addressed at all scales within the basin, and basin-scale stressors like climate change impacts on the hydrological cycle can be evaluated.

This work represents the second phase of a multiyear binational effort to frame the technical needs created by growing demands for groundwater resources in the region. The study results presented here expand on the Phase 1 study, which was conducted in 2017 and 2018. The Phase 2 report presented here describes the scientific, technical and management elements of a conceptual framework for a basinwide groundwater-surface water (GW-SW) numerical model or models. The intended audience is GW-SW researchers, managers and funders of research, and users of research products and tools such as regulators, water resources managers and users of water data. The focus of the study was GW-SW quantity; water quality, however, was a necessary secondary consideration as well.

Key stakeholders with an interest in this scale of modeling were identified and queried including assessment of their available data, technical capabilities and financial resources to support the development and maintenance of such models. New or ongoing work related to GW-SW modeling by government agencies, universities and private companies was identified and summarized. Potential lead agencies that can carry out such GW-SW model development and maintenance were also identified. Finally, the role of the International Joint Commission (IJC) in supporting these activities was considered in light of the organization’s mission and mandates. This report constitutes a synthesis of the study results. The study was conducted in support of the Hydrological Conceptual Modeling Work Group of the IJC’s Great Lakes Science Advisory Board-Research Coordination Committee (SAB-RCC). The assessment included expert interviews, development and deployment of a stakeholder questionnaire, and a review of recent reports and peer-reviewed literature developed since the Phase 1 report was completed in 2018. Major findings, gaps and recommendations are listed below.

Key finding

There is an urgent and growing need to develop a sound scientific understanding of groundwater-surface water interactions (GSI) on the scale of the binational Great Lakes basin in light of the cumulative pressures arising from agricultural and other high-volume uses of groundwater, population changes, economic-industrial demands and environmental flow requirements. The projected stresses that climate change will bring to the water cycle within the Great Lakes region and beyond are of particular concern. A basin-scale understanding can inform questions that apply at smaller scales within the basin by providing context and boundary conditions for addressing questions at subregional to local scales.

Other findings

- Primary information needs that were identified by the groundwater resources managers in the basin include: better water budgets for high use areas (municipal supplies, quarries, agricultural irrigation areas); improved monitoring and understanding of water table elevations, pressure heads and baseflow; and better forecasts of future conditions, including potential changes in year-round impacts on Great Lakes water levels and temperatures under changing climate conditions.

- Increased strategic investment in integrated GW-SW monitoring, modeling and research at the scale of the entire basin has the potential to provide substantial environmental, societal and economic dividends in terms of better determination of sustainable yields in withdrawal permitting and technical support for policy changes and program improvements, based on stakeholder feedback.

- Review of new reports and peer-reviewed literature (since Phase 1; e.g., Xu et al. 2021) with a focus on GW-SW quantity rather than quality confirmed that direct discharge and impacts of groundwater on Great Lakes shoreline areas are relatively small (less than 1 percent of water budget on average) except in embayments. However, riverine and tributary impacts of groundwater discharges can be quite large, particularly in areas with artificially modified drainage and in northern groundwater-fed streams that are incised into glacial deposits.

- Staff with technical expertise exist within agencies, academic institutions and private companies inside and outside the basin that could develop the needed GW-SW data management systems, models and decision-support tools for the Great Lakes states and provinces if sufficient resources were available. The technical community is highly dispersed and not always well-connected with the management community.

- Sources of sufficient resources and a commitment to consolidate efforts in a coordinated, integrated and sustained binational enterprise do not currently exist.

- Stakeholders and managers of GW-SW resources expressed a desire for model output and tools with seasonal to annual resolution, primarily at the tributary watershed, local and state/provincial scales. Models must generally be optimized to specific scales and designed to answer specific questions.

- Federal agencies including Natural Resources Canada and the US Geological Survey, with support from Environment and Climate Change Canada and the US National Oceanic and Atmospheric Administration, are best equipped to lead the development and maintenance of a basin-scale GW-SW model with technical support from other federal agencies, academics, private companies and state/provincial agencies.

Gaps

- This study identified key knowledge and data gaps that hinder well-informed management decisions including insufficient three-dimensional hydrogeological data synchronized across the border for the Great Lakes basin to construct high-resolution frameworks for subsurface flow modeling, and insufficient data on GW-SW occurrence, use, dynamics and interactions.

- Important emerging issues include the expected role of climate change in the alteration of the future GW-SW regimes in the basin, including related changes in competing human and ecological demands for groundwater extraction, water quality protection and maintenance of environmental flows.

- Institutional impediments include inadequate data management systems for existing data, insufficient funding to update existing numerical models or develop and maintain new models, and inadequate tools to link the output of modern GW-SW models that do exist with the practical needs of managers for decision support (e.g., insufficient transitioning of research products to practical applications).

Recommendations

- Three-dimensional hydrogeological data collection, surveillance and monitoring programs should be maintained and enhanced in areas where GW-SW conditions are changing most rapidly including well-equipped real-time sensor networks and associated maintenance and data management systems and staff. A basinwide monitoring enterprise plan should be developed by the lead GW-SW modeling agencies. The plan should be updated regularly, incorporating information on the current state of the network, data management and communications systems, and suggested enhancements to support priority modeling and management needs, along with associated resource needs.

    - The federal agencies with the strongest technical skills in GW-SW modeling should lead an effort to compile a joint technical scoping document or terms of reference for the development of a binational numerical GW-SW model for the Great Lakes basin. The document should include a concept of operations, data and technical requirements, critical use cases, a detailed wiring diagram of model components and software/hardware, a development schedule, a listing of management tools and products to be developed from models, operations and maintenance details, an estimate of financial and staffing needs and a timeline. The document should also specify in as much detail as possible: elements that would be conducted internally by the agencies themselves; and components that would be outsourced to academic or private sector partners via competitive grants or contracts.

      The outsourcing document could be formatted as a draft scope of work or request for proposals.

- The IJC, in collaboration with the Great Lakes Water Quality Agreement Annex 8 Groundwater Subcommittee and the Great Lakes Commission, should support a binational community of practice or a collaboration entity organized around the topic of Great Lakes GW-SW modeling, management and policy. The group would facilitate information exchange across disciplines and jurisdictions and maintain listings of supporting projects, subject matter experts, representatives of key stakeholder constituencies and potential funders.

1.0 Introduction

Demands for groundwater resources are growing across the Great Lakes basin and competition for groundwater is increasing to meet agricultural, residential, industrial and ecological needs. Climate change is putting particular stress on groundwater due to growing agricultural withdrawals to offset greater variability in precipitation (Gronewold and Rood, 2019) and more intense droughts. While demands on groundwater in the Great Lakes region are increasing, the technical framework on which to base informed decisions about sustainable aquifer pumping is lacking, and public and political focus on investment priorities is directed elsewhere. The result is political pressure and lawsuits among competing jurisdictions and users, drinking water supply shortages, dry or contaminated water wells and inadequate regulatory guidance. Excess groundwater withdrawals threaten water levels in lakes and wetlands and put aquatic life in streams at risk where groundwater discharge is required to maintain summer flows and cool water temperatures.

A substantial and strategic commitment of resources and staff will be necessary to appropriately model, track and adequately manage groundwater resources that we relied on in the past, to avoid real and consequential shifts in groundwater systems throughout the remainder of this century and to reduce competition and potential conflicts in the region. There is currently no quantitative and linked groundwater-surface water (GW-SW) tool available to assess the impacts of basin-scale stressors like climate change on the hydrological cycle of the Great Lakes basin.

The International Joint Commission (IJC) Great Lakes Science Advisory Board-Research Coordination Committee (SAB-RCC) conducted this work to address the technical needs created by growing demands for groundwater resources. Section one of this project report provides general background information for the project along with a brief overview of the objectives, team and terminology used. This project report represents the second phase of work, expanding on Phase 1 that was conducted in 2017 and 2018 by many of the same steering committee and contractor team members.

1.1 Study background

This project advanced the recommendations of the phase one report: "Great Lakes Surface and Groundwater Model Integration: Literature Review, Options for Approaches and Preliminary Action Plan for the Great Lakes Basin" (International Joint Commission Great Lakes Science Advisory Board 2018) toward the goal of developing a conceptual framework that defines aspects of numerical models to support the management of GW-SW as a single hydrologic system in the Great Lakes basin (the basin). With a growing interest in and reliance on groundwater in all aspects of human interaction (agriculture, drinking water, and ecological health and function), additional clarity over the tools for understanding groundwater and specifically groundwater-surface water interactions (GSI) are at a critical juncture (Costa et al. 2021). Climate change has already had a material effect on basin hydrology and our tools and processes for understanding its influence on groundwater systems are not keeping pace with our management and human needs.

Key data sources and research were reviewed that are pertinent to the development of the conceptual framework, including:

1. publications resulting from the US Geological Survey's Great Lakes Basin Pilot of the National Assessment of Water Availability and Use (e.g., see image on the cover of this report from Feinstein et al. (2010),

2. publications by the Geological Survey of Canada (e.g., Russell and Kjarsgaard, 2020),

3. the Great Lakes Water Quality Agreement Annex 8 (Groundwater) Subcommittee science synthesis report (Grannemann and Van Stempvoort, 2016), and

4. the review of nutrient delivery to the Great Lakes from groundwater (Robinson 2015).

Previous scientific review for the Groundwater Conservation Advisory Council of the Michigan Groundwater Withdrawal Assessment Tool was also incorporated. The tool was developed as required by water-use legislation in the State of Michigan and consists of a statewide groundwater-surface water-ecological consequence (impact) model and screening decision tool.

Modeling GSI at the basin scale poses organizational, technical and data challenges. The issue of scaling is a fundamental modeling problem and is a source of many of the uncertainties reflected in models. As agreed by all participants during the 2018 SAB-RCC workshop regarding modeling approaches, a model of the Great Lakes basin hydrologic system should be developed, similar to the smaller-scope initiative undertaken for the Milk River transboundary aquifer (Pétré et al. 2016). As outlined by Dr. Alfonso Rivera at the 2018 SAB-RCC workshop regarding the Milk River case study, regional-scale conceptual frameworks for such modeling are necessary to coordinate management across jurisdictions and users, but such frameworks can be challenging to assemble. They require harmonization of nomenclature, data techniques and mapping resolution, along with addressing scientific issues that are specific to the area of interest. A conceptual framework for the Great Lakes basin will facilitate essential future modeling initiatives as well as intermodel comparisons. The framework must cover the entire surface-subsurface system, which includes aquifers that contribute directly to the surface water features, but also those that extend beyond and below those features of the basin.

Recognizing the technical, scientific and interorganizational requirements for modeling a hydrologic system as complex as the Great Lakes basin, collaboration and maintenance of healthy, ongoing professional relationships are essential for success. For these reasons, the 2018 SAB-RCC workshop participants and the statement of work for this project stipulate the engagement of stakeholders in the development of a science management framework. Stakeholders from all relevant sectors, including government, academia and the private sector could contribute expertise, data and funding. In addition, experts, model users, researchers and students could build a community of practice to develop, implement and maintain models at the local, regional and basin scales. The number of potential questions with answers that could be supported by modeling GW-SW in the basin is vast. While the full potential for modeling applications may be an ultimate goal, at this initial stage there is a requirement to develop a set of well-defined key questions to be answered at the basin scale.

1.2 Terminology

Modeling experts apply the term 'conceptual model' in various ways, depending on their field of expertise. For this reason, we do not use the term 'conceptual model' in this report. Instead, we use the term 'conceptual framework' which indicates a narrative description or graphical depiction of the system elements in a manner that will sufficiently inform the next steps in the numerical model development. A conceptual framework precedes numerical modeling, which converts concepts and data into equations, workflows, computer files and code, and useful output. Once the key questions and objectives for a basin-scale GW-SW model are identified, a conceptual framework can be developed. The conceptual framework describes the intent and scope of a model and the key elements, relationships and data sources that it will incorporate. In this report, the conceptual framework includes the model objective, management elements, technical elements, geographic extent, hydrogeologic terranes, model domain, external and internal boundaries congruent with the objectives, and the temporal and spatial scales of the model and its elements. Additional definitions are included in the glossary in **Section 6.0**.

1.3 Study objectives

The key objective of this study was to develop a conceptual framework that:

1. establishes a set of questions to address with a future basin-scale GW-SW numerical model or models,
2. engages key stakeholders,
3. summarizes ongoing or planned work,
4. proposes a management framework that includes agencies with the capacity to carry out the required work,
5. articulates the role of the IJC in the effort, and
6. describes the critical GW-SW elements and movements in the Great Lakes basin that could be depicted in an integrated numerical model for the benefit of a diverse user community.

The three task elements included:

- **Task 1:** develop a conceptual framework of GW-SW water management elements with stakeholder input and context,

- **Task 2:** develop a conceptual framework of scientific elements of a basin-scale numerical model with a catalog of data sources; and
- **Task 3:** prepare a comprehensive report (herein) describing all project elements.

1.4 Study team

A multiagency steering committee was assembled by the SAB-RCC to guide the project. Co-chaired by the US Geological Survey (USGS) and Natural Resources Canada (NRCan), agencies represented included NRCan, the Ontario government, the USGS, US National Oceanic and Atmospheric Administration (NOAA), the University of Michigan. The LimnoTech team, including Canadian subcontractor firm, Envirings Inc., and three subject matter experts who contributed to the SAB-RCC's phase one report (International Joint Commission Great Lakes Science Advisory Board 2018), developed this report for the SAB-RCC. The consulting study team was led by LimnoTech senior scientist Dr. John Bratton, and Envirings Inc. director Dr. Mary Trudeau, with a team that included René Drolet of René Drolet Consulting Services, and subject experts Jim Nicholas of nicholas-h2o and consulting engineer Dr. Pedro Restrepo. The consulting team commenced work in October 2020 and the project concluded in September 2021.

1.5 Organization of this document

In addition to this introductory section, the report includes the following sections:

- **Section 2** summarizes the methodology used to conduct the study
- **Section 3** covers the management elements of the conceptual framework
- **Section 4** summarizes the scientific and technical elements of the conceptual framework that should be incorporated into a future GW-SW model
- **Section 5** presents findings, gaps and recommendations for implementing the conceptual framework
- The glossary of terms can be found in **Section 6** and references cited are in **Section 7**
- **Section 8** includes the following appendices: **Appendix A** includes supplemental information on the Great Lakes Intercomparison Project; **Appendix B** includes a table of interview and questionnaire/registry participants; **Appendix C** is a consolidation of all the information submitted through the stakeholder questionnaire; and **Appendix D** includes expanded information on the scientific elements of the conceptual framework, particularly the hydrological elements.

2.0 Methodology

A brief overview of the approach to the development of management elements of the conceptual framework is provided here, including references to appendices where more details are provided.

2.1 Developing management elements of the conceptual framework

The approach to developing management elements of the conceptual framework to create and operate a GW-SW model for the basin began with identifying the types and roles of stakeholders (**Table 1**, next section). Note that the management elements described here apply to model development and should not be confused with direct, hands-on water resources management elements like the issuance of withdrawal permits. Stakeholder engagement comprised two approaches: interviews and an online questionnaire.

Virtual interviews were conducted with stakeholders representing the key agencies most likely to have essential resources to support not only the development but also the implementation and ongoing maintenance of a basinwide model, specifically through funding and provision of in-kind expertise. We conducted online interviews with 12 representatives from stakeholder organizations who are potential owners/responsible agents. See **Section 3.2** for a synopsis of interview results, **Appendix A.1** for additional details of recent intercomparison studies provided by one interviewee, and **Appendix A.2** for interview questions.

Numerous other stakeholders in government, academia, private sector, and nongovernment organizations have an interest in the Great Lakes and GSI. To obtain supplemental stakeholder input beyond what was collected in Phase 1 and the key stakeholder interviews of Phase 2, the consulting team collaborated with the SAB-RCC steering committee to develop a list of over 100 individuals who were invited to complete a Google Forms questionnaire related to their particular organizational needs and potential contributions. Respondents were able to reply to a subset of the full list of questions based on their self-identification of their organizational roles.

A registry of stakeholders including people interviewed and those responding to the questionnaire is provided in **Appendix B**. Note that the list includes some steering committee members and IJC staff. Responses are not attributed to individuals. Graphical summaries of some responses and complete response information are provided in **Appendix C**). Data and contact information or websites collected through the questionnaire that constitutes a data catalog are also provided in **Appendix C**, along with information in **Section 4.3.2** below.

2.2 Developing scientific elements of the conceptual framework

The conceptual framework arises from stakeholder interactions, discussions with experts and assessment of the compiled data and information. The conceptual framework describes the integrated GW-SW system's external and internal boundaries, the hydrogeologic framework most relevant to GSI, the surface water network, fluxes and human impacts that should be included in the numerical model. The intended uses of the numerical model were first identified in simplified format (**Table 2**, next section). The process for developing the conceptual framework consisted of three steps: engaging with experts (as described in section 2.1 above); compiling data and information relevant to a conceptual framework; and developing the conceptual framework itself.

Where available, water budget information specifies the quantities and rates of scientific elements of the conceptual framework. Water budgets are resolved to varying degrees in different parts of the basin. Stakeholder needs for data and information were considered in determining the primary types and sizes of surface water features to target. A list of the data and information that are relevant to scientific elements of the conceptual framework is shown below in **Table 1**.

Table 1: Scientific elements of the conceptual framework and supporting data

Model Element	Data Necessary to Support a Numerical Model
Atmosphere	–Meteorological data: temperature, rainfall, snowfall, evaporation –Climatology and climate change trends
Major Aquifers	– Regional hydrogeological data on groundwater occurrence – Regional groundwater quality data, particularly including salinity, which impacts density
Groundwater and Surface Water	– Surface runoff, interflow, recharge, groundwater discharge, streamflow, groundwater flow
Tributary Interactions	– Streamflow, baseflow, environmental flow, sensitive fauna
Lake Interactions	– Direct discharge (diffuse and springs), seasonal gradient reversals, wave influences, ice and frost influences
Human Dimensions	– Demographics and trends, consumptive use forecasts, streamflow alterations (e.g., dam and reservoir operations), land use – Surface water withdrawals and return flows; groundwater withdrawals and discharge rates/locations for drinking water, irrigation, mining, artificial drainage, wastewater

3.0 Management Elements of the Conceptual Framework

This section first summarizes the roles of stakeholders in the development and operation of a numerical GW-SW model (**Section 3.1**) and then it summarizes the advice and input received through interviews with key stakeholders (**Section 3.2**). **Section 3.3** summarizes the input on model priorities identified through the stakeholder registry questionnaire. **Section 3.4** covers guiding questions and **Section 3.5** outlines the management elements of the conceptual framework.

3.1 Stakeholders and roles

The groups and roles of stakeholders involved in creating and managing a GW-SW numerical model extend beyond water science experts to decision makers and policy advisers, accountable funding agents, data owners and model end-users (**Table 2**). Stakeholder roles are not mutually exclusive and an individual agency may have several or even all roles.

For a basin-scale model to progress, the needs and requirements of key agencies with the expertise and potential to fund the model must be identified and considered in a management framework. These model owners/responsible agents also typically have model creators on staff, they own data, use models and provide advice to senior government decision makers and political leaders.

Table 2. Summary of stakeholder groups and roles

Stakeholder Group	Role (note: an organization may have more than one role)
Model owners/responsible agents	Contribute funding or in-kind resources Accountable for model development and maintenance
Model developers/creators	Technical/scientific development of model code or setup May create, own or use third-party software and tools
Data owners	Collect, store and/or develop data sets essential for model development, model refinement
Model users	Skilled group who run models or manipulate model output and understand underlying assumptions, parameters, etc.
Decision makers and policy advisers, influencers	Seek answers to questions about water quantity, quality and ecosystem health; prioritize investments of resources

3.2 Key stakeholder advice

3.2.1 Questions that a basin-scale model could address

A long list of potential questions to be addressed by a basin-scale GW-SW model was identified during Phase 1 of this project. The list was refined by modeling experts during the Phase 1 workshop to identify specific questions about water balance on a basin scale. These questions would need to be resolved in at least a preliminary manner to develop a water balance model and the associated infrastructure. The questions (from the Phase 1 report) include:

- What are the inter-lake groundwater flows and the geographic range for GSI-relevant groundwater transport within the basin system? What are the appropriate vertical, horizontal (cell size) and temporal scales for numerical modeling needed to respond to questions of basin-scale water balance?

- What precision is needed to represent vast areas of wetlands on a basin-scale model?

- How does frozen ground affect water cycling on a basin scale?

- What are the trade-offs and uncertainties associated with the choice of scale (spatial and temporal) for water balance questions?

- What are the appropriate vertical and longitudinal scales for basinwide numerical modeling needed to respond to questions of ecosystem flows in tributaries, water quality and climate change scenarios? If different from the water balance scales, can the utility of a water balance model be optimized for future applications to questions beyond water balance?

For Phase 2, key stakeholder representatives were interviewed and asked to identify the question(s) a basin-scale model could answer that would inspire funding and strategic resource investment to develop a GW-SW numerical model for the basin and associated infrastructure. The responses include five categories of issues as summarized below (numbers do not indicate priority):

Category 1. Better understand tributary baseflows to reduce uncertainty in Great Lakes water level forecasts and to protect environmental flows [1]

Development within the Great Lakes basin, population growth, interbasin diversions, irrigation, tile drains and climate change are all potential factors that will challenge the assumptions that groundwater is relatively stable on a basin scale. This assumption results in the belief that the errors contributed by variability in groundwater recharge and discharge are minor for surface water models and weather models that are used to make predictions about tributary flows and lake levels. Without an integrated understanding of GW-SW balance, there is no way of knowing

[1] Note that the term “environmental flows” may be defined by individual jurisdictions differently.

at what point the assumptions about the small influence of groundwater processes in current models for surface water levels and flows are no longer valid.

Further, groundwater is particularly important during low flow periods (Blum et al. 2019). Effluent discharge permits, mixing zone extent and pollutant concentrations, and flow alteration permits for instream structures and diversions are based on assumptions of baseflow conditions. If climate change decreases summer flows, there will be less margin for natural climate variability and before tributary ecosystems get pushed past limits of viability (e.g., too hot, too shallow/dry, dissolved oxygen too low). [2] Also, many organisms spawn in groundwater discharge areas or use them as critical habitat (e.g., native mussels), so biological aspects of groundwater discharge change might be substantial with changing climate.

Although direct groundwater contribution to the Great Lakes is small relative to the overall water budgets, groundwater contributions to tributary flow are important. Regional-scale influences of major withdrawals can have unanticipated local-scale impacts across jurisdictional boundaries or dynamic groundwatershed divides. Basin-scale and regional-scale models allow more localized models to be nested within a larger context. For the US contribution to the coordinated lake level forecast, the US Army Corps of Engineers runs a suite of net basin supply models, some of which are purely statistical, and which make certain assumptions about the stability of groundwater baseflow that may not be correct under changing climate conditions. They do run a physically based modeling framework (Great Lakes Seasonal Hydrologic Prediction System, replacing the Great Lakes Advanced Hydrologic Prediction System) that runs a large basin rainfall runoff model and lake thermodynamic model that use recent meteorology to get initial conditions. The groundwater component of the large basin rainfall runoff model, however, is not physically based. Better representation of initial conditions, including groundwater components, has been identified as an area for improvement of water level forecasting. Apart from the Great Lakes Seasonal Hydrologic Prediction System, initial conditions (current soil moisture, lake temperature, etc.) are primarily considered qualitatively in the interpretation and aggregation of results from the suite of net basin supply forecast models. The Canadian Meteorological Centre also operates their Water Cycle Prediction System and National Surface and River Prediction System.

Only one of the US Army Corps of Engineers models (Great Lakes Seasonal Hydrologic Prediction System) considers a highly simplified bucket storage model of groundwater. That model is used to estimate baseflow, but it does not use field observations of groundwater to update its state, and, as mentioned above, the groundwater component is not physically based. Other US Army Corps of Engineers models for the Great Lakes do not consider groundwater contributions, except in the fact that groundwater contributions are inherently integrated into the net basin supply estimates used in calibration. Soil moisture, in particular the saturation of the soil's storage capacity through successive precipitation events, is not well understood in the Great Lakes, leading to uncertainties in lake-level forecasts. A better understanding of storage could help to extend the level forecasts beyond current forecasting windows. In the summer of 2021, the US National Weather Service (NWS) extended the National Water Model into the

[2] Note that the effects of climate change on the water cycle, especially the groundwater system, in the Great Lakes basin are largely unknown, as this has not been a focus of investigations in most regions of the basin.

entire Great Lakes basin, including Canada. In addition, a new Great Lakes geodetic datum has been developed to incorporate post-glacial isostatic rebound since the last datum revision in 1985.

Improved water level forecasts could result in better management of lake level regulation on short timescales for navigation, hydropower generation and water intake operations, and on longer timescales for coastal infrastructure protection and coastal habitat benefits (Lake Ontario). Near-term regulation is presently based on statistical approaches that situate current water levels within a historical context, with binationally coordinated outflow control adjustments made once per month for Lake Superior and weekly for Lake Ontario and the St. Lawrence system. In the absence of an integrated basin-scale GW-SW model, adequate interannual to decadal guidance on lake levels for planning coastal infrastructure and building protection, renovation and construction is not available to members of the public, engineers and local or state/provincial governments.

Category 2. Enhance climate change modeling

The Great Lakes basin is not currently well represented in global and national climate change models in Canada or the United States. In Canadian models, the lakes are represented very simplistically on a national scale and by one-dimensional surface water modeling on a regional scale. Presently, the Great Lakes is one grid cell in US national climate change models and there is a desire in senior levels of the US Department of Energy to improve the resolution. Downscaling from General Circulation Models has been performed by modelers on both sides of the border to develop projections at finer geographic scales (e.g., Byun and Hamlet, 2018; Notaro et al. 2015). Ontario has funded the creation of fine-scale (10 km^2) climate change projection data for the entire province, including the Great Lakes, to support tracking and projections of future climate. These data are available at the Ontario Climate Data Portal. [3]

Over what spatial and temporal scales will the Great Lakes water balance change under climate change and increased demand scenarios? What changes in seasonality (e.g., shifts in spring freshet) translate to longer-term changes in water levels? Understanding the energy fluxes (e.g., conductive energy, heat budget) of the Great Lakes basin is an important aspect required to improve the resolution of national-scale climate change models. Understanding groundwater recharge is one important factor in surface water temperature modeling. Water temperatures and understanding of GSI are also important to ecosystem health, including for fish hatcheries and harmful algal blooms (Safaie et al. 2021).

Category 3. Ensure that the terms of the Great Lakes-St. Lawrence River Basin Sustainable Water Resources Agreement are met

Climate change impacts (Costa et al. 2021; Wuebbles et al. 2019) and increasing demand for water by agriculture are simultaneous trends that are straining surface water resources that are dependent on groundwater resources in select areas of the Great Lakes basin. For example, over a third of Michigan's nearly 11,000 agricultural wells were installed from 2010 to 2020 (Schneider 2021). What pumping activities require assessment: municipal drinking water supply;

[3] See more at: lamps.math.yorku.ca/OntarioClimate/, accessed February 1, 2022.

irrigation of exported crops (e.g., for biofuels); and mine and quarry dewatering? These questions are particularly relevant for large urban centers that are reliant on groundwater resources and with expected population increases in some locations. Commitments to improve water quality in the Great Lakes basin, including addressing nutrient stresses and legacy contaminants, would also be supported by a basin-scale GW-SW model and associated infrastructure. Nutrient and contaminant migration and concentration can be strongly linked to groundwater and surface water flow rates, discharge and recharge, seasonal changes and interactions.

A model would provide a critical tool to help meet the obligations of the international Great Lakes-St. Lawrence River Basin Sustainable Water Resources Agreement and the related legally binding instruments, including the US Great Lakes-St. Lawrence River Basin Water Resources Compact and Ontario and Quebec statutes and regulations. One specific example of a key commitment that would be informed by an integrated GW-SW model is "[t]o prevent significant adverse impacts of [w]ithdrawals and losses on the [b]asin's ecosystems and watersheds." [4] A model would further support the Great Lakes-St. Lawrence River Basin Sustainable Water Resources Agreement's requirement for developing a cumulative impact assessment for the Great Lakes basin every five years.

A basin-scale GW-SW model would fill an important technical gap by allowing IJC and other agencies to inform the Canadian and US federal governments and other constituencies on various management actions that require an integrated GW-SW approach to be executed effectively. For example, identifying watershed areas that are most favorable for wetland restoration to enhance nutrient management under the Great Lakes Water Quality Agreement Annex 4 requires knowledge of the interconnected shallow groundwater aquifers, surface soil infiltration properties, artificial drainage systems and surface flows. The Runoff Risk Advisory Forecast, currently issued by the US North-Central River Forecasting Center and being implemented at the North-East River Forecasting Center, and state-level advisory service websites advising farmers on timing for nutrient applications, make regional-scale contributions to nutrient management decision-making. It is planned that the US National Water Model will support similar management decisions.

Category 4. Provide context for regional and local water management

Development pressures and the resultant groundwater use that comes from that development are a growing concern for groundwater quantity management. The amount of development (e.g., withdrawals and related increases in impervious surface area in urban areas and along transportation corridors) that could be supported requires more basin-scale and regional-scale context. Climate change introduces additional uncertainty and variability in what potentially sustainable withdrawal quantities could be over time. A basin-scale GW-SW model is needed to run and calibrate regional scenario analyses for the future effects on water availability of pumping (withdrawal) permit decisions made by local and regional agencies. Tile drain systems also have very important effects on shallow groundwater flows and nutrient transport by

[4] Great Lakes-St. Lawrence River Basin Water Resources Compact, 2005. Section 1.3(2)(f). Available at: glslcompactcouncil.org/media/ud2domov/great-lakes-st-lawrence-river-basin-water-resources-compact.pdf, accessed March 7. 2022.

intercepting water that could have replenished local aquifers and shunting this recharge out of the system.

The coverage and density of tile drainage systems increase each year (e.g., Zulauf and Brown, 2019), particularly with tax incentives that have been part of US government stimulus packages. However, records of tiled locations in poorly-drained areas (e.g., Saginaw Bay watershed, Maumee River watershed, lower Thames River watershed) are not widely available from irrigation/water management districts in the United States, and Ontario records are incomplete (Valayamkunnath et al. 2020). Legacy contaminants are migrating at some local scales, raising questions of solute transport that are difficult to answer in the absence of a better understanding of linked regional and local flows. A basin-scale model would inform boundary conditions and provide a set of default parameters and assumptions that may be useful for regional and local models and decisions. It would also support running scenarios to assess the potential cumulative effects of multiple concurrent management decisions (e.g., water taking permits, land drainage networks, nutrient use) for a range of climate-induced changes.

Similarly, protecting environmental flows and predicting low-flow conditions requires an understanding of water withdrawals and integrated GW-SW relationships. Protection of environmental flows and sustaining critical ecological conditions, such as trout streams where groundwater discharge plays a significant role in water temperature and flows, requires a better understanding of basin-scale processes.

The lack of a basin-scale model means multiple short term and fragmented decisions are being made at smaller scales without understanding potential collective implications for the larger basin. Many local-scale models are available (see International Joint Commission Great Lakes Science Advisory Board 2018) but their users, including local watershed groups and municipalities, have no incentives or resources to expand into the modeling of federal or international baseline conditions. Yet, responsible agencies cannot build synoptic understanding and manage the larger system based on consolidating results of these more localized activities. A basin-scale model would be used for science-based support and the development of decision-making tools across and among larger jurisdictions. The model could be run for scenario analysis to assess risks associated with current regional-scale decisions and climate-related forecasts.

Category 5. Improve water quality models

Although not the focus of the present study, stakeholders shared that improved understanding of the pathways connecting land-based activities to the lakes from the tributaries is needed, for nutrients in particular, but for other contaminants as well. For instance, nonpoint source activities, particularly agriculture in tile-drained areas, contribute nutrients to tributaries and the lakes themselves. In addition, a reservoir of nutrients in the soil (legacy phosphorus) has developed over time in many places and it will continue to deliver nutrients within the basin even when proper best management practices have been implemented (H. Reeves, pers. comm.). Understanding this reservoir of nutrients and the rate at which nutrients will be conveyed to waters of the basin (Choquette et al. 2019) is essential for priority-setting and sound nutrient management decisions. Understanding the oxidation-reduction (redox) state of groundwater across the basin would inform natural contaminant levels (e.g., arsenic), transport and persistence. Climate-induced changes to processes that affect water quality, including seasonal nutrient transport, need to be better understood.

3.2.2 Temporal scale

Broadly speaking, the issues identified for the application of a basin-scale GW-SW model(s) call for the tool(s) to provide information on the longer-term impacts of shorter-term decisions. Examples include:

- water level and flow management via regulation points in tributaries at the Lake Superior and Lake Ontario outflows,
- implications of climate change on determinations of sustainable groundwater pumping rates for permits,
- low flow predictions for biological needs and calculating assimilative capacity of pollutant and heat for discharge permits that account for future droughts,
- nutrient transport resulting from agricultural management decisions,
- management of GSI for spawning and fish rearing in coastal habitats that are dependent on groundwater discharge, and
- other biological and human-centric processes.

As such, a model or models would be used to improve forecasts at monthly to annual resolution with special attention to extremes (high flow, low flow) and interannual to decadal trends, as well as providing boundary conditions for finer and coarser-scale models (e.g., national climate change models). The importance of keeping the model current was also emphasized by stakeholders, although the sources of data, data integration protocols, and other details will need to be addressed at a future stage. For instance, running a model regularly (e.g., monthly) would support rapid integration of data and provide confidence in it as a tool to support federal, state and provincial operational models, but sufficient monitoring data would need to be available to justify monthly or more frequent runs.

3.3 Broader stakeholder priorities

Thirty-seven individuals completed the questionnaire. Although a larger set of respondents would have been desirable to get a broader sense of stakeholder priorities and perspectives, the diversity of organizations that did respond represents a reasonable approximation of the views of the broader community, and results seem consistent with expected outcomes. Questionnaire respondents represented a range of organizations including federal (13 responses), state/provincial (13 responses), private (four responses), academic (four responses) and nongovernmental (three responses). Most respondents were senior scientists, engineers or technical managers in their organizations. Organizational roles were spread evenly among the options provided (see **Figure 1** below), with model users and data owners most abundant, and model creators and owners least abundant. Note that respondents could select more than one option.

Figure 1. Organizational roles of survey respondents. Note that more than one role could be selected, so percentages sum to greater than 100 percent.

3.3.1 Key findings from stakeholder input

Respondents shared some common perspectives but also reflected diversity in individual responses based on organization type, location and role (**Appendices B** and **C**). Among some of the most valuable information obtained were responses related to model temporal and spatial scales, and information on individual data holdings. In addition, respondents shared the following intended uses for the GW-SW model output (although not all would be applicable to the scale of the proposed model).

- Inform decisions by state-level agencies related to the consequences of agricultural, mining and other water withdrawals on broader water availability, water levels and streamflow.
- Help private consultants provide integrated modeling services at an affordable price to public and private clients in Canada and the United States.
- Support a state-level agency that evaluates the effects of large-quantity surface water and groundwater withdrawals on streamflow and fish populations.
- Assist an organization that conducts source water protection, performs subwatershed studies, determines water balances and carries out municipal supply studies.
- Protect both natural resources and riparian rights.
- Support education and outreach on water conservation and efficiency.
- Make recommendations to government (state, province and federal) environmental agencies and legislatures on improvements in data collection, modeling and conservation.

- Compare outputs of a basin-scale model with outputs from existing models or other new models (highlighting the value of an ensemble as a quality check).

- Use as part of a dispute resolution program to address private wells that are impacted by high-capacity wells.

- Use groundwater models as part of the permitting process for critical dune areas, inland lakes and streams, and wetlands. Modeling staff within a state-level agency's Water Use Assessment Unit to provide technical assistance to other staff.

- Support health aspects of permit application for bottled water withdrawals and public water supply withdrawals.

- Use groundwater modeling for Per- and Polyfluoroalkyl Substances groundwater contamination site evaluation and consideration of pathways and impacts for groundwater contamination sites and siting or management of solid waste and hazardous waste treatment, storage and disposal facilities.

- Development of the conceptual geological model is key including the basin geology and bathymetry, as well as the subsurface geology of land areas around the lakes, which largely dictates rates and ease of flow from the land surface into groundwater systems and surface water at multiple scales.

- With sufficiently high-quality data and modeling outputs, the model could be incorporated into a planned state-level hydrologic framework that will connect and coordinate models of different scales into regulatory water use programs.

- Model output can inform ongoing clarification of data needs.

Commonalities

Most of the organizations responding to the questionnaire encompass two or more roles in terms of GW-SW research and management. Responses regarding both temporal and spatial scales showed a consistent preference for small/short to intermediate scales. The highest spatial scale preference was the tributary watershed scale, followed closely by local and state/provincial (see **Figure 2** below). The next tier of responses, with eight to 12 responses for each, included county/district, Great Lakes connecting channel, the watershed of an individual Great Lake within a single country or spanning the border, the binational watershed of the entire basin and embayment watershed scales.

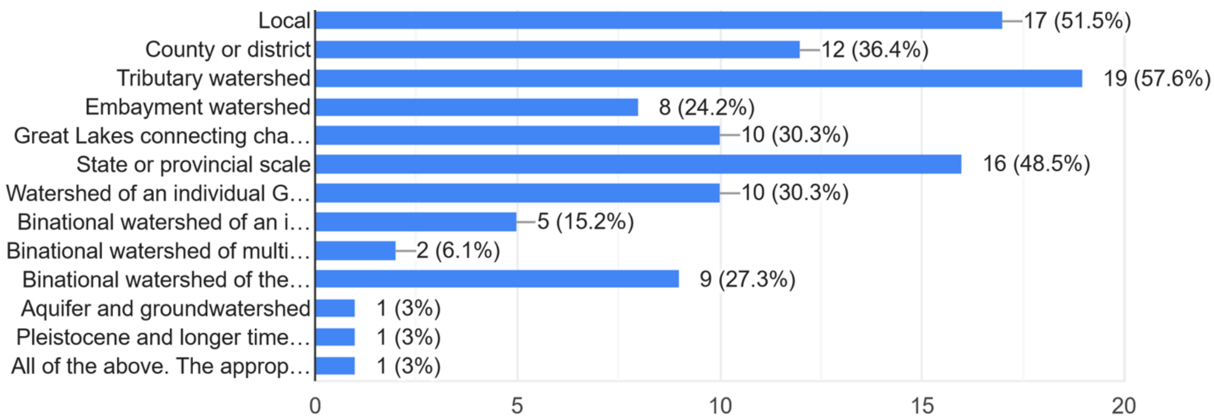


Figure 2. Spatial scale preferences of survey respondents.

The full text of choices of **Figure 2** above (in order):

- Local
- County or district
- Tributary watershed
- Embayment watershed
- Great Lakes connecting channel watershed
- State or provincial scale
- Watershed of an individual Great Lake within a single country (Canada or the United States)
- Binational watershed of an individual Great Lake
- Binational watershed of multiple Great Lakes, but not all five
- Binational watershed of the entire Great Lakes basin, including Lake Michigan
- Other:

- Aquifer and ground watershed
- Pleistocene and longer timescales
- All of the above. The appropriate scale depends on the question being addressed by the model

Temporal scale preferences also showed distinct clustering of results. The most common responses (more than one could be selected) were in the monthly to decadal range (greater than 50 percent response for each), with the highest response rate (88 percent) for the annual scale (see **Figure 3** below).

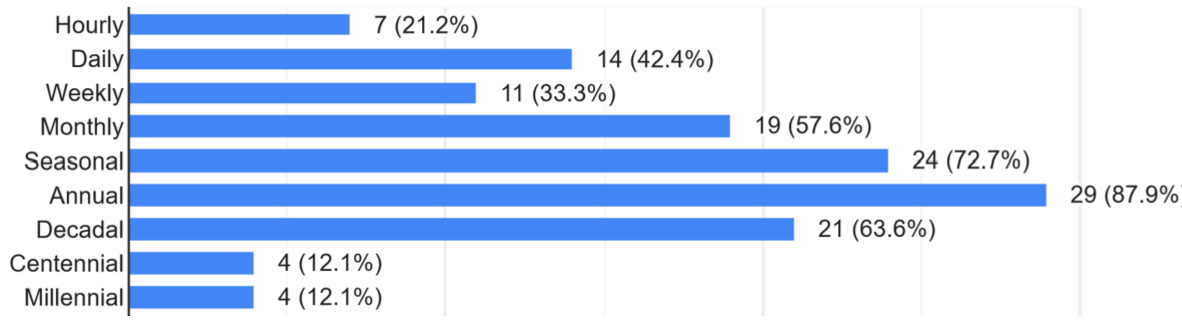


Figure 3. Temporal scale preferences of survey respondents.

Responses tended to reflect the scales at which management decisions are made. The fact that the largest percentage of respondents (35 percent for each) represented federal or state/provincial organizations did not result in a corresponding bimodal split in temporal or spatial preferences, suggesting that federal organizations recognize the primary management scales of their constituents rather than having a preference for large-scale (basinwide) or long-term (centennial) model outputs.

Differences

One of the primary differences noted among respondents was the relative abundance of model users and data owners, in comparison with model creators and model owners. Although large federal organizations such as Environment and Climate Change Canada (ECCC) and USGS incorporate most of the possible organizational roles that were provided as options on the questionnaires, the greater relative abundance of the model user community among respondents, which necessarily holds or accesses data, in comparison with the model creator/owner roles shows that skills and resources for developing and maintaining models are concentrated in a smaller part of the community compared to the model users. This shows the value to the broader community of ongoing strategic investments in the development end of the stakeholder spectrum.

Additional Findings

Public data availability for surface water appears to be moderately higher than for groundwater, with groundwater withdrawal in particular being less available. Respondents cited the 2016 Great Lakes Water Quality Agreement Annex 8 report [5] (Grannemann and Van Stempvoort, 2016) as a good source of information on groundwater data gaps in the region, and several current projects were noted as working toward filling some of these gaps. A general need for better three-dimensional hydrogeologic data was noted for the region.

Half of the respondents indicated that their organizations could be considered as potential funders of a basin-scale GW-SW model, and a greater percentage (59 percent) said that their

---

[5] Available at: binational.net/wp-content/uploads/2016/05/GW-Report-final-EN.pdf, accessed February 1, 2022.

organizations could lead model development and management, which suggests that some development expertise exists outside of the agencies that would provide funding—likely at academic institutions and private companies. About one-third (32 percent) of respondents indicated that they have related model development programs currently underway, and more than two-thirds (68 percent) said that they had in-house expertise that could be applied to such efforts.

3.4 The central guiding theme for the conceptual framework development

This section provides the rationale for the selection of the central theme that was developed for the conceptual framework. At the highest level, the framework itself consists of an integrated GW-SW model that is the result of combining or coupling two models—a surface hydrology model and a groundwater flow model. An appropriate central organizing theme that was selected by the contractor team and the steering committee is the impact of climate change on GSI (Costa et al. 2021) and specifically on aquifer recharge rates and baseflow, in the context of changing human and ecological needs. The rationale is three-fold:

1. The questions to be answered require a basin-scale model. Aspects of some of the issues identified in **Section 3.2** could be answered through models of a region smaller than the entire basin. A basin-scale model would be ideal but is not strictly and immediately necessary to respond to some of the questions. Nutrient transport questions are an example that would benefit from a basin-scale model but that are nominally being addressed through lake-scale or tributary-scale models.

2. Water balance issues were identified as a priority for a basin-scale GW-SW model during the Phase 1 workshop and were indicated in the terms of reference for this Phase 2 project report. Other modeling initiatives can build on a solid understanding of water balance dynamics on a basin scale that would result from a future GW-SW model to be developed as described here, although this effort also necessarily includes consolidation of information and scientific understanding developed at smaller scales.

3. Climate change and the uncertainty introduced by climate change were present in all stakeholder-informed categories of questions about the Great Lakes water balance, water quality and ecosystem health. Further, national- and continental-scale models would benefit from the better resolution of climate-change impacts on GSI in the Great Lakes basin.

A model (or models) that can answer questions or test scenarios about the effects of climate change on the water balance of the Great Lakes basin, on a basin scale, will be responsive to high-priority questions posed by lead agencies with the resources, mandates and expertise necessary to make use of the knowledge generated. Such basin-scale model(s) could also provide a framework and boundary conditions for models at regional and local scales within the Great Lakes basin.

3.5 Management elements of the conceptual framework

A management framework for a basin-scale GW-SW model or models needs to be open to new resources, skills, stakeholder interests, agency partnerships and collaborations, and technological advances. Despite the various potential paths for model development, the essential management elements can be described in a general sense (**Figure 4** and **Table 3**). As outlined in this section, a management framework includes principles for decision-making about basin-scale modeling, funding and budget management, a community of practice for model development and intercomparisons, and data protocols. At this early stage of basin-scale modeling, these framework elements can only be broadly described.

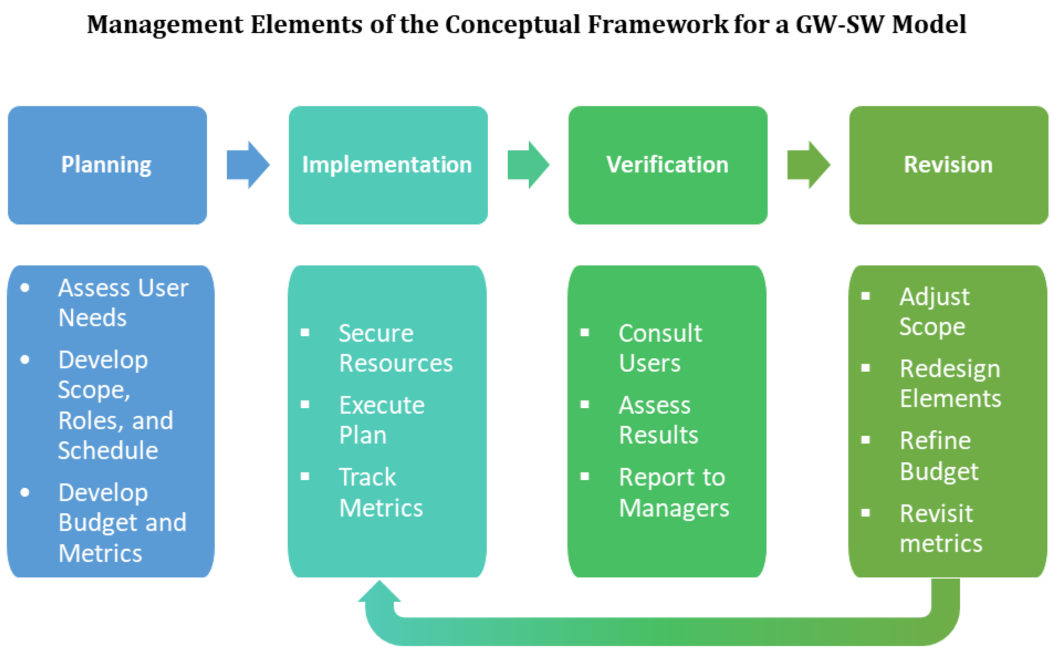


Figure 4. Schematic diagram of the phases and key process management elements of a conceptual framework for a GW-SW modeling program for the Great Lakes basin. Note the feedback loop along the bottom from revision to [re-]implementation, assuming an adaptive approach to improvement over time based on lessons learned and changing needs.

Table 3. Management elements of the conceptual framework for a GW-SW model

Phase	Elements	Key Stakeholders
Planning	– Define scope (key questions) – Define conceptual functionality – Develop budget, resource needs and schedule – Develop initial performance metrics	– Model owners/ responsible agents – Model creators – Model users – Data owners – Broader stakeholder groups
Implementation	– Obtain funding and staff commitments – Execute plan with revisions as needed – Track performance metrics against targets	– Model owners/ responsible agents – Model creators – Data owners – Model users and decision-makers within scope of plan
Verification/ revision	– Assess performance – Report per responsible agent needs – Revise technical and management elements for next cycle planning	– Model owners/ responsible agents – Model users – Data owners – Broader stakeholder groups

3.5.1 Principles for a basin-scale GW-SW model

The following overarching principles or characteristics to guide model design decisions were identified based on interviews, steering committee discussions, agency and stakeholder priorities, and emerging best practices:

- **Flexible**: to answer future questions not currently a priority or even known and to provide support to models at other scales
- **Accessible**: open source, publicly available model code and data
- **Collaborative**: leveraging resources across institutions and borders to maximize benefits and minimize duplication or incompatibility

- **Opportunistic**: taking advantage of existing or planned efforts, innovations and short-term funding opportunities

- **Practical**: feasible and cost-effective, with realistic access within the modeling community to the required skills and knowledge to develop and maintain a model and to apply the results

- **Sustainable:** considering long-term support, use and maintenance, including management and technical staff

- **Innovative**: using up to date but proven technological approaches

3.5.2 Funding and approvals for a basin-scale GW-SW model

Several formal or informal options exist for developing and documenting funding commitments for efforts of this sort, including: the development of memoranda of understanding regarding shared funding, shared model development, and data access/sharing; informal arrangements similar to weather models and surface runoff models, with IJC potentially serving as observer and convenor; independent but collaborative model development on both sides of the border; and IJC-managed advisory groups. No single agency was identified with the resources and expertise to be the lead steward of a modeling initiative.

There is currently no precedent for an international GW-SW modeling initiative in the Great Lakes basin, although the US National Water Model was expanded to include the Canadian part of the basin in summer 2021. Similarly, at the time of writing this report, a model was under development by Aquanty in collaboration with NRCan for a Canadian basin-scale model (Xu et al. 2021). Collaborative modeling initiatives would need to include protocols to ensure that data are available and comparable and to establish protocols for intercomparison studies and benchmarking of various modeling platforms (discussed below).

Funding should be supported by a multiparty, binational and Indigenous consortium of partners. A US-based example of a project that received funding through Congress is the USGS Mississippi Alluvial Plain Regional Water Availability Study. Other cross-border models do exist, such as: the NOAA Great Lakes Environmental Research Laboratory's Large Basin Runoff Model; transboundary Milk River, Columbia Basin, Rio Grande, and Yukon collaborations; and collaboration between the NWS River Forecast Centers and Canadian provinces regarding flood forecasting in the Lake Champlain-Richelieu River system and elsewhere. Collaboration was very important for the National Sciences and Engineering Research Council of Canada-supported Canadian FloodNet project to adopt the Flood Early Warning System (by Deltares, an independent institute for applied research) as its basis for the future Canadian Adaptive Flood Forecasting and Early Warning System. Flood Early Warning System is also the basis for the NWS Community Hydrologic Prediction System. Although no specific recommendation is made here regarding the actual funding model, the examples mentioned here can be considered as guides to how a successful approach could be developed.

3.5.3 Model development and intercomparisons

The role of model intercomparisons, according to the Intergovernmental Panel on Climate Change is to ensure a "coordinated and well-documented suite of model simulations…that represent critical tests of a model's ability to simulate the observed climate…[and] offers the possibility to compare their results not just with observations, but with other models as well" (Flato et al. 2013). During the workshop in Phase 1, attendees agreed that forcing data and metrics for assessing the results of a basin-scale GW-SW integrated model should be established, once the endpoints for modeling are identified (e.g., lake levels, nutrient loading, etc.).

As part of the management of basin-scale models, agreements would need to be developed around the protocols for model calibration (or, possibly, corroboration), comparison studies and scheduling comparison exercises, data sharing, results sharing, publication rights and other issues.

Through an interview and subsequent correspondence with the study team, Dr. Juliane Mai, University of Waterloo, provided a summary of the model intercomparison experience in the Great Lakes basin and advice for the implementation of intercomparison model studies (see **Appendix A.1**).

3.5.4 Data management protocols

For the sake of efficiency and standardization, it would be most effective to create a single data management plan and system for the development and operation of a binational GW-SW numerical model. Standard data protocols (e.g., Michener 2015) from a single lead agency or hybrid protocols should be followed in the creation of this shared system including: planning and system setup for data collection and assembly; data discovery and ingestion; quality assurance and harmonization; merging of datasets and supplemental metadata creation; data use in the numerical model; data and output archiving; and communication of results. Along with the development of a robust enterprise architecture for data management, documentation of data provenance, assembly, model configuration and operational decisions should all be recorded routinely such that approaches used can be transparent and consistent from run to run, and that enhancements can be done systematically and logically. In addition, detailed documentation can reduce the impacts of staffing changes due to unexpected illness or attrition.

4.0 Scientific and Technical Elements of the Conceptual Framework for a Basin-Scale Model

Here we first present the general conceptual framework to inform the design of a GW-SW model(s) of the Great Lakes basin, followed by additional considerations for simulating various system elements, including consideration of data availability, to help ensure future models can meet stakeholder needs. **Figure 5** below shows the surface water basin boundary and major tributaries. The groundwatershed extends beyond the surface watershed in a few key areas, particularly along southwest Lake Michigan in the Milwaukee-Chicago area (Feinstein et al. 2010).

Transboundary issues occur only in the western part of the Lake Superior basin, where transboundary flows may occur, and in deeper aquifers that span connecting waters between lakes. Past regional hydrologic studies provided valuable information on the groundwater flow systems and interaction with surface water in some large areas of the basin, for instance, the Lake Michigan region (Feinstein et al. 2010), Southern Ontario (Russell and Kjarsgaard, 2020), Regional Aquifer System Analysis for the Lake Michigan basin (Westjohn and Weaver, 1996), and northern Ohio and Indiana (Eberts and George, 2000). Surface water modeling for the Great Lakes basin is ongoing at NOAA's Great Lakes Environmental Research Laboratory and NWS, and by USGS as part of the Great Lakes Restoration Initiative, along with other programs in Canada and the United States.

The conceptual framework accounts for the fact that some areas of the basin are data-rich, whereas others are data-poor, which can impact numerical model design for the basin. Additionally, the framework accounts for the fact that aquifers contributing to streamflow are highly variable, and can include heterogeneous glacial deposits, regional Cambrian-Ordovician aquifers, and fractured carbonates, igneous and metamorphic rocks, or combinations of these geologic formations in specific areas.

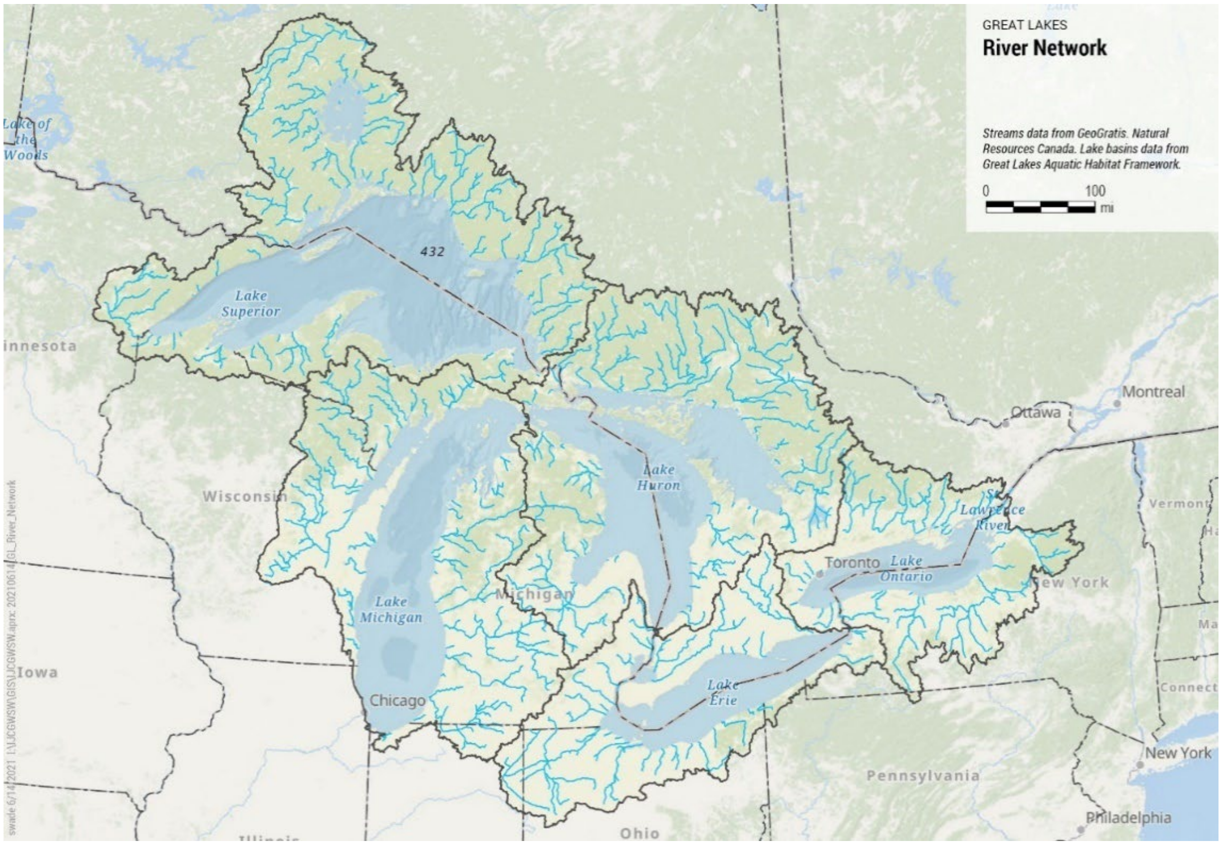


Figure 5. Map showing the Great Lakes basin boundary and major tributaries developed from Great Lakes Aquatic Habitat Framework geospatial data (dataset does not extend down the St. Lawrence River Basin to the international boundary at Cornwall, ON).

4.1 Design objectives for the conceptual framework

As indicated in **Section 3.4**, more thoroughly understanding climate change effects on basin hydrology and groundwater systems in particular (Costa et al. 2021) is a theme that ran through all issues identified as a high priority for the management of the Great Lakes basin. The scientific and technical elements of the conceptual framework have been designed to provide the following future modeling outputs:

- A basin-scale estimate of shallow groundwater flow paths and discharges to streams will be quantified in tributaries to establish baseline conditions, including simulations of seasonal fluctuations within documented ranges.

- A framework for local applications at seasonal to annual resolution will be developed, including minima and maxima and determination of especially sensitive regions or stream reaches (e.g., areas of tight coupling between groundwater and surface water, including recharge to groundwater from surface water due to pumping or seasonally high surface water levels).

- Time series of atmospheric variables (air temperature, precipitation, evapotranspiration rates, etc.) that can be used to drive simulations of changes in groundwater discharge to streams, with estimates of changes to baseflow levels, flow rates and water temperatures; changes in water table depth(s) will also be estimated.

- Anthropogenic variables (groundwater pumping, tile drainage densities and operation) that can be used to simulate changes in groundwater discharge to streams, with estimates of changes to baseflow levels, flow rates, water temperatures will be estimated; changes in water table depth(s) will also be estimated.

Future work in subsequent phases, if resources are identified to execute an initial quantity-oriented phase, could extend such initial model results to address water quality (nutrient loading, discharge permits, etc.). Future work could be undertaken to create more highly granular inset models at regional or local scales for groundwater discharges to streams, and to assess the effects of a range of anthropogenic uses and interventions, including restoration initiatives (such as wetland construction or enhancing infiltration with green infrastructure) and further economic development activities. Future work may also inset the Great Lakes basin-scale model into national- or continental-scale climate change models, with associated changes to energy fluxes.

4.2 Scientific and technical considerations in numerical model development

The conceptual framework includes the broader management elements as well as the specific scientific and technical design considerations. The objective of the discussion here is to guide the development of a numerical model to simulate GSI in the Great Lakes basin. This part of the framework discussion has two sections. The first section (**4.2**) describes numerical model classes and elements that inform choices about the general type(s) of numerical model(s) that should be used for collaborative international basin-scale modeling. The numerical model will need to optimize access to knowledgeable modelers and open access resources, in keeping with the principles of accessibility, practicality, and sustainability. The second section (**4.3**) describes hydrology and data availability specific to the Great Lakes basin.

Numerical models are a simplified representation of a natural system and can have many types of objectives. This framework assumes two specific objectives of a numerical model for simulating GSI in the Great Lakes basin. The first objective is to simulate basinwide GSI under a range of climate change scenarios and related hydrological and temperature scenarios, including establishing clear baseline conditions including natural variability. Applications of these simulations include changes to baseflow from the baseline that may have implications for aquatic ecology and permitting of discharges to streams, as two examples. The second objective is to provide a basin-scale model within which smaller-scale models can be developed to simulate local GSI, such as the response of stream reaches to a well or set of wells. The primary surface water features of interest are streams, although GSI with larger inland lakes or the Great Lakes and connecting channels may also be considered.

Model classes

Two classes of hydrologic models are considered here: physically based (mechanistic) and conceptual. The selection of the most appropriate set of models is a function of the main objective for the simulation of the hydrologic cycle. For example, for larger areas and management policies, a simpler model with larger time steps may be sufficient. For short-term simulations or forecasting purposes, the ability to predict future flows is an important criterion, while the ability of a model to represent changes in the parameters of the model due to anthropogenic factors may require a more physically based model or a conceptual model with physically observable parameters.

Physically-based or mechanistic models

These models use equations that follow physics, chemistry and other such natural laws as closely as possible. Some degree of simplification from a natural system is always required due to several factors such as data availability and computational burden, among others. For instance, the level of detail in modeling evapotranspiration from plants could go from modeling plant physiology down to the opening and closing of stomas and capillary water intake, plant by plant, to a more lumped class in which the model will define plant evaporation from plant growth curves and apply the value to an entire crop. One particularly difficult issue to model is realistic water infiltration. Typically, physically based models commonly use the Richards' equation (Ross 1990) to simulate the variable rate of water infiltration through non-saturated soil. However, in addition to water infiltrating through a soil column, other preferential flow paths allow water movement at considerably higher flow rates than those resulting from the Richard's equation. In theory, mechanistic models could be used with parameters extracted from databases or GIS. In practice, however, given the impossibility of considering all factors in the hydrologic cycle, some parameter adjustment (e.g., calibration) is done.

Another example of physically-based models is hydraulic models. These models describe the movement of water on rivers and lakes considering factors such as wind velocity and direction. Strictly speaking, the movement of water is always three-dimensional, but when one considers the dimension of rivers in the Great Lakes basin it is clear that a longitudinal dimension along the river is highly dominant in terms of hydrology. Furthermore, there is simply not enough river channel bathymetry information in the Great Lakes basin to support three-dimensional hydraulic models of the whole basin. Finally, the computational burden of two- and three-dimensional models makes the consideration of that class of models to be unfeasible for the objectives of the Great Lakes integrated surface and subsurface model. Therefore, typically, hydraulic models used in river routing are one-dimensional only. The time step required in these models is a function of the spatial discretization according to the current conditions. In one-dimensional models, spatial discretization is the distance between cross-sections. Later in this section, we discuss when hydraulic models could be needed.

Physically-based groundwater models depict the important subsurface processes that take place between the points of recharge and discharge. These can include unsaturated zone processes, flow through porous media, fractured rock and karst flow, and groundwater extraction by wells and dewatering. The key consideration in the development of a basin-scale GW-SW model is the linkage between the physical processes that happen above the ground surface and those that happen below, given that each realm influences the other.

Conceptual models

Conceptual models, as used here and distinct from the conceptual framework terminology, are those that by definition further simplify the quantitative representation of the hydrologic cycle beyond the simplification of a typical mechanistic model (Jaiswal et al. 2020). The equations in conceptual models are analytical simplifications of the solutions of the governing differential equations that describe the water movement on the surface and subsurface. Some conceptual models have parameters that are easily obtained from Geographic Information System and facilitate the model calibration. There are a large number of conceptual models. Some have parameters that are more observable than others, being derived from physical characteristics. For instance, surface topography as well as aquifer properties and bedrock surface morphology are nonchanging characteristics of the Great Lakes basin on the timescales of interest. Surface topography is the basis for the natural drainage network, slope, aspect and elevation of the catchments. Other characteristics of the basin, such as land use, can certainly change as a function of time, as is the case when looking at the impact of climate change on groundwater in the Great Lakes basin (Costa et al. 2021; Taylor et al. 2013). Some of those changes are anthropogenic, such as urban development and farming. We could expect that some other land uses are a direct result of natural processes over very long planning periods, including changes in the vegetation of nonfarmed lands. Consequently, having a surface hydrology model that can change some of the land characteristics over time is a requirement for a GW-SW numerical model of the basin.

4.2.1 GW-SW numerical model elements and considerations

Numerical models are simplified representations of natural systems. For practical, technical and financial reasons, models need to be no more complex than the questions they are designed to address. For this report, we will define a few important concepts.

Scientific elements of a GW-SW conceptual framework

The movement of water on the surface and subsurface of a basin is complex. Its behavior is modeled by differential equations that the model integrates in discrete time steps. Models may be composed of several components, or submodels, that take care of simulating individual scientific or physical components and processes of the system. Model complexity decisions must be linked closely to needs and use cases, as higher complexity leads to higher costs and greater data needs.

Numerical models have three kinds of elements:

1. **Equations:** Numerical relations that describe the behavior of the real-life system.

2. **Parameters**: In this document, we refer to parameters as those values in the numerical relations that are constant or quasi-constant. Porosity, hydraulic conductivity and parameters that depend on topography are time-constant parameters. Surface parameters (e.g., impervious area, land use) are essentially constant for model simulations of durations of up to a couple of years. Model simulations for periods of dozens of years will need to consider those parameters to be time dependent. In essence, those model values that are controlled by the user are parameters, whether they are constant or quasi-constant.

3. **Variables**: There are two broad categories of variables, as follows:

   - *States:* define the status of the model at every time step. For instance, the amount of soil moisture in the unsaturated layer, depth of the water table, and river level are state variables

   - *Fluxes:* input to the model, output from the model, or results from the model's internal components. For example, precipitation, infiltration, and baseflow are fluxes.

The figures below show simplified schematic diagrams of the scientific or physical (**Figures 6** and **7**) and technical elements (**Figure 8**) of a conceptual framework that could produce a useful GW-SW numerical model. The elements are explained in the following subsections.

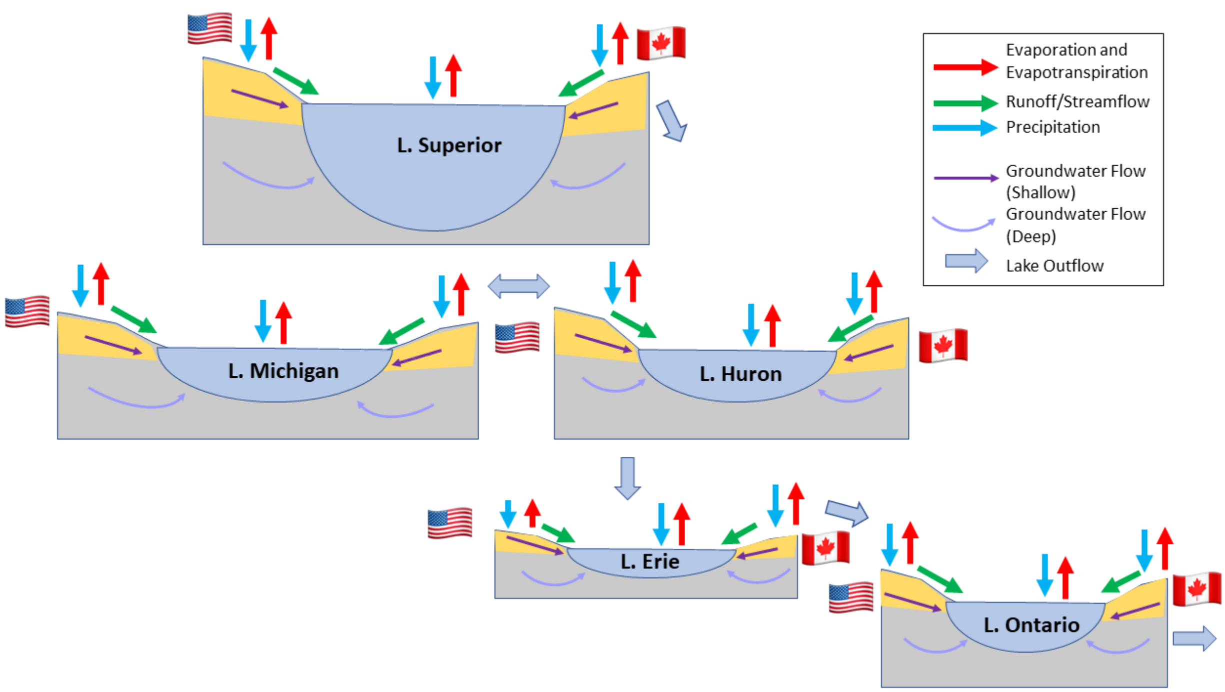


Figure 6. Schematic representation of the primary atmospheric, surface water and groundwater fluxes that constitute the scientific elements of the Great Lakes GW-SW conceptual framework. Note that the magnitude of groundwater fluxes directly to the lake basins is much less than that of other fluxes. Note that constructed canals are not included in the diagram.

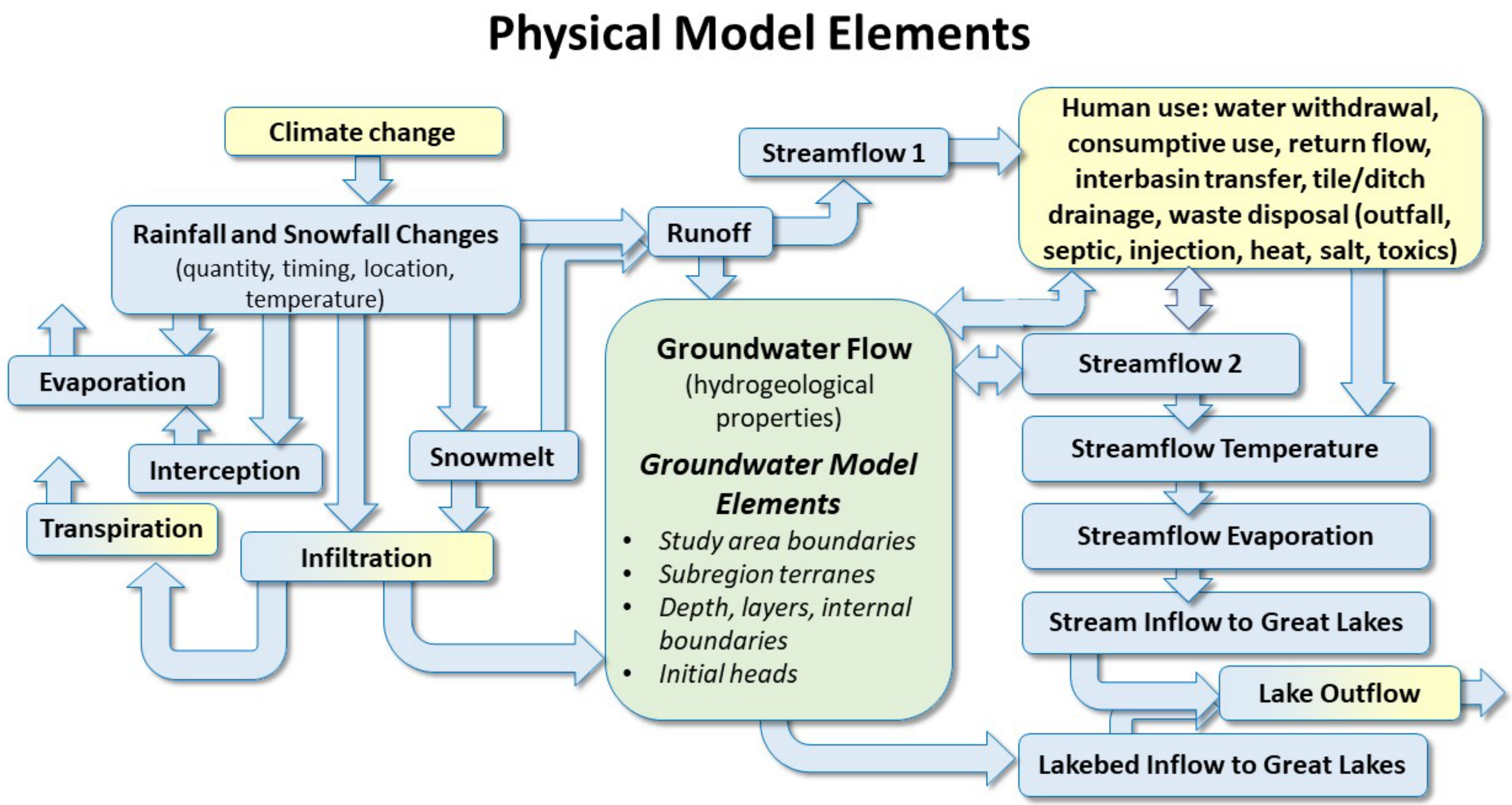


Figure 7. Simplified diagram of the natural (blue or green) and human-influenced (yellow) scientific or physical elements of the conceptual framework. Boxes with gradient fills reflect a mixture of natural and strongly human-influenced conditions based on urban, industrial and agricultural development and flow alteration. Neither arrows nor boxes are drawn to scale. All elements except for groundwater flow (green box) can be simulated with a surface hydrology model (outer boxes) but the simultaneous simulation of the subsurface requires the coupling of a surface hydrology model and a groundwater model.

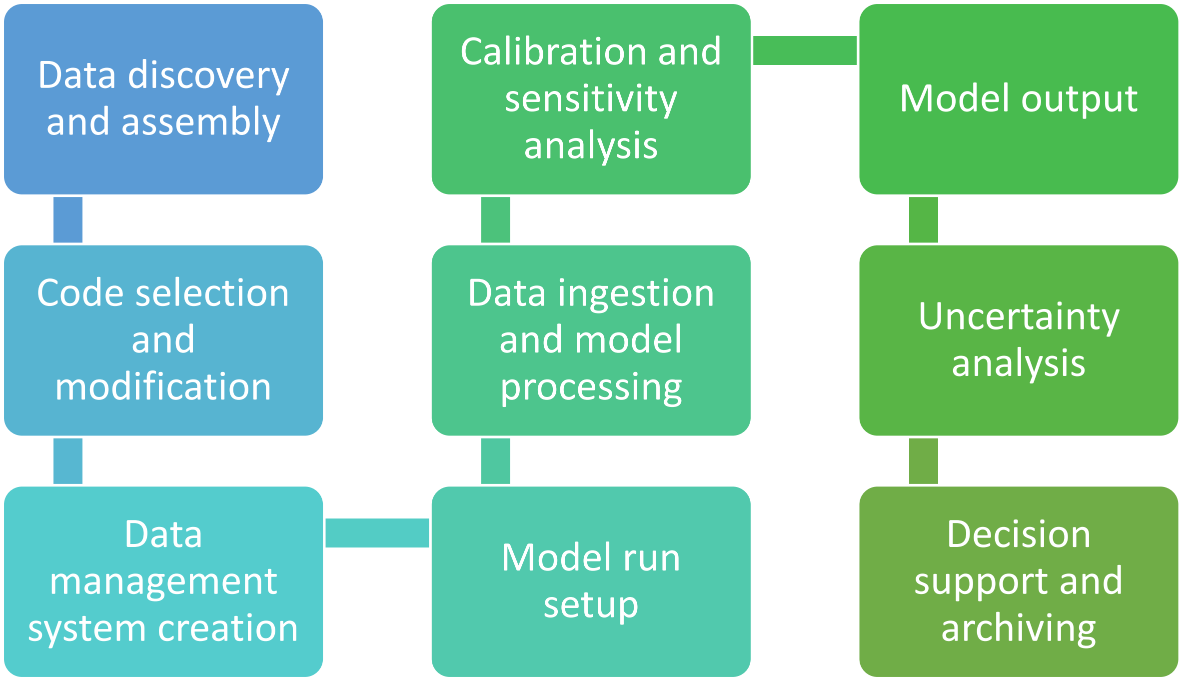


Figure 8. Schematic diagram of technical elements of the conceptual framework of the numerical model arranged sequentially. Elements that are not shown would include data management and quality assurance planning, feedback loops back to additional data discovery or refinement of system conceptualization, and incorporation of feedback from stakeholders based on reactions to output and consequences of decisions. The sequencing of some of the early steps could be modified or they could operate in parallel.

Temporal discretization

Temporal discretization is the time step used in data records and by the model for its calculations. For the model, temporal discretization is determined by the question posed, data available, computational requirements and numerical stability.

Table 4 (below) shows a typical temporal discretization of simulation models as a function of the simulation horizon. Some observations, such as radar-based precipitation, can be obtained in temporal discretization as short as five minutes and even less. It is impractical, however, to use such short time intervals for simulation horizons of more than a few hours, given the heavy computational requirements, as well as the lack of discretization to the same level for other input variables.

Table 4. Typical temporal discretization as a function of the planning horizon.

		Model Time Step				
		Minutes	Hours	Days	Months	Seasons
Planning Horizon	Days	=========	=========			
	Months		=========	=========		
	Seasons		=========	=========		
	Years				========	========

Simulations with a horizon of a few days to months commonly have time steps in the order of hours, but often could use hourly observations if available. When the horizon is a duration of a few months, the most commonly used time steps are in the order of days, or even hours, without undue computational expense. For instance, the computational models used by the NWS River Forecast Centers have horizons of up to one season and they use a time step of six hours.

When the planning horizon spans several years, models typically use computational steps in the order of one month. For example, groundwater models with a multiple-year planning horizon use a monthly time step, where changes in the model states are noticeable.

Characteristic times for hydrologic processes in the Great Lakes basin

Table 5 presents the characteristic times for hydrologic (surface) processes in the Great Lakes basin. A similar table could be developed for hydrogeological (subsurface) processes. Characteristic times for hydrogeological processes are typically longer on average than those for the hydrologic processes included in **Table 5** but are still likely relevant when the stressor of climate change is considered. By characteristic times we mean those minimum times in which a substantial change in the components of the hydrologic cycle can be noticed. For example, river routing in the Great Lakes basin can change substantially during simulations that last hours and days. A time step on the order of minutes is too short for alterations in river routing to be noticed. Likewise, given the short length of most of the rivers contributing to the Great Lakes, the travel time in the rivers is relatively short, so time steps of a week or more are not visible to a model simulating with time steps of months or seasons.

In **Table 5** below a bar shows the time intervals in which the identified processes can change considerably. Another example that illustrates this point relates to the precipitation process. Assume, for example, that a single storm delivers one inch of net rain, after interception, in one hour, and that this is the only precipitation within one week. At that heavy rate the vast majority of the rain will end up as surface runoff because it will very quickly exceed the infiltration capacity of the soil. A model that uses weekly time steps will assume that the rain only had an intensity of one inch per week and would most likely allocate it to groundwater.

The groups of entries in **Table 5** include climate forcings, fluxes in the hydrologic process, alterations in fluxes created by anthropogenic intervention, hydrologic states, and model uses.

These are discussed below. The table contents are presented in alphabetical order, followed by a section with detailed descriptions. **Appendix D** provides additional information on the elements presented in **Table 5**.

Table 5. Characteristic times for hydrologic processes in the Great Lakes basin.

Process or Phenomenon	Minutes	Hours	Days	Weeks	Months	Seasons
Climate forcings	**Characteristic times**					
Precipitation	■	■				
Potential evapotranspiration	■	■	■			
Solar radiation		■				
Cloudiness	■	■				
Relative humidity		■	■			
Wind	■	■				
Temperature		■	■			
Hydrologic processes	**Characteristic times for watersheds in the Great Lakes basin**					
Baseflow				■	■	
Direct runoff	■	■				
Impervious runoff	■	■				
Infiltration		■	■	■		
Interception	■	■				
Interflow		■	■			
Streamflow		■	■			
Snow accumulation		■	■			
Snow melt		■	■	■		■
Surface runoff		■	■			

Table 5. continued

Process or Phenomenon	Minutes	Hours	Days	Weeks	Months	Seasons
Anthropogenic changes to hydrologic cycle	**Characteristic times for watersheds in the Great Lakes basin**					
Canals and interbasin transfers		■				
Irrigation from groundwater			■			
Irrigation from rivers or lakes			■			
Land use change						■
Streamflow alteration			■	■		
Tile drains					■	
Urban development					■	
Water returns from irrigation and water supply			■			
Water supply from groundwater			■			
Water supply from rivers/lakes			■			
Natural Changes to Land Use/Land Cover					■	■
Hydrologic Storage						
Surficial aquifers			■	■		
Ice on natural lakes			■	■	■	
Ice on reservoirs			■	■		
Ice on rivers			■	■	■	
Ice on the canopy	■	■	■	■		
Snow on the canopy	■	■	■			
Snow on the land surface	■	■	■			
Soil moisture	■	■	■			
Water in natural lakes		■	■	■	■	■
Water in reservoirs			■	■	■	■
Water in rivers		■	■			
Water on the land surface	■	■	■			
Water on the canopy	■	■	■	■		

Model coupling considerations

When two models are said to be tightly coupled it means that they share the same resolution in space and in time. Fluxes between the models, including feedback loops, are computed within the same time step. This allows for the integration of models and feedback between them after each time step or a predetermined number of time steps, given the time increments are aligned.

Time resolution

In the previous sections we discuss the great differences in the characteristic times among the processes involved in the hydrologic cycle. The two critical questions concern what spatial and temporal discretization should be used for coupling a surface hydrology model and a groundwater model that simulates subsurface flow for the Great Lakes basin. The answer must consider model objectives that range from regional applications of short time horizons to basinwide applications for climate change impact studies.

Time resolution for short-term applications

For the model users in the Great Lake basin, simulation studies could determine, for instance, the impact of changing land use on tributaries to the Great Lakes over long time horizons (Gebert et al. 2016). In these cases, there may be little change to the baseflow, which could be considered constant for a short time horizon. Therefore, it will not be necessary to run a complete groundwater model when the output is not going to change when compared with the overall flow in the river during flooding conditions. In the case of short-term applications, a tightly coupled model is not required and the Great Lakes basin model would not be appropriate to apply at short timescales.

Time resolution for long-term applications

Long-term applications for this project are primarily intended to be used to study the impact of climate change on a basin. Clearly, in these studies, the groundwater contribution, as baseflow, is of fundamental importance. Therefore, the minimum time step that should be used would be in the order of months. In a tightly coupled model this requirement implies that the surface hydrology component should also use the same time step. The characteristic times of the hydrologic processes for the surface and the transient unsaturated/saturated soil zone are considerably shorter. This difference implies that, at a monthly time step, the surface hydrology mechanisms cannot be properly simulated, and, therefore, the connection between the surface and subsurface model will be inadequate.

A good solution to this problem is to couple the models such that the surface component runs at a shorter time step (e.g., days), and the groundwater model runs at a longer time step (e.g., one month). The coupling mechanism will take care of integrating the results of the shorter time steps and feeding them forward to the groundwater model. In other words, the model is loosely coupled. One issue that needs to be discussed is the consideration of feedbacks between the groundwater and the surface water, although we believe that these feedbacks will not be important for the model in the Great Lakes for long-term simulations. This approximation of assuming that the feedbacks will not be important for long-term simulations forces the baseflow to be constant for the entire set of surface water model time steps that follow the current groundwater model time step. The effect of bank storage and bank flow will then be invisible. We consider this approximation to be only a minor issue and its effects can be ignored.

A practical and commonly used approach to applying climate change scenarios to the short time steps of a surface hydraulic model is to use historical time series of precipitation and temperature (and other variables that the model may require, such as solar radiation). The precipitation time series is then modified to match the percent change predicted by the climate change scenarios. Temperature is changed by the fraction of degrees predicted. Solar radiation on the ground is a function of the cloudiness, and, if the model uses that input, a change to historical solar radiation observations that would be used for climate change forecasts will need to be made. Although simple to implement, this approach does not necessarily reflect some statistical measures, for example, variation in precipitation anticipated with climate change. If desired, a more detailed approach to include predicted precipitation alterations could be used, such as the one described by Roy et al. (2018).

The model should allow for anthropogenic and natural modifications to the land surface (land use, irrigation) and subsurface (tile drains, pumping).

Spatial resolution for the surface hydrology model

Surface hydrology models that are suitable for depicting GSI are always distributed. Some of them work on a fixed regular grid and some on irregular grids. Examples of regular gridded models are the Canadian Grid model, the NWS Distributed Sacramento Model, the National Water Model and many others. Examples of irregular grid models are the tRib model, a mechanistic model from the Massachusetts Institute of Technology (developed in large part by Valeriy Ivanov, now at the University of Michigan), and Precipitation-Runoff Modeling System (developed by George Leavesly at the USGS).

There are advantages and disadvantages to the regular grid versus the irregular grid. Regular grids would make it easier to couple to the larger grids of groundwater models. But regular grids need to lump different properties to fit into one grid cell. For example, a regular grid cell that covers different types of land use will need to choose the most prominent land use as representative of the whole cell.

Irregular grid models, on the other hand, have their cells based on uniform characteristics, such as terrain or even land use or soil types. The Precipitation-Runoff Modeling System, for instance, uses the Hydrologic Response Units (HRUs), in which the person who is applying the model uses Geographic Information Systems to define the HRUs. There is a considerable level of freedom to define those HRUs, to include the properties that should be specifically considered. One possible difficulty lies in the coupling of multiple HRU cells into a single groundwater cell. However, given the latitude the users have in defining the HRUs, the borders of the larger groundwater cells can also be considered when defining the HRUs, thus solving that problem.

One may argue that reducing the cell size is a way to solve the requirement of regular grid models to use the most prominent feature to be representative of the entire cell. There are several problems with this approach:

1. some features of the model may not be available at the higher resolution;
2. there will be a considerable increase in the computational time; and
3. perhaps, more importantly, higher resolution models do not necessarily imply better simulation results.

The NWS Office of Hydrologic Development ran experiments that showed that reducing grid cell size would improve simulation accuracy only up to a certain point, beyond which it does not (Koren et al. 2003). One possible cause would be that the higher resolution estimates of precipitation are noisier than lower resolution estimates, and therefore a noisier input to a highly nonlinear model will result in less accurate simulations.

Spatial resolution for the groundwater model

Model cell dimensions need to be sufficiently small that the internal boundaries associated with streams and inland lakes do not overly constrain simulations. The model software should allow the upper groundwater model layer to have finer resolution than lower layers, except for cells representing large parts of the Great Lakes. The only limitation on how fine a resolution can be used is computational. Examples of how other modelers have dealt with issues of cell dimensions and vertical layering are discussed in the next section.

Previous regional numerical models in the Great Lakes basin

There is only one completed GW-SW model for the entire Great Lakes basin (Xu et al. 2021). The model uses the software HydroGeoSphere (HGS), which is owned by Aquanty. HGS is a three-dimensional control-volume finite element simulator that is designed to model the entire terrestrial portion of the hydrologic cycle. It uses a globally implicit approach to simultaneously solve the two-dimensional diffusive-wave equation for overland/surface water flow and the three-dimensional form of Richards' equation for variably saturated groundwater flow (Ross 1990). The main objective of the HGS modeling of the Great Lakes basin was to simulate groundwater interaction with the Great Lakes water bodies.

A regional GW-SW model using HGS was developed for Southern Ontario (Frey et al. 2020). The model includes very detailed three-dimensional hydrostratigraphy and streams of Strahler order three or larger. One goal of the modeling was to determine how GSI is affected by coarser and finer discretization, and the authors found the two levels of discretization had only a small effect on GSI. Only a subset of high-capacity wells was included, which may limit the application of this finding to a similar experiment using all available high-capacity well data.

USGS developed a groundwater model using Modular Three-Dimensional Finite-Difference Groundwater Flow Model (Feinstein et al. 2010) for the Lake Michigan basin. The objectives of the modeling were to provide: a forecasting tool to assess the regional effects of future changes in water use and climate in the western part of the Great Lakes basin; a platform for the development of embedded, higher-resolution models used to address water management issues at smaller (local) scales; a means of documenting and archiving information from a wide variety of sources on the hydrogeology and water use in the region; and a basis for developing indicators of the sustainability of water resources.

USGS also developed a surface-water model using the Precipitation-Runoff Modeling System for the Lake Michigan basin (Christiansen et al. 2014). The Lake Michigan basin Precipitation-Runoff Modeling System model focuses on forecasts of monthly and annual stream flow. Downscaled model output from four carbon emissions scenarios and eight general circulation models were used as input to forecast potential future hydrologic changes within the Lake Michigan basin caused by potential future climate change scenarios.

4.3 Great Lakes hydrogeology and data availability

The study area includes the Great Lakes basin (**Figure 5,** page 24) and areas outside of the Great Lakes basin that contribute groundwater to streams within the basin. The latter areas have not been identified throughout the basin but are known to occur in southeastern Wisconsin and northeastern Illinois (Feinstein et al. 2010). The Groundwater Information Network (GIN) has been developed to improve knowledge of groundwater systems and enhance groundwater management through increased access to groundwater information. The network compiles and connects a variety of groundwater information from authoritative sources such as water well databases, water monitoring data, aquifer and geology maps, and related publications. Provincial and territorial collaborators include Ontario and Québec; international collaborators include the USGS and others.

4.3.1 Great Lakes basin hydrogeology and numerical model considerations

The hydrogeological conditions of the Great Lakes basin can be broadly generalized into regions of similar unconsolidated (glacial and postglacial) and bedrock composition. These are described briefly here along with related implications for numerical model configuration.

Hydrogeologic terranes: The Great Lakes basin has diverse hydrogeologic terranes. The entire basin is glaciated, and unconsolidated deposits of glacial and postglacial origin occur in most of the basin, though these deposits are a thin veneer or absent in areas. Approximately the northern half of the basin has Precambrian igneous and metamorphic rocks either at the surface or beneath a thin layer of unconsolidated deposits. Approximately the southern half of the basin has Paleozoic sedimentary rocks including carbonates, sandstone and shale that are mostly covered by unconsolidated deposits of glacial origin. Major terranes are discussed below.

> **Surficial unconsolidated terranes**: Glacial and postglacial deposits are highly variable at the surface (Neff et al. 2005). The same textural variability typically occurs vertically so that a map of surficial deposits does not necessarily inform about the deposits at depth. Bayless et al. (2017) developed three dimensional maps for the glaciated part of the conterminous United States, but the scale may be too coarse for use in a model focusing on GSI. There is very limited detailed three-dimensional geologic mapping of these deposits in the US part of the basin. The Ontario Geological Survey has completed three

dimensional maps for southern Ontario (Logan et al. 2020; 1:50,000 scale surficial maps and up to 20 stratigraphic units). Recharge rates for these deposits vary based on precipitation, slope, soil permeability, and land cover, among other factors (**Figure 9**).

Many municipal and most domestic and irrigation withdrawals are from aquifers in coarse-textured glacial deposits in Wisconsin, Indiana, Michigan, Ohio, New York and Ontario. These deposits are also typically associated with higher groundwater contributions to streamflow. In some areas of Michigan, for instance, where coarse-textured glacial deposits dominate and streams are incised due to postglacial isostatic rebound, groundwater discharge constitutes nearly 100 percent of streamflow (**Figure 10**). Many of these streams also provide ideal habitat for important trout populations.

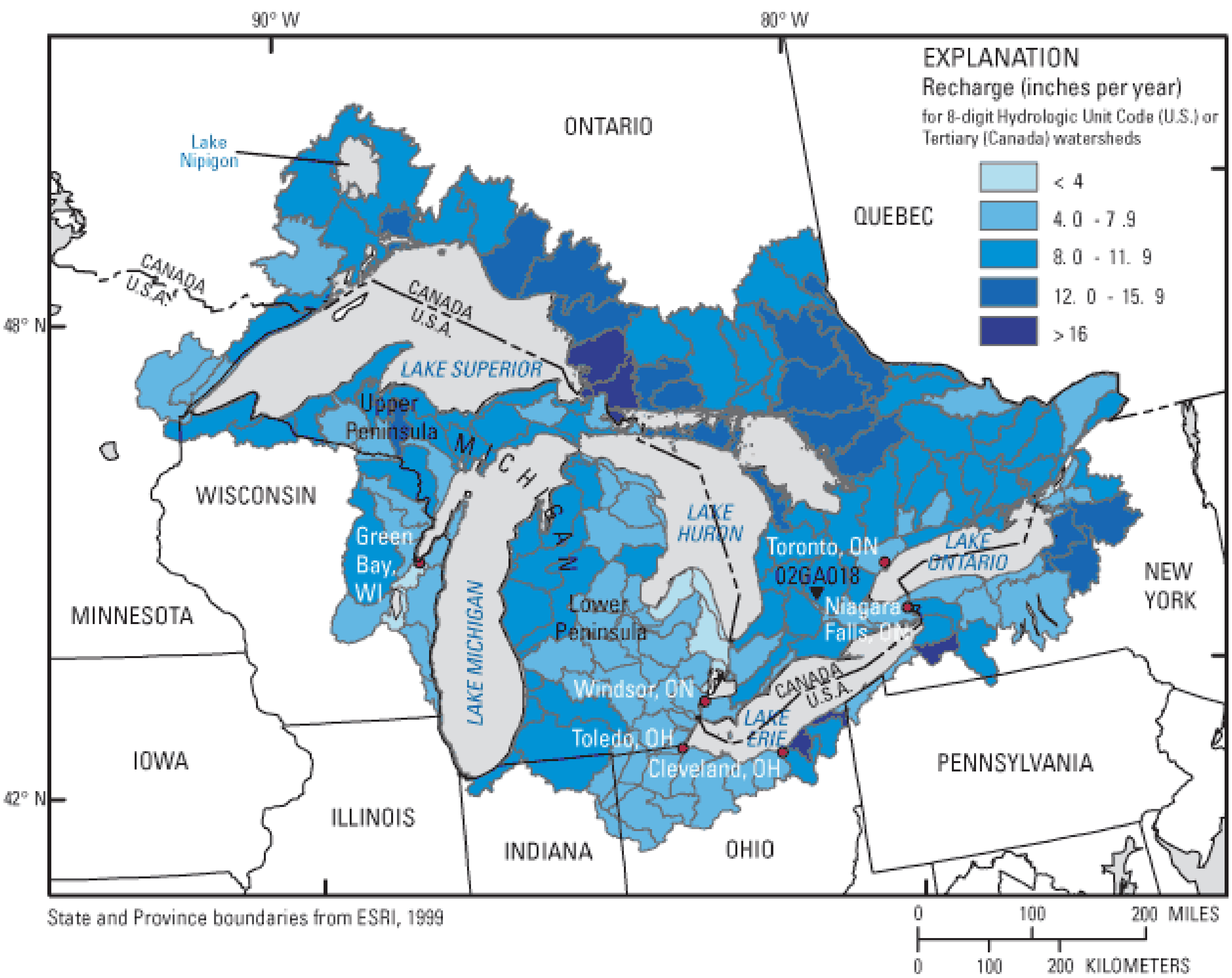


Figure 9. Annual recharge of shallow groundwater in the Great Lakes basin (Neff et al. 2005).

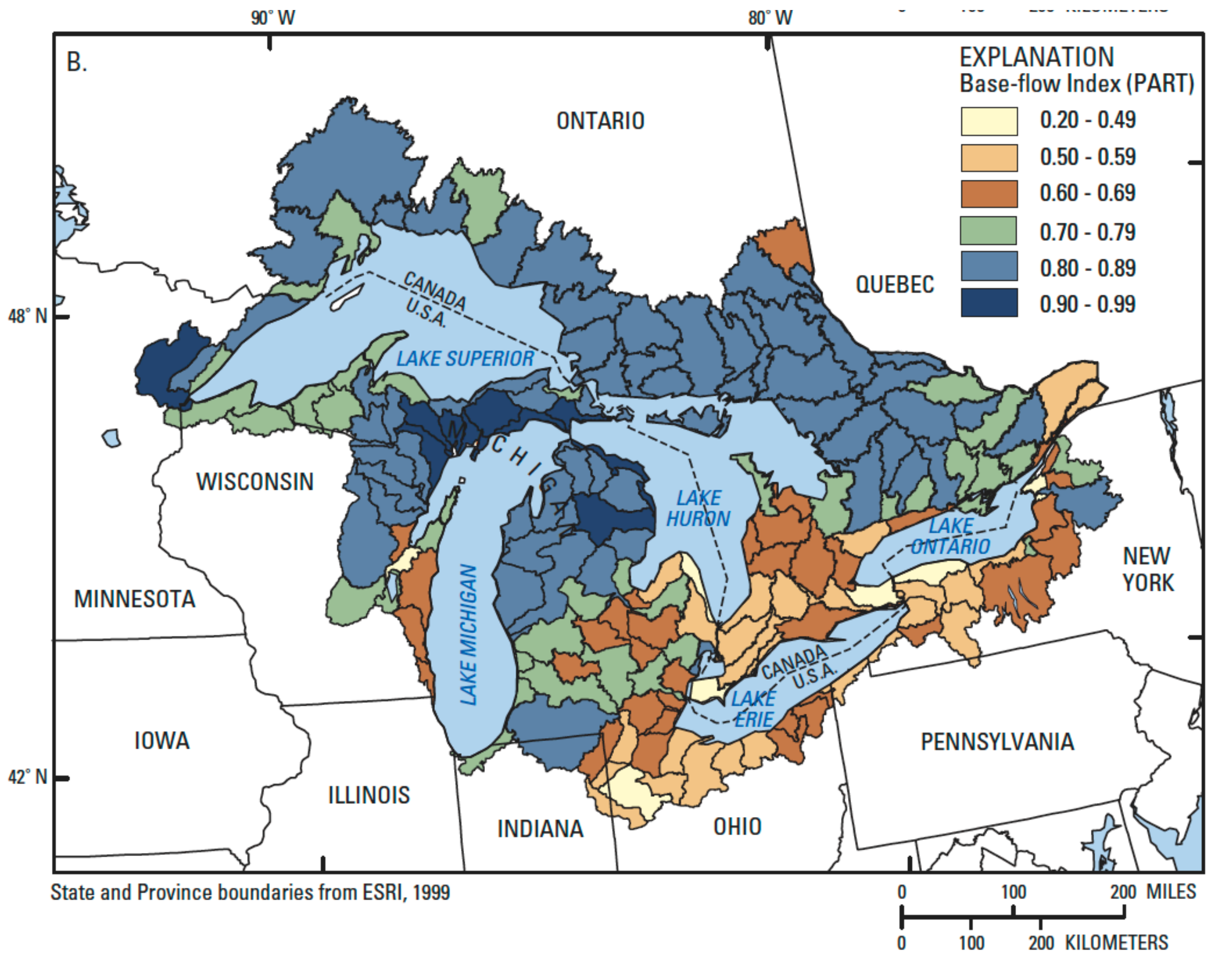


Figure 10. Map of normalized baseflow index showing greater baseflow in the northern parts of the basin (Neff et al. 2005). Base-flow index is the average rate of baseflow divided by the corresponding average rate of total streamflow so a number closer to one indicates a greater baseflow percentage for the watershed.

Shallow carbonate terranes: Shallow carbonates occur around the rim of the Lake Michigan basin in Wisconsin, Michigan and Ohio forming the archipelago and the Bruce Peninsula in Lake Huron and the Niagara Escarpment in Ontario and New York (**Figure 11**). In many of these areas, glacial deposits are thin or absent.

Most groundwater flow in carbonate terranes is through secondary features, such as sub-vertical fractures and sub-horizontal bedding plane openings that have been enlarged by dissolution. Sinkholes and other karstic features occur in Ontario and Michigan. In some areas, internal drainage to sinkholes results in locally high volumes of submerged discharge to Lake Huron which is sometimes saline and anoxic and supports microbial communities.

Poor water quality can limit withdrawals for drinking water, though there are domestic and municipal withdrawals in Wisconsin, Michigan, Ohio and Ontario. Water is withdrawn to operate the many quarries in the region, including the largest limestone quarry in the world at Rogers City, Michigan.

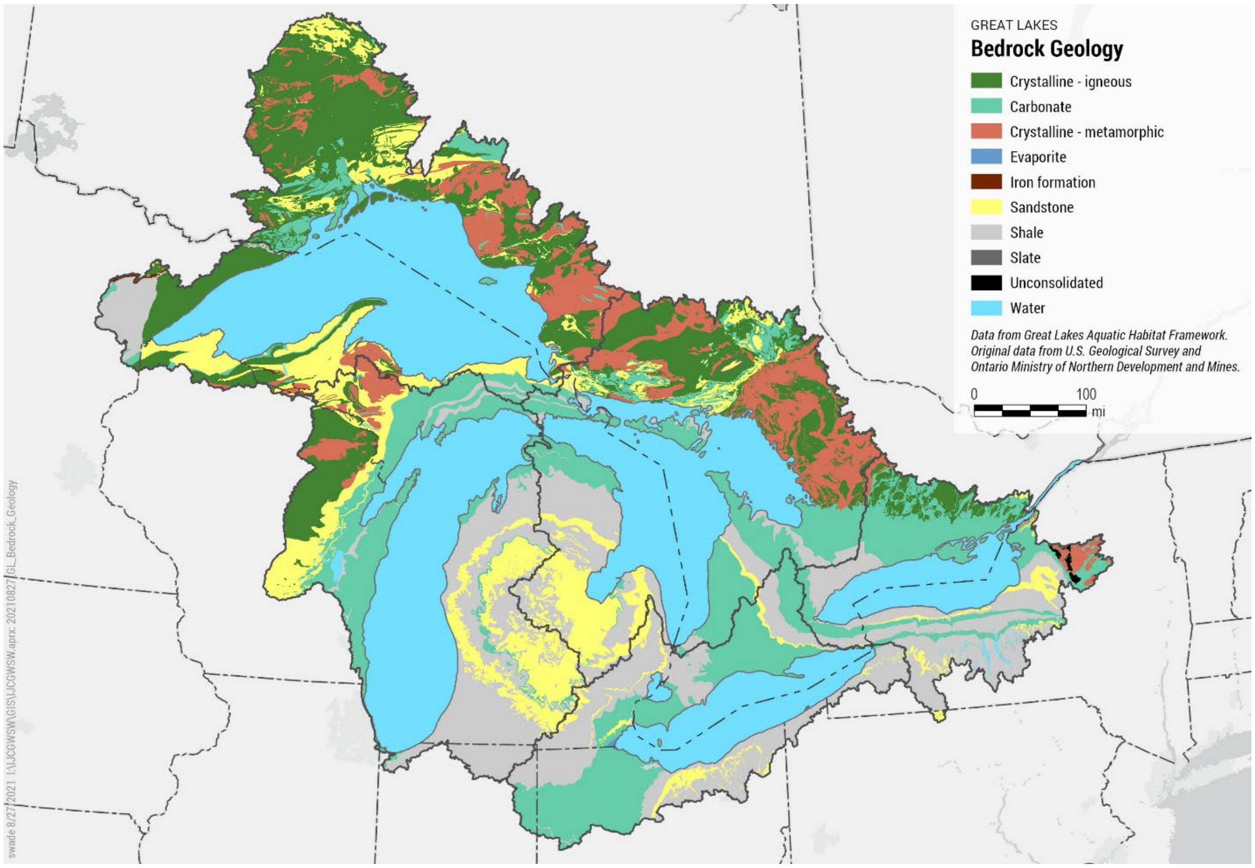


Figure 11. Simplified bedrock geology of the Great Lakes basin, harmonized across the international border; modified from Great Lakes Aquatic Habitat Framework data.

Igneous and metamorphic terranes: Much of the Lake Superior basin, the northeastern part of the Lake Michigan basin and the northern part of the Lake Huron basin have igneous or metamorphic rocks at or near the land surface. These rocks are of low primary porosity but can be highly fractured or covered with a conductive regolith. Population and water use are generally low. Domestic and municipal water supplies tend to be from surface water. Therefore, hydrogeologic data tend to be sparse. Significant ore mining does occur, particularly in the Lake Superior basin, and mine drainage can require large withdrawals of water. A recent model of GSI near Lake Superior provides a good example of model development in this terrane (Leaf et al. 2015).

Sandstone aquifers: Sandstone aquifers historically have been important for municipal supply in areas of southeastern Wisconsin and northeastern Illinois, mostly from areas outside of the Great Lakes basin which contribute water to streams in the basin or Lake Michigan. Withdrawals have been declining as more municipalities switch to Lake Michigan as a water source. Only one large municipality in Lansing, Michigan withdraws water from these aquifers.

Artificially drained terranes: Poorly drained soils (see the **Figure 14** map, page 48) in the areas of Green Bay, Saginaw Bay, western Lake Erie and southern Ontario have been tiled and ditched for over one hundred years. Tiling is increasing in these areas and also in areas with coarser soils where irrigation is being applied, such as northwestern Indiana and southwestern Michigan. Locations of tiles are poorly known, some are more than a century old, and maps of tiles are unavailable. One can make assumptions about the locations of tiles by mapping a combination of slope, soil type and land use.

Numerical GW-SW model external boundaries: In areas of southeastern Wisconsin and northeastern Illinois, large amounts of groundwater withdrawals have caused, and continue to cause, shifting of groundwater divides of the Great Lakes basin (Feinstein et al. 2010), so this is a situation where the 'near field' needs to include areas outside of the basin in the groundwater model. Such areas have not been delineated across the Great Lakes basin, so the precautionary approach would be to include areas outside of the basin in the near field if groundwater divide information is not available. The model domain should include a 'far field,' sufficiently distant from the study area that simulations of groundwater flow are not affected by the location and type of external boundaries.

Numerical GW-SW model internal boundaries: The Great Lakes and connecting channels (the St. Marys River, St. Clair River, Lake St. Clair, Detroit River, Niagara River and St. Lawrence River) are strong regional groundwater sinks. It is assumed that little or no groundwater flow relevant to GSI crosses these sinks. [1] This assumption is discussed later in **Section 4.4** (Considerations for model calibration). The integrated model should be designed to account for changes in water levels in the Great Lakes and connecting channels, as these water levels will affect groundwater flow to and from these surface water features.

Other internal boundaries of the numerical GW-SW model: The stream network is comprised of streams, canals and interbasin connections. Canadian and US datasets have been harmonized by the Great Lakes Aquatic Habitat Framework (GLAHF). The Great Lakes Hydrologic Data was created from multiple up-to-date Canadian and US data sources including the National Hydrography Dataset Plus, Version 2, the Ontario Integrated Hydrology Dataset, the National Hydrography Dataset and the National Elevation Dataset. [2] In addition to the stream network, the GLAHF data include major inland lakes and wetlands. Additional boundary sinks to include would be locations, depths and magnitudes of withdrawals and hydraulic gradient impacts by high-yield wells, well fields, dewatering operations (e.g., mines, quarries) and areas of tile

---

[1] In an oral presentation for the project team about the Great Lakes basin groundwater-surface water model by Xu et al. (2021), an author noted that the only transboundary flow was a small amount in Lake Huron that would likely not affect simulations focused on GSI.
[2] See more at: glahf.org/watersheds/, accessed February 1, 2022.

drainage. Locations and magnitudes of high-volume enhanced recharge (sources) via infiltration beds, injection wells or similar operations would also be necessary to include. Water table elevations can be obtained from state, provincial and federal agencies based on monitoring well measurements.

Vertical extent and layering in the numerical GW-SW model: The primary vertical distinction for subsurface water flow simulation in a basin-scale numerical model would be between surficial unconsolidated layers and bedrock layers. A secondary distinction could be established as the base of fresh groundwater (chloride less than 250 mg/L) within the saturated zone, given that brackish and saline groundwater are fairly common at depth throughout much of the basin. The vertical extent of the subsurface portion of an integrated model may depend upon the hydrogeologic terrane and an understanding or assumption regarding GSI for and management priorities for different aquifers. The number of layers would be constrained mostly by computational limitations and subsurface data availability. Some examples of studies related to the vertical extent and model layering are referenced below.

- In Ontario's Ambient Groundwater Geochemical database, water from drilled wells is classified stratigraphically into overburden (regolith), overburden-interface, bedrock interface, subcropping bedrock, and deeper bedrock. Overburden wells are completed in unconsolidated sediments, which are almost always glacially derived, and necessarily have screens. Interface wells are completed within three meters above or below the bedrock surface, and even when completed in overburden their waters usually have the chemical character of bedrock because locally derived basal tills are similar in composition with an even higher surface area. For geochemical research purposes, they are often grouped with subcropping bedrock wells, which are completed in the underlying mapped bedrock unit. Deeper wells are interpreted to be completed beneath the mapped surface bedrock layer in a deeper bedrock unit (Hamilton 2020).

- The HydroGeoSphere model of southern Ontario extends across the Phanerozoic terrain of southern Ontario and localized areas of exposed Precambrian shield, such that the model boundary is coincident with watershed boundaries. The spatially heterogeneous subsurface component of the regional model includes three soil layers, five quaternary layers, and either seven or eleven bedrock layers for the respective low (coarsely discretized) and high (finely discretized) resolution model versions (Frey et al. 2020).

- To better represent the configuration of the stream network and simulate local GSI, a revised version of the USGS Lake Michigan basin groundwater model applied a semistructured grid with finer resolution in the upper layer and had fewer layers (Feinstein et al. 2016). The original model had 20 layers, of which three are glacial and 17 are bedrock. The revised model had four layers. The uppermost layer in the revised model is identical in thickness to the original model, representing, where present, the top 100 feet of unconsolidated material. The second layer combines layers two and three of the original model, incorporating the remainder of the glacial thickness when greater than 100 feet. The third layer represents the unconfined bedrock and corresponds to the thickness of carbonate, shale and sandstone units above the first bedrock confining unit, defined as a layer at least five feet thick assigned a vertical hydraulic conductivity less than 0.001 feet/day (0.0003 meters/day) in the original model. The fourth layer represents the confined bedrock, including the first bedrock confining unit. The finer discretization in the upper permitted a more complete inclusion of the stream network, allowing for better simulation of GSI.

4.3.2 Data availability

- A large amount of data are available in Canada and the United States for setting up and calibrating a numerical GW-SW model. Some of these data have been harmonized for the Great Lakes basin by GLAHF. [3] Relevant data sets are summarized in **Table 6** and discussed in more detail below.

[3] The GIS coverages are available at glahf.org/data/, accessed on February 1, 2022.

Table 6. Summary of available data.

Data type	Data collection or management agencies	Reference or website
Surface water network	ECCC, NDMNRF, [1] NOAA, USGS	water.noaa.gov/about/nwm waterdata.usgs.gov/nwis/rt wateroffice.ec.gc.ca/google_map/google_map_e.html
Bedrock geology	NDMNRF, NRCan, USGS	glahf.org/data/
Glacial geology	NDMNRF, NRCan, USGS	glahf.org/data/
Conductance and aquifer storage	NDMNRF, State agencies	gis-egle.hub.arcgis.com/pages/all-maps-and-apps geologyontario.mndm.gov.on.ca/index.html
Land use/land cover	North American Land Change Monitoring System, USGS National Land Cover Database	glahf.org/data/ mrlc.gov/data/north-american-land-change-monitoring-system
Soils	Agriculture and Agri-Food Canada, US Department of Agriculture	glahf.org/data/
Air temperature and precipitation	ECCC, NOAA	ncdc.noaa.gov/ mrcc.purdue.edu/ canada.ca/en/services/environment/weather.html
Water use	Ontario Ministry of the Environment, Conservation and Parks, USGS	water.usgs.gov/wateravailability/greatlakes/index.html
Ground-water levels	GIN, Ontario Ministry of the Environment, Conservation and Parks, USGS	gin.gw-info.net/service/api_ngwds:gin2/en/gin.html waterdata.usgs.gov/nwis/gw gin.gw-info.net/service/api_ngwds:gin2/en/gin.html ontario.ca/page/map-provincial-groundwater-monitoring-network
Streamflow and stage	ECCC, Regional Conservation Authorities, USGS	waterdata.usgs.gov/nwis/rt
Great Lakes and connecting channel stage and flow	Department of Fisheries and Oceans Canada, NOAA, US Army Corps of Engineers, USGS	tidesandcurrents.noaa.gov/ lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Water-Level-Data/
Lakebed geology	NDMNRF, NOAA, State agencies	glahf.org/data/ ngdc.noaa.gov/mgg/greatlakes/
Well, mine, and ground-water extraction or recharge/ injection locations and properties	Ontario Ministry of the Environment, Conservation and Parks, NDMNRF, State agencies, USGS	gis-michigan.opendata.arcgis.com/search?collection=Dataset&q=wells dnr.wisconsin.gov/topic/Groundwater/Data.html data.ontario.ca/dataset/well-records waterdata.usgs.gov/nwis/gw
Climate change projections	Great Lakes Integrated Sciences and Assessments, York University	lamps.math.yorku.ca/OntarioClimate/ glisa.umich.edu/project/great-lakes-ensemble/

[1] NDMNRF is the acronym of the Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry.

Surface water network: As noted earlier, GLAHF provides a harmonized binational data set for surface water.

Bedrock geology: GLAHF provides a harmonized binational data set for bedrock at the surface or immediately beneath glacial deposits based on USGS and Ontario Ministry of Northern Development and Mines data sets. Deeper bedrock units that may be relevant to GSI are mapped for some areas of the basin, such as eastern Wisconsin, northeastern Illinois, parts of the lower peninsula of Michigan, northern Indiana and Ohio, and southern Ontario (see, for example: Feinstein et al. 2010; Frey et al. 2020). Additionally, state and provincial drillers' log databases can be used to supplement the other data. One example is the Ontario Paleozoic bedrock synthesis by Carter et al. (2021). Another example is maps and grids of hydrogeologic information created from standardized water well drillers' records of the glaciated United States (Bayless et al. 2017).

Glacial geology: GLAHF provides a harmonized binational data set for quaternary surficial geology based on USGS and Ontario Ministry of Northern Development and Mines data sets (**Figure 12**). Surficial geology does not always reflect subsurface geology in glacial terranes. Drillers' logs provide a crude but large amount of data that can be used to determine layering and conductance zonation for model layers representing glacial deposits. Modeling work by Aquanty and USGS within the Great Lakes basin can provide guidance on this issue. In Ontario, a three-dimensional surficial geology model of southern Ontario is being developed (Logan et al. 2020) The Ontario Geological Survey has been conducting three-dimensional sediment mapping in southern Ontario since 2002. As of 2020, over 300 continuously cored boreholes had been drilled through the quaternary sediment cover and uppermost bedrock (Mulligan and Burt, 2020). Additionally, USGS developed a hydrogeologic framework that divides the glaciated part of the United States into 17 distinct hydrogeologic terranes based on depositional history, texture and thickness (Haj et al. 2018; Yager et al. 2019). This approach may be helpful if applied to the Great Lakes basin. Other derived data sets using this framework include: mean groundwater age, groundwater age distribution, and susceptibility to land surface contamination (Solder et al. 2020; Starn et al. 2021); reducing conditions (Erickson et al. 2021a); and arsenic and manganese occurrence (Erickson et al. 2021b). These data and maps may provide insight into groundwater flow in the US part of the basin.

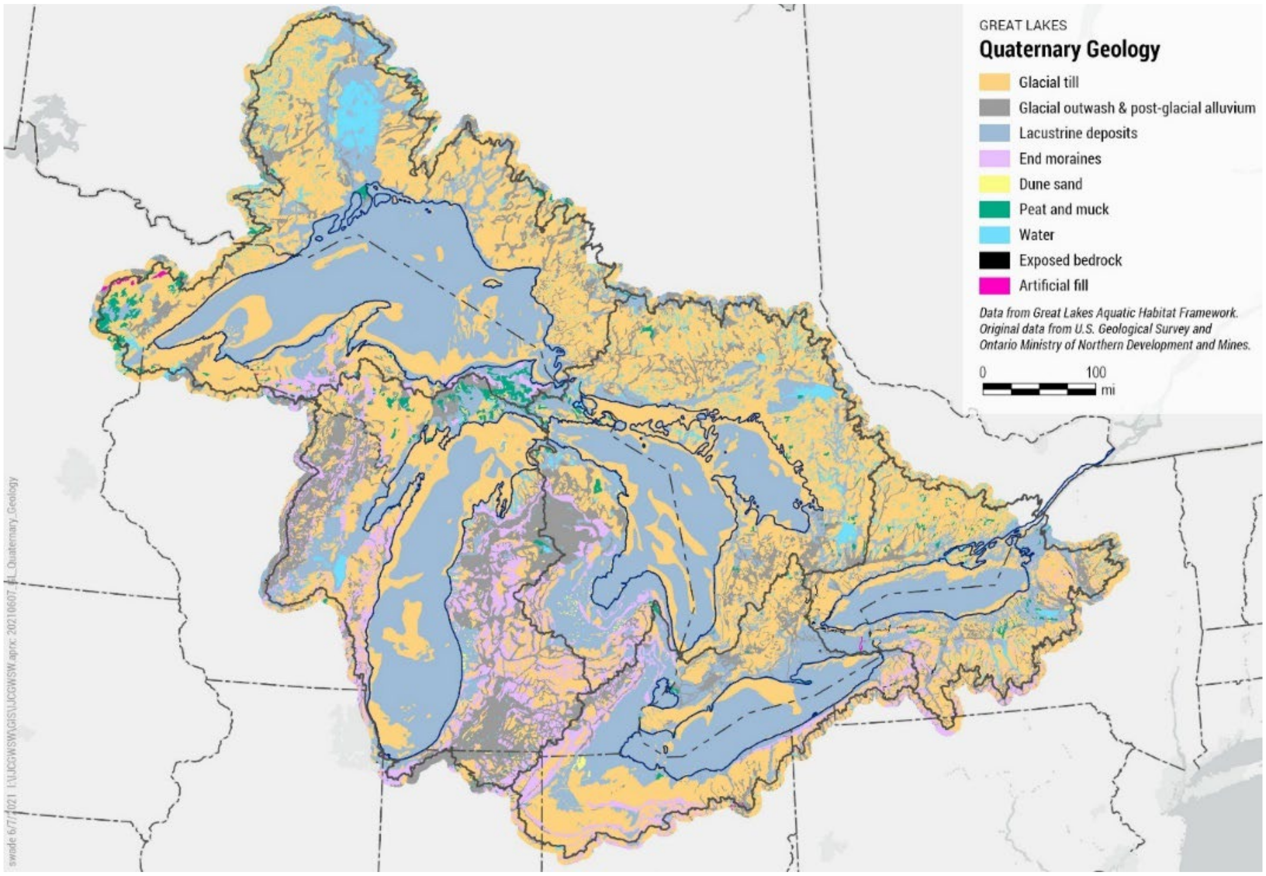


Figure 12. Binational data set for quaternary geology compiled and harmonized by GLAHF, based on USGS and Ontario Ministry of Northern Development and Mines data sets.

Conductance and aquifer storage: Aquifer and aquitard conductance values are available from various groundwater flow models in the Great Lakes basin (e.g., Xu et al. 2021, entire basin; Feinstein et al. 2010, Lake Michigan basin; Frey et al. 2020, southern Ontario). Although some of these models are not calibrated, they are still useful to guide appropriate layering and zonation within layers. Additionally, Canadian and US water agencies have data from aquifer tests that can be used for the same purpose. In Michigan, thousands of water well logs were used to estimate effective transmissivity in glacial deposits [1] and bedrock [2] for about 5600 subwatersheds throughout the state.

Land use and land cover: GLAHF provides a harmonized binational data set for land use and land cover for 2000/2001 and 2010/2011 based on USGS National Land Cover Database and Ontario Ministry of Natural Resources and Forestry information (**Figure 13**). Urban areas have uses and features that complicate hydrology (e.g., stormwater,

[1] More information available at: egr.msu.edu/igw/GWIM%20Figure%20Webpage/Webpages%20-%20Links/Figure17.html, accessed February 1, 2022.
[2] More information available at: egr.msu.edu/igw/GWIM%20Figure%20Webpage/Webpages%20-%20Links/Figure19.html, accessed February 1, 2022.

wastewater, impervious surfaces). For forecasts under climate change, USGS is working on predictions at a 250 meter scale (Sohl 2021, written communication). A recent Ontario analysis was published by Eimers et al. (2020).

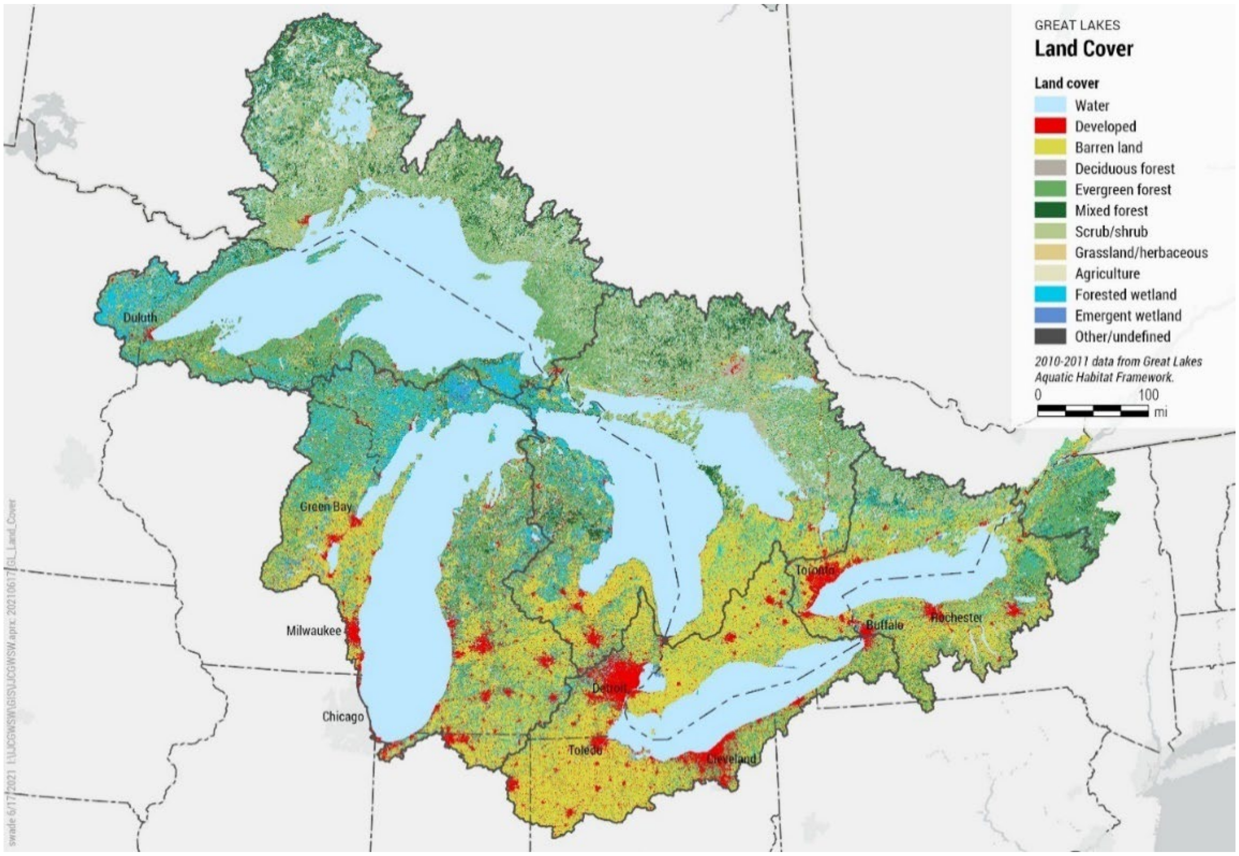


Figure 13. Current land use in the Great Lakes basin shows agricultural and urban development in the south and forested areas in the north.

Soils: GLAHF provides a harmonized binational data set for soils using Natural Resources Conservation Service and Agriculture and Agri-Food Canada databases (**Figure 14**). Harmonized common classes for the Great Lakes basin are soil slope, drainage and rooting depth.

Air temperature and precipitation: High-quality air temperature and precipitation observations over the US portion of the Great Lakes basin are available from NOAA's National Centers for Environmental Information. As part of the National Centers for Environmental Information's mission as one of the two World Data Centers, some of the Canadian observations are also available there. The Midwest Regional Climate Center hosts the binational gridded precipitation product, combining Canadian Precipitation Analysis and the NWS Mean Precipitation Estimation.

Water use: Great Lakes states and Ontario compile these data for large quantity withdrawals as defined by the Great Lakes-St. Lawrence Sustainable Water Resources Agreement, which is 100,000 gallons per day. Site-specific data for municipal withdrawals should be available for a sufficient length of time for model calibration. Site-specific data for agricultural, commercial and industrial withdrawals may not be available in some states and Ontario due to privacy issues and these data will need to be pursued on a state-by-state or provincial basis. Compiling historical water use data for model calibration will be a major effort.

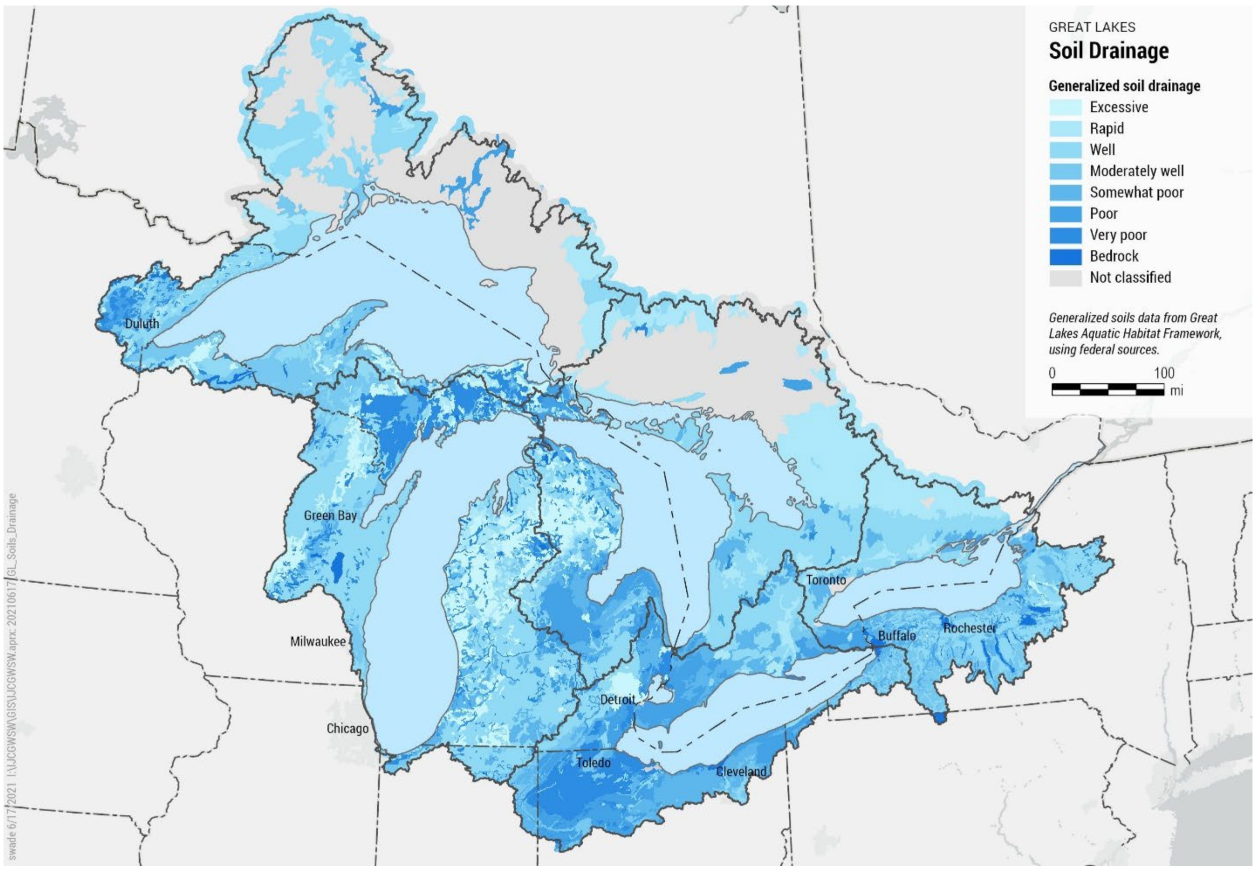


Figure 14. Harmonized binational soil classification by drainage properties compiled by GLAHF using US Natural Resources Conservation Service and Agriculture and Agri-Food Canada databases. Note the very poor soil drainage areas around Saginaw Bay and western Lake Erie, including southernmost Ontario, and the unclassified areas in the Canadian parts of the Lake Huron and Lake Superior watersheds.

Groundwater levels: Groundwater levels are primary calibration targets for the simulation of groundwater flow in the integrated model. A large amount of data for most aquifers has been compiled by state, provincial and federal agencies and is sufficient for calibration in most areas. There are areas of the basin, however, where anthropogenic groundwater withdrawals are small and data are sparse, for instance, the Lake Superior basin in Ontario. The Ontario provincial groundwater monitoring network maintains approximately 450 wells in which groundwater levels are monitored. The GIN [3] also has coordinated provincial and binational data.

Streamflow and stage: Streamflow and stage are primary calibration targets along with groundwater levels. Water Survey of Canada and USGS have long-term data from streamflow gages suitable for calibrating a GW-SW model. As with groundwater levels, data are sparse in areas of small populations such as the Lake Superior basin in Ontario. Federal, state and provincial areas also have streamflow data from periodic measurements at non-gaged locations, often during periods of low streamflow.

Great Lakes and connecting waters stages: These data, along with discharge at control points, are coordinated binationally by US Army Corps of Engineers, NOAA, ECCC, and dam or hydropower operators at short time intervals. Especially rapid and unpredictable changes can occur due to ice damming of constricted points such as the Lake St. Clair outlet.

4.4. Considerations for model calibration

Given potential computational limitations with fine discretization over the large study area, consideration should be given to calibrating a model on a lake-by-lake basis, since cross-lake groundwater flow is assumed not to occur. A similar but simplified approach was employed by Zell and Sanford (2020) for a Modular Three-Dimensional Finite-Difference Groundwater Flow Model of the contiguous United States where the model was divided into 75 subdomains for calibration using Parameter Estimation Software. The assumption of no cross-lake flow can be tested once a basin-scale model is developed and refined.

The use of a semistructured grid can provide for more detailed GSI evaluation without significantly increasing computational times. Feinstein et al. (2016) reduced the original Lake Michigan basin groundwater model upper layer grid spacing from 5000 feet to 500 feet in the revised model to better incorporate streams, a 90 percent decrease in the cell area. The grid spacing of the lower three layers was reduced from 5000 feet to 2500 feet. As noted above, the number of layers was also reduced from 20 to four.

[3] More information at: gin.gw-info.net/service/api_ngwds:gin2/en/gin.html, accessed February 1, 2022.

5.0 Findings, Gaps and Recommendations

This project identified research questions and a set of management needs that could be addressed using basinwide GW-SW numerical models for the Great Lakes basin. The report describes the scientific, technical and process management elements of a conceptual framework for the GW-SW model. Key stakeholders with an interest in this scale of modeling were identified and queried including assessment of their available data, technical capabilities and financial resources to support the development and maintenance of such models. New or ongoing work related to GW-SW modeling by government agencies, universities and private companies was identified and summarized. Potential lead agencies that can carry out such GW-SW model development and maintenance were also identified. Finally, the role of the IJC in supporting these activities was considered in light of the organization's mission and mandates. The assessment included expert interviews, development and deployment of a stakeholder questionnaire, and a review of recent reports and peer-reviewed literature developed since the Phase 1 report was completed in 2018. Major findings, gaps and recommendations are listed below.

Key finding

There is an urgent and growing need to develop a sound scientific understanding of GSI on the scale of the binational Great Lakes basin in light of the cumulative pressures arising from agricultural and other high-volume uses of groundwater, population changes, economic-industrial demands and environmental flow requirements. The projected stresses that climate change will bring to the water cycle within the Great Lakes region and beyond are of particular concern. A basin-scale understanding can inform questions that apply at smaller scales within the basin by providing context and boundary conditions for addressing questions at subregional to local scales.

Other findings

- Primary information needs that were identified by the groundwater resources managers in the basin include better water budgets for high use areas (municipal supplies, quarries, agricultural irrigation areas); improved monitoring and understanding of water table elevations, pressure heads and baseflow; and better forecasts of future conditions, including potential changes in year-round impacts on Great Lakes water levels and temperatures under changing climate conditions.

- Increased strategic investment in integrated GW-SW monitoring, modeling and research at the scale of the entire basin has the potential to provide substantial environmental, societal and economic dividends in terms of better determination of sustainable yields in withdrawal permitting and technical support for policy changes and program improvements, based on stakeholder feedback.

- Review of new reports and peer-reviewed literature (since Phase 1; e.g., Xu et al. 2021) with a focus on GW-SW quantity rather than quality confirmed that direct discharge and impacts of groundwater on Great Lakes shoreline areas are relatively small (less than 1 percent of water budget on average) except in embayments. However, riverine and tributary impacts of groundwater discharges can be quite large, especially in areas with artificially modified drainage and in northern groundwater-fed streams that are incised into glacial deposits.

- Staff with technical expertise exist within agencies, academic institutions and private companies inside and outside the basin that could develop the needed GW-SW data management systems, models and decision-support tools for the Great Lakes states and provinces if sufficient resources were available. The technical community is highly dispersed and not always well-connected with the management community.

- Sources of sufficient resources and a commitment to consolidate efforts in a coordinated, integrated and sustained binational enterprise do not currently exist.

- Stakeholders and managers of GW-SW resources expressed a desire for model output and tools with seasonal to annual resolution, primarily at the tributary watershed, local and state/provincial scales. Models must generally be optimized to specific scales and designed to answer specific questions.

- Federal agencies including NRCan and the USGS, with support from ECCC and NOAA, are best equipped to lead the development and maintenance of a basin-scale GW-SW model with technical support from other federal agencies, academics, private companies and state/provincial agencies.

Gaps

- This study identified key knowledge and data gaps that hinder well-informed management decisions including insufficient three-dimensional hydrogeological data synchronized across the border for the Great Lakes basin to construct high-resolution frameworks for subsurface flow modeling, and insufficient data on GW-SW occurrence, use, dynamics and interactions.

- Important emerging issues include the expected role of climate change in the alteration of the future GW-SW regimes in the basin, including related changes in competing human and ecological demands for groundwater extraction, water quality protection and maintenance of environmental flows.

- Institutional impediments include inadequate data management systems for existing data, insufficient funding to update existing numerical models or develop and maintain new models, and inadequate tools to link the output of modern GW-SW models that do exist with the practical needs of managers for decision support (e.g., insufficient transitioning of research products to practical applications).

Recommendations

- Three-dimensional hydrogeological data collection, surveillance and monitoring programs should be maintained and enhanced in areas where GW-SW conditions are changing most rapidly including well-equipped real-time sensor networks and associated maintenance and data management systems and staff. A basinwide monitoring enterprise plan should be developed by the lead GW-SW modeling agencies. The plan should be updated regularly, incorporating information on the current state of the network, data management and communications systems, and suggested enhancements to support priority modeling and management needs, along with associated resource needs.

    - The federal agencies with the strongest technical skills in GW-SW modeling should lead an effort to compile a joint technical scoping document or terms of reference for the development of a binational numerical GW-SW model for the Great Lakes basin. The document should include a concept of operations, data and technical requirements, critical use cases, a detailed wiring diagram of model components and software/hardware, a development schedule, a listing of management tools and products to be developed from models, operations and maintenance details, an estimate of financial and staffing needs and a timeline. The document should also specify in as much detail as possible: elements that would be conducted internally by the agencies themselves; and components that would be outsourced to academic or private sector partners via competitive grants or contracts. The outsourcing document could be formatted as a draft scope of work or request for proposals.

- The IJC, in collaboration with the Great Lakes Water Quality Agreement Annex 8 Groundwater Subcommittee and the Great Lakes Commission, should support a binational community of practice or a collaboration entity organized around the topic of Great Lakes GW-SW modeling, management and policy. The group would facilitate information exchange across disciplines and jurisdictions and maintain listings of supporting projects, subject matter experts, representatives of key stakeholder constituencies and potential funders.

6.0 Glossary

Baseflow is the portion of streamflow that is sustained between precipitation events that provides a relatively stable supply of water to streams and other surface water bodies, often with high clarity and stable temperature. Baseflow is alternatively termed indirect groundwater discharge by some authors. This streamflow is important to stream biota and helps support recreation-based industries (Neff et al 2005). The term also is used as two words (base flow) by some researchers and agencies.

Basin scale refers to the entire Great Lakes watershed and groundwatershed extending downstream to the international boundary on the St. Lawrence River at Cornwall, Ontario.

Conceptual framework, as used in this report, refers to a narrative description or a graphical depiction of a physical or nonphysical system, often a complex system, that is simplified into the key components necessary to communicate important elements and relationships within the system. The term is used in contrast to terms such as numerical model, computer model or quantitative model, which indicate computational structure and code that can be executed to produce outputs such as groundwater flow parameters, sustainable yields or capture zones for wells. The term conceptual model can be used in some contexts to describe something similar but is not used in this sense in this report for the sake of clarity.

Conceptual model, as distinct from conceptual framework, is a term used in a narrow sense within the hydrological science community to mean a simplified mathematical conceptualization of a hydrological system consisting of interconnected storage elements that is used to represent different components of the hydrological process, similar to a box model. This report only uses the term conceptual model in this narrower way.

Direct runoff is comprised of precipitation falling directly on river and lake surfaces.

Distributed models are those models that divide a watershed into subcomponent areas. These areas take the form of regular uniform-sized grid cells, irregular cells such as in Triangulated Irregular Networks , or subareas of quasi-uniform properties such as Hydrologic Response Units (HRUs) or sub-basins. Some authors refer to models in which a basin has been divided into sub-basins as semi-distributed models.

Downscaled models (climate) use results from one or more general circulation models as boundary conditions applied to smaller areas to obtain higher resolution predictions for the same climate phenomena.

General circulation models (climate) address the physics of the atmosphere for the entire globe at a coarse grid size in three dimensions to provide predictions of climate phenomena such as changes in precipitation, temperature or relative humidity. These models are sometimes coupled with ocean, land surface and cryosphere models to allow for feedbacks.

Groundwater is the water that occurs below the ground surface in the pore space of saturated unconsolidated deposits (e.g., sand and gravel) and in fractures or dissolution features of bedrock. Groundwater originates as percolating precipitation and follows gravity-driven flow paths from areas of higher to lower elevation/pressure. Groundwater flow paths terminate where groundwater discharges to surface water in the form of springs, streams, rivers, lakes or the ocean, or where water is withdrawn from wells. Groundwater and surface water exist as an interconnected system but they are frequently managed independently (Winter et al. 1998).

Groundwater models are mathematical representations of subsurface water flow and transport of dissolved constituents through saturated sediment and rock. The land surface and the bed of surface water bodies are typically used as the boundaries for these models. They are used to determine sustainable yields of water pumped from aquifers and to simulate the subsurface movement of contaminants.

Hydrologic models are mathematical tools used to simulate, understand, predict and manage water resources. They convert elements such as precipitation and evaporation into runoff and streamflow, typically with an emphasis on surface water processes and simplified treatment of groundwater processes.

Lake scale refers to the watershed and groundwatershed of a single Great Lake, typically including any upstream connecting channel (also downstream channel in the case of Lake Ontario).

Loosely-coupled models are executed asynchronously whereby results from one model are obtained before being shared with the other models. Time steps are not necessarily identical.

Lumped models consider a watershed as a whole with average uniform parameters spatially constant throughout.

Managers/management community refers to those with direct responsibility for making decisions about water resources and issuing permits or approvals for water withdrawals, discharges and management plans such as state, provincial and municipal employees in regulatory agencies. These individuals and groups are often distinct from researchers and technical staff who support water management by developing models, tools, instruments, experiments and publications that guide managers.

Numerical models are computer programs that incorporate complex mathematical relationships among elements of the natural world and human interactions to find an approximate solution to a physical problem. For example, a numerical model could be constructed to simulate the impact of pumping from a new well on surrounding wells under different pumping scenarios.

Operational models are calibrated and high-performing numerical simulation packages that are transitioned from a research or prototype status to a stable long-term organizational home where they are used to produce forecasts, scenario simulations or other products regularly for a particular user community.

Physical or mechanistic models are computer programs that attempt to reproduce the interactions among actual physical processes and reservoirs within a natural flow system. Historically, this was done with actual scaled mechanical constructions of hydrologic systems before computing capabilities surpassed their performance at lower costs.

Regional scale refers to the combined watersheds and groundwatersheds of two or more Great Lakes or tributaries, or of a political jurisdiction such as a state or province that consolidates parts of two or more lakes or tributary watersheds.

Surface runoff refers to the overland flow of water that occurs when precipitation or snowmelt cause the top layer of the soil to reach saturation and excess water flows across flat land and down topographic slopes to surface water bodies.

Tightly-coupled models are those models that are executed synchronously, such that time steps are identical, and information among models is shared at each time step.

Tributary scale refers to the watershed and groundwatershed of any Great Lakes or connecting channel tributary. The connecting channels themselves are not considered to be tributaries.

7.0 References

Bayless, E.R., Arihood, L.D., Reeves, H.W., Sperl, B.J.S., Qi, S.L., Stipe, V.E., Bunch, A.R., 2017. Maps and grids of hydrogeologic information created from standardized water-well drillers' records of the glaciated United States: US Geological Survey Scientific Investigations Report 2015–5105. 34 p. DOI: 10.3133/sir20155105.

Blum, A.G., Archfield, S.A., Hirsch, R.M., Vogel, R.M., Kiang, J.E., Dudley, R.W., 2019. Updating estimates of low-streamflow statistics to account for possible trends. Hydrol. Sci. J. 64(12), 1404-1414. DOI: 10.1080/02626667.2019.1655148.

Bornhorst, T.J., 2016. An overview of the geology of the Great Lakes basin. A. E. Seaman Mineral Museum. Web Publication 1. 8 p. Accessed at: museum.mtu.edu/sites/default/files/2019-11/AESMM_Web_Pub_1_Great_Lakes_Geology_0.pdf, February 3, 2022.

Byun, K., Hamlet, A.F., 2018. Projected changes in future climate over the midwest and Great Lakes region using downscaled CMIP5 ensembles. Int. J. Climatol. 38(S1), e531-e553. DOI: 10.1002/joc.5388.

Carter, T.R., Fortner, L.D., Russell, H.A., Skuce, M.E., Longstaffe, F.J., Sun, S., 2021. A hydrostratigraphic framework for the Paleozoic bedrock of southern Ontario. Geosci. Can. 48(1), 23-58. DOI: 10.12789/geocanj.2021.48.172.

Choquette, A.F., Hirsch, R.M., Murphy, J.C., Johnson, L.T., Confesor Jr., R.B., 2019. Tracking changes in nutrient delivery to western Lake Erie: Approaches to compensate for variability and trends in streamflow. J. Great Lakes Res. 45(1), 21-39. DOI: 10.1016/j.jglr.2018.11.012.

Christiansen, D.E., Walker, J.F. Hunt, R.J., 2014. Basin-scale simulation of current and potential climate changed hydrologic conditions in the Lake Michigan basin, United States. US Geological Survey Scientific Investigations Report 2014-5175. 86p. DOI: 10.3133/sir20145175.

Costa, D., Zhang, H., Levison, J., 2021. Impacts of climate change on groundwater in the Great Lakes basin: A review. J. Great Lakes Res. 47(6), 1613-1625. DOI: 10.1016/j.jglr.2021.10.011.

Eberts, S.M., George, L.L., 2000. Regional ground-water flow and geochemistry in the Midwestern Basins and Arches Aquifer System in parts of Indiana, Ohio, Illinois, and Michigan. US Geological Survey Professional Paper 1423-C. 116 p. Accessed at: pubs.usgs.gov/pp/1423c/report.pdf, February 4, 2022.

Eimers, M. C., Liu, F., Bontje, J., 2020. Land use, land cover, and climate change in southern Ontario: implications for nutrient delivery to the lower Great Lakes, in: Crossman, J., and Weisener, C. (Eds.) Contaminants of the Great Lakes. The Handbook of Environmental Chemistry, Vol. 101. Springer International Publishing. ISBN: 978-3-030-57874-9. 235-249.

Erickson, M.L., Elliott, S.M., Brown, C.J., Stackelberg, P.E., Ransom, K.M., Reddy, J.E., 2021a. Machine learning predicted redox conditions in the glacial aquifer system, northern continental United States. Water Resour. Res. 57(4), e2020WR028207, DOI: 10.1029/2020WR028207.

Erickson, M.L., Elliott, S.M., Brown, C.J., Stackelberg, P.E., Ransom, K.M., Reddy, J.E., Cravotta III, C.A., 2021b. Machine-learning predictions of high arsenic and high manganese at drinking water depths of the Glacial Aquifer System, northern continental United States. Environ. Sci. Tech. 55(9), 5791-5805. DOI: 10.1021/acs.est.0c06740.

Feinstein, D.T., Hunt, R.J., Reeves, H.W., 2010. Regional groundwater-flow model of the Lake Michigan basin in support of Great Lakes basin water availability and use studies. US Geological Survey Scientific Investigations Report 2010-5109. 379 p. Accessed at: pubs.usgs.gov/sir/2010/5109/, February 3, 2022.

Feinstein, D.T., Fienen, M.N., Reeves, H.W., Langevin, C.D., 2016. A semi-structured MODFLOW-USG model to evaluate local water sources to wells for decision support. Groundw. 54(4), 532-544. DOI: 10.1111/gwat.12389.

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., Rummukainen, M., 2013. Evaluation of climate models, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 759 p. DOI: 10.1017/CBO9781107415324.

Frey, S.K., Khader, O., Taylor, A., Erler, A.R., Lapen, D.R., Sudicky, E.A., Berg, S.J., Russell, H.A.J., 2020. A fully integrated groundwater–surface-water model for southern Ontario, in Russell, H.A.J., Kjarsgaard, B.A. (eds.), Southern Ontario groundwater project 2014–2019: summary report. Geological Survey of Canada. Open File 8536 245 p. DOI: 10.4095/321108.

Gebert, W.A., Garn, H.S., Rose, W.J., 2016. Changes in streamflow characteristics in Wisconsin as related to precipitation and land use. US Geological Survey Scientific Investigations Report 2015-5140. 34p. DOI: 10.3133/sir20155140.

Grannemann, G., Van Stempvoort, D. (eds.), 2016. Groundwater science relevant to the Great Lakes Water Quality Agreement: A status report. Annex 8 Subcommittee of the Great Lakes Executive Committee. Environment and Climate Change Canada and US Environmental Protection Agency. 109 p. Accessed at: binational.net/wp-content/uploads/2016/05/GW-Report-final-EN.pdf, February 3, 2022.

Gronewold, A.D., Rood, R.B., 2019. Recent water level changes across earth's largest lake system and implications for future variability. J. Great Lakes Res. 45(1), 1-3. DOI: 10.1016/j.jglr.2018.10.01.

Haj, A.E., Soller, D.R., Reddy, J.E., Kauffman, L.J., Yager, R.M., Buchwald, C.A., 2018. Hydrogeologic framework for characterization and occurrence of confined and unconfined aquifers in quaternary sediments in the glaciated conterminous United States-A digital map compilation and database. US Geological Survey Data Series 1090. 31 p. DOI: 10.3133/ds1090.

Hamilton, S.M., 2020. A publicly accessible regional groundwater geochemical dataset for southern Ontario: Available to support public health, development and environmental research, in: Regional-scale groundwater geoscience in southern Ontario: An Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Geoscientists Open House. Proceedings of a virtual event, February 2020. 24 p. Accessed at: multibriefs.com/briefs/apgo/2021_OGSGroundwaterOpenHouse.pdf, March 7, 2022.

International Joint Commission Great Lakes Science Advisory Board, 2018. Great Lakes surface and groundwater model integration review: Literature review, options for approaches and preliminary action plan for the Great Lakes basin. Prepared by the Great Lakes Science Advisory Board, Research Coordination Committee. 62 p. Accessed at: ijc.org/en/sab/great-lakes-surface-and-groundwater-model-integration-review-october-2018, February 3, 2022.

Jaiswal, R.K., Ali, S. Bharti, B., 2020. Comparative evaluation of conceptual and physical rainfall-runoff models. Appl. Water Sci. 10(1), 1-14. DOI: 10.1007/s13201-019-1122-6.

Koren, V., Reed, S., Zhang, Z., Seo, D., Moreda, F., Kuzmin, V., 2003. Use of spatially variable data in river flood prediction. In EGS-AGU-EUG Joint Assembly. Nice, France. 14670 p. Accessed at: ui.adsabs.harvard.edu/abs/2003EAEJA....14670K/abstract, February 4, 2022.

Leaf, A.T., Fienen, M.N., Hunt, R.J., Buchwald, C.A., 2015. Groundwater/surface-water interactions in the Bad River watershed, Wisconsin. US Geological Survey Scientific Investigations Report 2015–5162. 122 p. DOI: 10.3133/sir20155162.

Logan, C.E., Russell, H.A.J., Bajc, A.F., Burt, A., Mulligan, R.P.M., Sharpe, D.R., 2020. A three-dimensional surficial geology model of southern Ontario: Progress report, in: Russell, H.A.J. and Kjarsgaard, B.A. (Eds.), Southern Ontario groundwater project 2014–2019: summary report. Geological Survey of Canada. Open File 8536. 245 p. Accessed at: ftp.maps.canada.ca/pub/nrcan_rncan/publications/STPublications_PublicationsST/321/321078/of_8536.pdf, February 7, 2022.

Michener, W.K., 2015. Ten simple rules for creating a good data management plan. PLoS Comput. Biol. 11(10), e1004525. DOI: 10.1371/journal.pcbi.1004525.

Mulligan, R.P.M., Burt, A.K., 2020. What lies beneath: Scratching the surface of glacial landforms in southern Ontario, in: Regional-scale groundwater geoscience in southern Ontario: An Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Geoscientists Open House. Proceedings of a virtual event, February 2020. 24 p. Accessed at: multibriefs.com/briefs/apgo/2021_OGSGroundwaterOpenHouse.pdf, February 9, 2022.

Neff, B.P., Piggott, A.R., Sheets, R.A., 2005. Estimation of shallow ground-water recharge in the Great Lakes basin. US Geological Survey Scientific Investigations Report 2005-5284. 20 p. Accessed at: pubs.usgs.gov/sir/2005/5284/pdf/SIR_2005_5284-Web.pdf, February 3, 2022.

Notaro, M., Bennington, V., Lofgren, B., 2015. Dynamical downscaling–based projections of Great Lakes water levels. J. Clim. 28(24), 9721-9745. DOI: 10.1175/JCLI-D-14-00847.1.

Pétré, M.A., Rivera, A., Lefebvre, R., Hendry, M.J., Folnagy, A.J., 2016. A unified hydrogeological conceptual model of the Milk River transboundary aquifer, traversing Alberta (Canada) and Montana (USA). Hydrogeol. J. 24(7), 1847-1871. DOI: 10.1007/s10040-016-1433-8.

Robinson, C., 2015. Review on groundwater as a source of nutrients to the Great Lakes and their tributaries. J. Great Lakes Res. 41(4), 941-950. DOI: 10.1016/j.jglr.2015.08.001.

Ross, P.J., 1990. Efficient numerical methods for infiltration using Richards' equation. Water Resour. Res. 26(2), 279-290. DOI: 10.1029/WR026i002p00279.

Roy, T., Valdés, J.B., Lyon, B., Demaria, E.M., Serrat-Capdevila, A., Gupta, H.V., Valdés-Pineda, R., Durcik, M., 2018. Assessing hydrological impacts of short-term climate change in the Mara River basin of East Africa. J. Hydrol. 566, 818-829. DOI: 10.1016/j.jhydrol.2018.08.051.

Russell, H.A.J., Kjarsgaard, B.A. (eds.), 2020. Southern Ontario groundwater project 2014-2019: summary report. Geological Survey of Canada Open File 8536. Natural Resources Canada. 245 p. DOI: 10.4095/321078. Accessed at: drive.google.com/file/d/1bHJ0PbfRiCrsflJjdGMXg20tCgiwLBBZ/view?usp=drive_web, February 3, 2022.

Safaie, A., Litchman, E., Phanikumar, M.S., 2021. Decreasing groundwater supply can exacerbate lake warming and trigger algal blooms. J. Geophys. Res. Biogeosciences. 126(9), e2021JG006455. DOI: 10.1029/2021JG006455.

Schneider, K., 2021. As drought grips American West, irrigation becomes a Michigan selling point. Bridge Michigan. September 27, 2021. Accessed at: bridgemi.com/michigan-environment-watch/drought-grips-american-west-irrigation-becomes-michigan-selling-point, February 4, 2022.

Solder, J.E., Jurgens, B., Stackelberg, P.E., Shope, C.L., 2020. Environmental tracer evidence for connection between shallow and bedrock aquifers and high intrinsic susceptibility to contamination of the conterminous US glacial aquifer. J. Hydrol. 583, 124505. DOI: 10.1016/j.jhydrol.2019.124505.

Starn, J.J., Kauffman, L.J., Carlson, C.S., Reddy, J.E., Fienen, M.N., 2021. Three-dimensional distribution of residence time metrics in the glaciated United States using metamodels trained on general numerical models. Water Resour. Res. 57(2), e2020WR027335. DOI: 10.1029/2020WR027335.

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M., Konikow, L., 2013. Ground water and climate change. Nat. Clim. Chang. 3(4), 322-329. DOI: 10.1038/nclimate1744.

Valayamkunnath, P., Barlage, M., Chen, F., Gochis, D.J., Franz, K.J., 2020. Mapping of 30-meter resolution tile-drained croplands using a geospatial modeling approach. Sci. Data. 7(1), 1-10. DOI: doi.org/10.1038/s41597-020-00596-x.

Westjohn, D.B., Weaver, T.L., 1996. Hydrogeologic framework of Mississippian rocks in the central Lower Peninsula of Michigan. US Geological Survey, Water Resources Investigations Report 94-4246. 50 p. Accessed at: pubs.usgs.gov/wri/1994/4246/report.pdf, February 4, 2022.

Winter, T.C., Harvey, J.W., Franke, O.L., Alley, W.M., 1998. Ground water and surface water: A single resource. US Geological Survey Circular 1139. 79 p. DOI: 10.3133/cir1139.

Wuebbles, D., Cardinale, B., Cherkauer, K., Davidson-Arnott, R., Hellmann, J., Infante, D., de Loë, R., Lofgren, B., Packman, A., Seglenieks, F., Sharma, A., Sohngen, B., Tiboris, M., Vimont, D., Wilson, R., Kunkel, K., Ballinger, A., 2019. An assessment of the impacts of climate change on the Great Lakes. Environmental Law and Policy Center. 74 p. Accessed at: elpc.org/wp-content/uploads/2020/04/2019-ELPCPublication-Great-Lakes-Climate-Change-Report.pdf, February 4, 2022.

Xu, S., Frey, S.K., Erler, A.R., Khader, O., Berg, S.J., Hwang, H.T., Callaghan, M.V., Davison, J.H., Sudicky, E.A., 2021. Investigating groundwater-lake interactions in the Laurentian Great Lakes with a fully-integrated surface water-groundwater model. J. Hydrol. 594, 125911. DOI: 10.1016/j.jhydrol.2020.125911.

Yager, R.M., Kauffman, L.J., Soller, D.R., Haj, A.E., Heisig, P.M., Buchwald, C.A., Westenbroek, S.M., Reddy, J.E., 2019. Characterization and occurrence of confined and unconfined aquifers in Quaternary sediments in the glaciated conterminous United States. US Geological Survey Scientific Investigations Report 2018-5091. 90 p. DOI: 10.3133/sir20185091.

Zell, W.O., Sanford, W.E., 2020. Calibrated simulation of the long-term average surficial groundwater system and derived spatial distributions of its characteristics for the contiguous United States. Water Resour. Res. 56(8), e2019WR026724. DOI: 10.1029/2019WR026724.

Zulauf, C., Brown, B., 2019. Use of tile, 2017 US Census of Agriculture. farmdoc daily 9,141. Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign. Accessed at: farmdocdaily.illinois.edu/2019/08/use-of-tile-2017-us-census-of-agriculture.html, February 4, 2022

8.0 Appendices

Appendix A.1 Model intercomparison experience in the Great Lakes basin

Based on the experience of the Great Lakes Runoff Intercomparison Project (GRIP) for Lake Michigan (GRIP M), [1] Lake Ontario (GRIP-O), [2] Lake Erie (GRIP-E), [3] and the Great Lakes (GRIP-GL), the most important feature of a model intercomparison exercise is the establishment of a forum for discussion and information exchange. [4] Except under very stringent conditions of model setup and use, intercomparisons of models provide very limited insights to the source(s) of differences in model outputs. Researchers who have already embarked on a modeling project (e.g., researchers who have independent funding sources) do not necessarily wish to conform to the conditions of a controlled experiment for model comparisons. A controlled experimental setup is required if the same model is contributed by different groups for the same area/phenomena. A controlled experiment means that the model should be set up in the same way, with changes to only one aspect of the model. Very careful analysis is then required to discern the reasons for variation in model results. This analytical effort is not typically congruent with the original objectives of two independent modeling projects. Nevertheless, an intercomparison project with broad guidelines for participation and an agreed set of data and protocols can advance the state of knowledge for all involved in the project.

Following is a brief description of GRIP features that are potentially applicable to an integrated GW-SW model for the Great Lakes basin:

- The same model is not set up by more than one group, unless it is a controlled experiment (e.g., in cases where the same model is used and only one aspect of the model is changed).

- A common dataset is developed, based on agreement among a core team of modelers. GRIP modelers use only open-source data from North American or global datasets (e.g., data harmonization across the border has already been resolved).

- Models are set up using the common data set. GRIP modelers use the same soil, land cover and meteorological forcing data (e.g., precipitation, temperature).

---

[1] Fry, L.M., Gronewold, A.D., Fortin, V., Buan, S., Clites, A.H., Luukkonen, C., Holtschlag, D., Diamond., L., Hunter, T., Seglenieks, F., Durnford, D., Dimitrijevic, M., Subich, C., Klyszejko, E., Kea, K., Restrepo, P., 2013. The Great Lakes runoff intercomparison project phase 1: Lake Michigan (GRIP-M). J. Hydrol., 519(D), 3448-3465. DOI: 10.1016/j.jhydrol.2014.07.021.
[2] Gaborit, E., Fortin, V., Tolson, B., Fry, L., Hunter, T., Gronewold, A.D., 2016. Great Lakes runoff inter-comparison project, phase 2: Lake Ontario (GRIP-O). J. Great Lakes Res. 43(2), 217-227. DOI: 10.1016/j.jglr.2016.10.004.
[3] Mai et al., 2021. The Great Lakes runoff intercomparison project phase 3: Lake Erie (GRIP-E). J. Hydrol. Eng. 26(9), 05021020. DOI: 10.1061/(ASCE)HE.1943-5584.0002097.
[4] Personal Communication, Dr. Juliane Mai, University of Waterloo, December 2020.

- Calibration data and validation data are identified in advance. Approximately two-thirds of a dataset is allocated to calibration and one-third to validation. Validation is performed in space and time. Only years with 90 percent of data in both the validation and calibration period were selected for the dataset. In setting up the two datasets, attention was paid to spatial location and stream size to balance representation in each of the datasets. GRIP-GL calibration and validation data consist of streamflow, snowpack, evapotranspiration, and soil moisture. [5]

- Validation data are not released until models are calibrated and the calibration results are noted as final for all participating modelers.

- Once calibration results are finalized by a modeling group through one-on-one communication with the intercomparison lead, their results are submitted to a pool where the calibration results from other models are also visible. Model results can be tweaked during calibration even after they are visible to the pool but never once the validation phase has been started.

- Validation is based on a set of data that are not previously known to modelers. Validation includes both spatial validation for which data are selected from the same period as the calibration data, and temporal validation that requires years of consecutive data outside the calibration period. The GRIP-GL forcing dataset was 18 years in total; calibration was allocated 11 years, including one spin-up year, and validation was allocated seven years. It is assumed any climate change trends within the dataset will result in generally decreased performance, except for models that can adequately capture key climate variables.

- No adjustments to models are allowed during validation.

- Model performance is assessed by the inter-comparison lead and communicated to the group of modelers.

In terms of managing an intercomparison model forum, the following are key features of the GRIP configuration that may be transferrable to a GW-SW integrated model:

- Monthly meetings are scheduled on the same day each month, with attendance by any available members.

- The intercomparison lead takes time to prepare a presentation and recommendations for each meeting and facilitates discussion so decisions can be made.

- Due to the growing size of the group, for some decisions a vote is needed. In these cases, an online poll is set up where each member shares his/her opinion without being able to see others' responses. The anonymized results of the poll are then shared with the group and provide the basis for majority decisions. This approach has worked well to ensure all

[5] Precipitation and temperature were inputs from the agreed dataset.

members feel their voice has been heard, even when decisions go a different way from their choice.

- All data, meeting recordings, presentations, project members, email addresses and other resources are on a shared drive accessible to the members (GitHub is the platform used).

- Participation is voluntary and unfunded, so members participate through their own motivations.

- Signed agreements are in place to only publish based on a research team's data until the owner of other data used has published it. The intercomparison project and the intercomparison lead should be acknowledged in publications. The intercomparison lead coordinates publications on the intercomparison project, in collaboration with group members as coauthors.

Estimated resource requirements to establish and manage an intercomparison project for an integrated GW-SW model include:

- A manager with experience at the mid-career or postdoc level who is familiar with modeling needs, can coordinate/manage a group of independent modelers, is a good communicator and can present the work of the group at conferences. [6] For significant periods during the project, the position would need to be dedicated full time, for example when a dataset is being identified.

- A second resource with specialized knowledge of one or two models and coding would be needed about 50 percent of the time to provide support to modelers and to provide a second set of eyes on the deliverables of the project.

- Funding for presentations at conferences (attendance fees, travel and related expenses) would also be needed to ensure the forum is well known and the results are disseminated.

[6] In the experience of Dr. Mai, this position does not necessarily need to be a modeling expert; hiring managers would need to define the needs per their own experience.

Appendix A.2 Interviewee questions

Interview questions for select key stakeholders

1. What are the key water budget questions you/your organization have identified as a priority to be addressed by a model on a Great Lakes basinwide scale, specifically a surface water-groundwater interaction model?

2. How will this information be used in decision-making by your organization?

3. Please describe the temporal modelling needs of your organization (e.g., does your organization require real-time operational model(s) and/or modelling for research purposes?)

4. In the absence of a basinwide water budget model, how are decisions currently being made?

5. What data and information are currently used to make these decisions?

6. Are there ecological, socio-economic or legal constraints related to water quantity and use that affect your decision-making and that might be resolved by a water-budget model in the future?

7. Are there plans by your organization to fill data gaps and/or address the constraints related to water quantity and use in the Great Lakes basin?

8. Does your organization currently have available resources to contribute to development of a water budget model? Are there plans for such resources in the future?

9. If yes, please describe the resources (expertise, funding, data management, etc.), the approval process to allocate resources to a model (level in the organization with authority, approximate time interval required for approval), accountability requirements (reporting, results-based objectives, other).

10. Would it be feasible for your organization to become a lead agency to carry out basin-scale water budget modelling? To manage and run such a model on an ongoing basis (operational model; research model)?

11. If not your organization, how do you see a basin-scale water budget model being managed over the long term (what organization(s), management structure)?

12. What role do you see the IJC playing in the ongoing development and management of a basin-scale water budget model for the Great Lakes basin?

Appendix B Interview and questionnaire/registry participants

Name	Organization	Unit, department or division	Title
Daron Abbey	Matrix Solutions Inc. Water Resources Consulting	Technical Practice Areas Geoscience, Eastern Hydrogeology	Principal hydrogeologist, and practice lead: Geosciences
Christine Alexander	Michigan Department of Environment, Great Lakes and Energy	Groundwater Permits Section	Section manager
Eric Anderson	NOAA (now Colorado School of Mines)	Great Lakes Environmental Research Laboratory	Physical scientist
Sam Bellamy	Matrix Solutions		Vice president operations, East
Richard C. Berg	Illinois State Geological Survey		Director and state geologist
Sandra Bihn	Lake Erie Waterkeeper		
Heather Brodie-Brown	Ontario Ministry of the Environment, Conservation and Parks	Assistant Directors Office, Environmental Monitoring and Reporting Branch, Environmental Sciences and Standards Division	Project manager, water quantity
Laura Campbell	Michigan Farm Bureau	Agricultural Ecology Department	Agricultural ecology manager
Diogo Costa	ECCC	WHERD: Watershed Hydrology and Ecology Research Division	Research scientist
Brian Cosgrove	NOAA	National Weather Service	Research hydrologist
Rejean Couture	NRCan	Geological Survey of Canada	Director, Quebec Division
Serban Danielescu	ECCC	Science and Technology Branch, Watershed Hydrology and Ecology Research Division	Research scientist

Name	Organization	Unit, department or division	Title
Sandra Eberts	USGS	Water Resources Mission Area, HQ Office of Planning and Programming	Program science coordinator
Diane English	New York Department of Environmental Conservation	Division of Water	Section chief, water quantity management section
Katelyn FitzGerald	National Center for Atmospheric Research	Research Applications Lab/Hydrometeorological Applications Program	Associate scientist
Vincent Fortin	ECCC	Canadian Meteorological Center	Scientific researcher, hydrological forecasting
Pradeep Goel	Ontario Ministry of the Environment, Conservation and Parks	Water Monitoring Section, Environmental Monitoring and Reporting Branch	Research scientist (surface water)
Drew Gronewold	University of Michigan	School for Environment and Sustainability	Associate professor
Michael Hill	Pennsylvania Department of Environmental Protection	Planning and Conservation, Office of Water Resources Planning	
Jon Hortness	USGS	Regional Office	Great Lakes program coordinator
Steve Holysh	Oak Ridges Moraine GW Program		Program manager/hydrogeologist
Paul Juckem	USGS	Upper Midwest Water Science Center	Hydrologist
Walt Kelly	University of Illinois at Urbana-Champaign	Prairie Research Institute, Illinois State Water Survey, Groundwater Science Section	Head, groundwater science section

Name	Organization	Unit, department or division	Title
Sandra Kosek-Sills	Ohio Lake Erie Commission		Environmental specialist
Michael Kuzia-Carmel	New York Department of Environmental Conservation	Division of Water - Bureau of Water Resource Management	Assistant geologist
Andrew LeBaron	Michigan Department. of Environment, Great Lakes, and Energy	Water Resources Division, Water Use Program	Analyst
Debbie Lee	NOAA	Great Lakes Environmental Research Laboratory	Director
Kathy McKague	Ontario Ministry of Environment, Conservation, and Parks	Environmental Monitoring and Reporting	Director
Jim Milne	Michigan Department. of Environment, Great Lakes, and Energy	Water Resources Division, Water Assessment Unit	Water use assessment unit supervisor
David Moulton	US Department of Energy	Los Alamos National Laboratory	Research scientist
Scott Painter	US Department of Energy	Oak Ridge National Laboratory	Watershed systems modeling hroup lead
Mark Person	New Mexico Tech	Department of Earth and Environmental Sciences, Hydrology Program	Professor
Shaili Pfeiffer	Wisconsin Department of Natural Resources	Bureau of Drinking Water and Groundwater, Water Use Section	Natural resources staff specialist
Elizabeth Priebe	Ontario Geological Survey	Earth resources on geoscience mapping	Hydrogeologist

Name	Organization	Unit, department or division	Title
Rachel Proctor	Consumers Energy Company		Senior engineer
Howard Reeves	USGS	Michigan-Ohio Water Science Center	Research hydrologist
Nadine Roy	Ministère de l'Environnement et de la Lutte contre les changements climatiques Québec	Direction générale des politiques de l'eau, direction de l'eau potable et des eaux souterraines	Ingénieure (engineer)
Hazen Russell	NRCan	Geological Survey of Canada	Sedimentologist
Frank Seglenieks	ECCC	National Hydrological Service	Water resources engineer
Jon Starn	USGS	New England Water Science Center	Research hydrologist
Edward Sudicky	Aquanty, Inc.	Board chair	Aquanty founder, professor emeritus (University of Waterloo)
Harvey Thorleifson	University of Minnesota	Minnesota Geological Survey	Professor
Lizhu Wang	IJC	Great Lakes Regional Office	Scientist
John H. Williams	USGS	New York Water Science Center	Groundwater specialist
Ram Yerubandi	ECCC	Watershed Hydrology and Ecology Research Division	Research scientist and manager
Helen Zhang	Ontario Ministry of the Environment, Conservation and Parks	Groundwater and Surface Water Unit, Environment Monitoring and Reporting Branch	Senior hydrogeologist, climate change vulnerability
John Zygaj	US Federal Energy Regulatory Commission	Dam Safety	Regional engineer

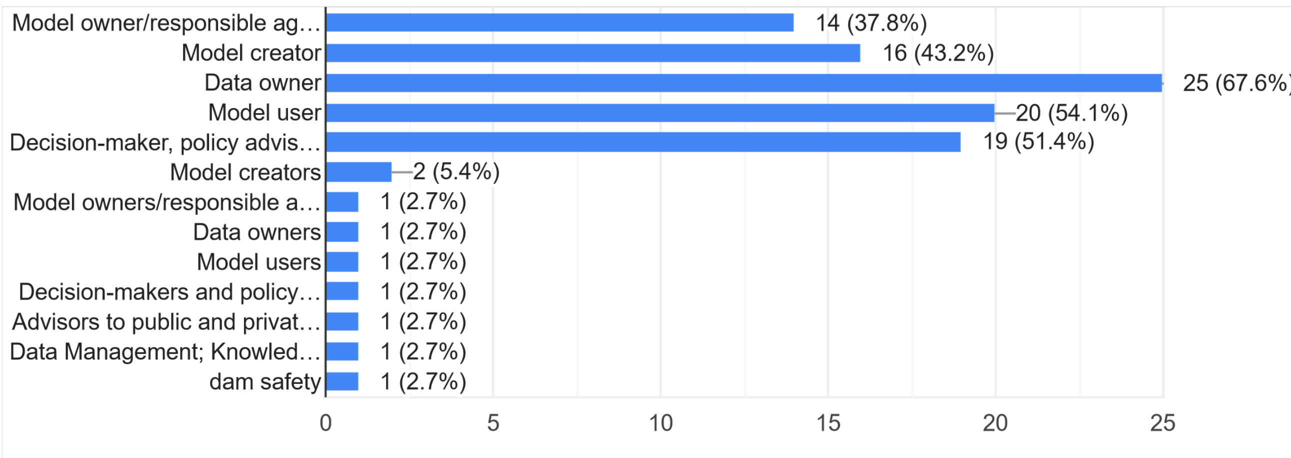
Appendix C Information submitted through the stakeholder questionnaire

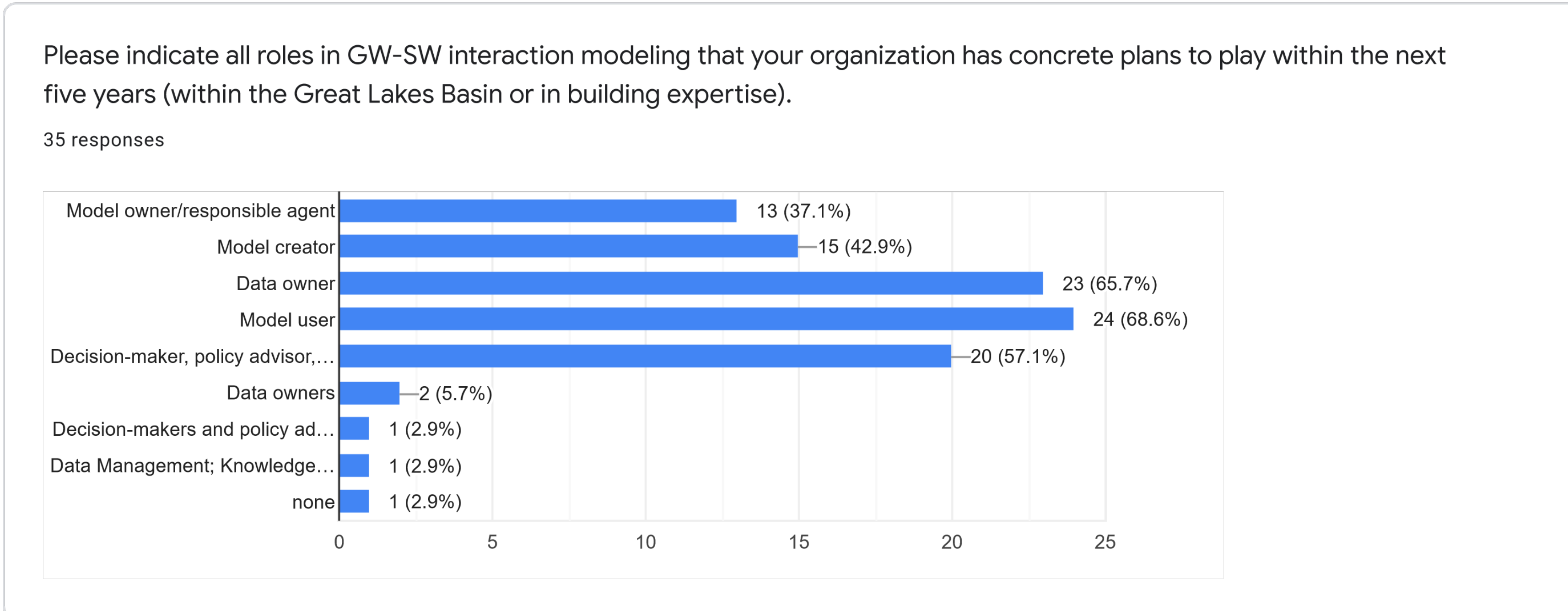
Appendix C.1 Stakeholder questionnaire results

(Some narrative responses are truncated in the charts below and are repeated in full starting on page 96)

Please indicate all roles your organization plays in GW-SW interaction modeling for the Great Lakes Basin.

37 responses





Provide any additional comments about you or your organization's role(s) that don't fit neatly into the previous categories. Seven total responses:

1. Development of the conceptual geological model is key for a GW-SW model, and this includes the lake basin geology and bathymetry, as well as the subsurface geology of land areas around the lakes, the latter of which, largely dictates rates and ease of flow from land surface into groundwater systems, both regional and local.
2. We have roles at the state level and also participate within the GLEC/GLWQA framework representing agriculture on the Michigan Water Use Advisory Council, we make recommendations for state agency funding and activities to improve data collection, modelling, and implementation of water withdrawal regulations. We are committed to engaging in a program that provides accurate information about potential impacts to both surface and groundwater from water withdrawals, and finding ways to protect both natural resources and riparian rights.
3. We are a consulting organization that provides integrated modelling services to Ontario clients (both private and public groups)
4. Focus for over 15 years has been the integration of sw and gw, and have authored many source protection, subwatershed, water balance and municipal supply studies using surface water, groundwater and integrated models.
5. MI EGLE uses an on-line screening tool, the Water Withdrawal Assessment Tool (WWAT), to evaluate the effects of large quantity surface water & groundwater withdrawals on stream flow & fish populations. EGLE staff use all available information to conduct site-specific reviews for proposed large quantity withdrawals that can't be authorized by the WWAT. We also create & use other models that are more on a project specific or sub-watershed

scale, as opposed to a Great Lakes Basin or statewide scale. MI EGLE and MI Dept. of Agriculture and Rural Development also administer an aquifer dispute resolution program to address private wells that are impacted by high-capacity wells. This can involve groundwater modeling to identify the suspected source of the private well impact(s). Other resource permitting programs within EGLE Water Resources Division use groundwater models as part of their permitting process for critical dune areas, inland lakes and streams, and wetlands. Modeling staff within EGLE Water Use Assessment Unit provide technical assistance to other staff. EGLE Water Use Assessment Unit staff also provided groundwater modeling technical support to EGLE Drinking Water and Environmental Health Division for their permit application for a bottled water withdrawal. EGLE WUAU staff also review proposed new or increased public water supply withdrawals for EGLE Drinking Water & Environmental Health Division. EGLE Water Resources Division also uses groundwater modeling for PFAS groundwater contamination sites. Other divisions within EGLE, e.g., Remediation & Redevelopment Division and Materials Management Division, also use groundwater modeling for groundwater contamination sites, solid waste and hazardous waster treatment, storage, and disposal facilities.

6. Representing agriculture on the Michigan Water Use Advisory Council, we make recommendations for state agency funding and activities to improve data collection, modelling, and implementation of water withdrawal regulations. We are committed to engaging in a program that provides accurate information about potential impacts to both surface and groundwater from water withdrawals, and finding ways to protect both natural resources and riparian rights.
7. Development of the conceptual geological model is key for a GW-SW model, and this includes the lake basin geology and bathymetry, as well as the subsurface geology of land areas around the lakes, the latter of which, largely dictates rates and ease of flow from land surface into groundwater systems, both regional and local.

General questions for all respondents

Please identify up to three key questions that an integrated GW-SW model for the Great Lakes on a basin scale should answer. 35 total responses:

1. What are the impacts of changes in baseflow on aquatic ecosystems? How do groundwater extraction activities influence changes in baseflow and recharge in streams and wetlands?
2. Can Canada's high level nuclear waste be safely stored within the Michigan Basin proximal to the Great Lakes as proposed by the NWMO? To what extent is deep (> 1km) groundwater flow contributing the hydrologic budget of the great lakes?
3. What will be the impact of climate change on groundwater water quantity and quality? What will be the combined effect of climate change and land use changes (i.e., agriculture and urbanization) on groundwater water budget? What mitigation, remediation or adaptation measures should be taken to protect groundwater in the future?
4. Quantity of water available (in sub-basin) for groundwater water-taking permits and surface water water-taking permits / Spatially distributed annual recharge of aquifer / Climate change effects on these quantities
5. How much direct input to the lakes comes from Groundwater (ie. not into streams and then into the lakes)? How much does this input change every month?
6. Have enough support (HR) to allow for development, calibration, maintenance; 2. Be focused on "priority/ key/indicator areas/watersheds; 3. Be able to simulate the various water "fractions" and their interactions (e.g. surface runoff/overland flow/channel flow; subsurface flow; shallow drainage, shallow and deep groundwater), the contaminant concentrations, loads, fate, attenuation, etc...

7. What are the areas of infiltration, recharge linked to discharge areas that support aquatic habitat? What are the seasonal characteristics of recharge and discharge areas. What is the effectiveness of source control stormwater (source control) management in protecting groundwater quality from salt and other contaminants. What is the appropriate time-scale of the simulation for each decision?
8. 1) increased understanding of overall water budget; 2) role of GW in nutrient and contaminant transport within the basin
9. Existing and future potential water scarcity
10. 1. What is the Great Lakes basin water budget comprised of, especially the role that the groundwater component plays and its spacial and temporal dynamics? 2. Will a basin-wise GW-SW model be able to provide critical information (e.g., data, model structures, boundary conditions, modeling results) for local water management projects?
11. Storage; flux; chemistry
12. Do we adequately understand the groundwater system of the Great Lakes Basin to quantify transfers into/out of the Great Lakes Basin? At a 'workable' scale (maybe on a Lake by Lake watershed basis) the model should identify those areas where understanding of flow dynamics is lacking. Where can water-related decisions lead us to costly mistakes? A model of this magnitude is likely to be used in guiding longer term decision making at very high levels (i.e. diversions or exports of water out of basin, etc.). Since, in our work, we are more focused on shorter term, more localized scale decisions, I keep having to remind myself to pull back from the question of whether we we are building the model for the sake of building a model? At the end of the day, as long as the infrastructure is in place to build on and maintain the model going forward - then it might help to answer questions that we don't yet know to ask. I imagine that the questions coming in might not require a model at the scale of the Great Lakes Basin to answer.
13. What percent of the water budget is from GW? What is the role of GW in nutrient (&other chem) transport & loading to the lakes and tribs? I'm not certain that a level of detail (particularly in the sub-surface) can be included in a basin-scale model that would support answering questions that are being asked of numerical models these days - that being said, the 3 major questions I see are: sustainability of existing and future water uses; ecologic dependencies on sw/gw interactions and their inter/intra-annual variability; and how climate change may impact the two previous questions. Water balance, climate change impact, nutrient pathways in streams and the lakes. Define in-basin groundwater vs. out-of.
13. What percent of the water budget is from GW? What is the role of GW in nutrient (&other chem) transport & loading to the lakes and tribs?
14. I'm not certain that a level of detail (particularly in the sub-surface) can be included in a basin-scale model that would support answering questions that are being asked of numerical models these days - that being said, the 3 major questions I see are: sustainability of existing and future water uses; ecologic dependencies on sw/gw interactions and their inter/intra-annual variability; and how climate change may impact the two previous questions.
15. Water balance, climate change impact, nutrient pathways in streams and the lakes
16. Define in-basin groundwater vs. out-of-basin groundwater; identify areas of direct/immediate GW/SW interconnection; identify areas where groundwater resource availability is stressed/limited.
17. (1) What is the groundwater contribution to the water budget? (2) What is the groundwater impact on surface water and lake hydrodynamics?
18. Where, when and on what spatiotemporal scales is groundwater important for fluxes and stores of water in the Great Lakes Basin (and what is the uncertainty)? Where should future observational data collection be focused? Where should future model development and implementation (including calibration, data assimilation, model physics, parameterization, etc.) be focused?
19. 1. What are the quantities and patterns of groundwater and stream water contribution to the Great Lakes and the inland water systems, the associated contaminant loadings, and the effects to water quality dynamic change? 2. How will the hydrological system (surface, soil and ground water) of the Great Lake basins respond to future climate change scenarios? 3. Gain a better understanding, on a basin wide and regional basis, of: a) Whether water is available and sustainable to meet demands for agricultural and industrial use, drinking water and healthy ecosystems b) Nutrient pathways through the watershed and nutrient loadings to the lakes c) The role of groundwater in sustaining nearshore and tributary ecosystems
20. not in my field of expertise
21. Role of groundwater in maintaining stream baseflow, impact of ground quality on surface water

22. climate effects on GW and SW levels
23. 1) Direct groundwater input; 2) groundwater discharge to streamflow entering lakes; 3) nutrient inputs to lakes from 1) and 2); 4) deleterious lake levels
24. To what extent does GW quality affect SW quality; is GW quality and quantity sufficient for drinking water use in those areas where it is a critical resource; where are the GW sources to SW
25. 1. Interface of groundwater and lake connection and how lake levels influence ground water levels? 2. Where groundwater is impacted by lake levels, what adjustments are made to water withdrawals to take into account these fluctuations? 3. How are changes in lake water quality impacted by inputs from groundwater like PFAS?
26. 1) Create a hydrologic framework for the Great Lakes that includes climatological data, surface water hydrology, groundwater, and hydrogeologic data. Identify key gaps. 2) Water budgets at the Basin scale, individual Great Lake scale, major watershed scale, sub-watershed scale, and aquifer scales, that includes providing information on precipitation, groundwater recharge, groundwater discharge to surface water, interconnections between shallow and deeper aquifers. Identify key data gaps. 3) Surface water and groundwater resource sustainability, including climate change impacts. Identify key data gaps.
27. role and influence of groundwater in water budget
28. 1. Influence of large-scale (e.g., major municipal) GW withdrawals on GW/SW dynamics. 2. Identify and locate contaminant risks to primary source aquifers. 3. Develop long-term aquifer trends.
29. Role of GW-SW model in nutrient transport, overall water budget and ecosystem services
30. What data and parameters will go into the model's assessment of groundwater and surface water interaction and impacts from withdrawals? How will the model be validated and at what scales will it operate? How will this model be shared with state and federal agencies with responsibility to manage water quantity and use and what expectations are there for its incorporation or implementation?
31. 1. What is the contribution of groundwater to each Great Lake water budget 2. What are changes in the deep aquifer cone of depression in Wisconsin and Illinois 3. Quantifying water loss and impact to groundwater/surface water interactions.
32. What is the relation between GW levels / GW storage and lake levels? How have GW levels / GW storage changed over time? What is the relation between groundwater supply and groundwater demand and how might it change in the future given projected climate change and groundwater demand forecasts?
33. What is the stream baseflow contribution to chemical loads to the Great Lakes? How does the contribution of stream baseflow change seasonally and annually? How does land use affect groundwater quality?
34. What is the vulnerability of aquifers to potential contaminants that might discharge into streams or discharge in the lakes themselves?

What is groundwater flux at various temporal and spatial scales? What settings, landforms and geological features are associated with groundwater discharge? What scale of characterization/mapping of these features is necessary to support model development? How can we use an integrated SW-GW model to test and improve our conceptual model?

35. What is the relation between GW levels / GW storage and lake levels? How have GW levels / GW storage changed over time? What is the relation between groundwater supply and groundwater demand and how might it change in the future given projected climate change and groundwater demand forecasts?

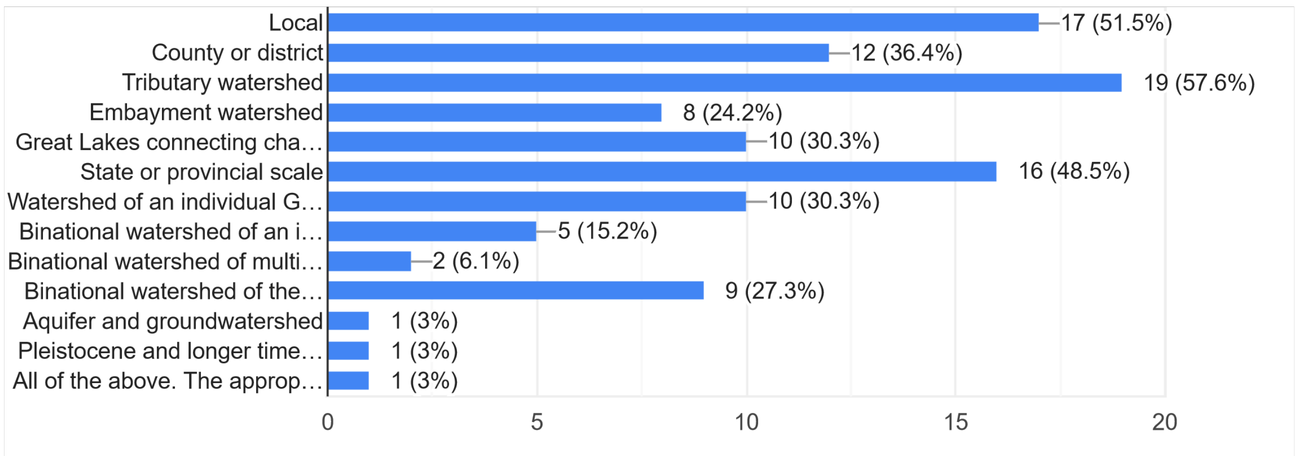
What data sources and information are being used to inform water-budget related decisions described in the previous question?

1. Water level data from monitoring and production wells, collected by us and water plant operators. Geological information from Illinois State Geological Survey and USGS for model development. Water quality data. Pump test data. Stream stages (USGS). Water demands, including amounts extracted.

2. Monitoring and modelling studies by various levels of government, industry and academia.
3. We source information from our state environmental agency, the Michigan and U.S. Geological Surveys, Michigan State University, and from industry professionals conducting data collection and modeling projects around the state.
4. Geoscience surveys; drillhole databases.
5. Climate data, streamflow data, groundwater levels, water well/boreholes and their associated stratigraphy, land cover, topography/DEM.

What spatial scales are of greatest interest to you or your organization on this topic (check all that apply)?

33 responses



Full text of choices:

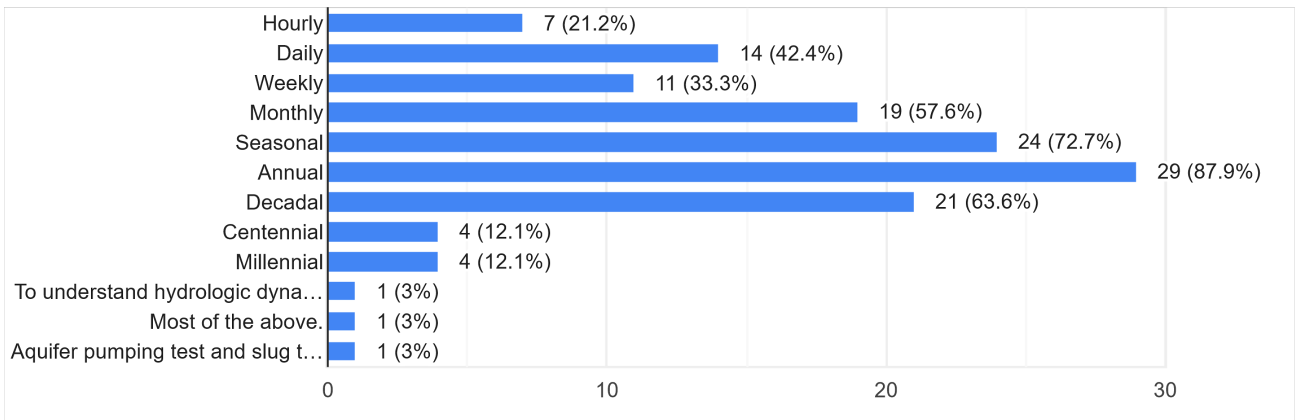
- Local
- County or district
- Tributary watershed
- Embayment watershed
- Great Lakes connecting channel watershed
- State or provincial scale

- Watershed of an individual Great Lake within a single country (Canada or the United States)
- Binational watershed of an individual Great Lake
- Binational watershed of multiple Great Lakes, but not all five
- Binational watershed of the entire Great Lakes basin, including Lake Michigan
- Other:

▪ Aquifer and ground watershed
▪ Pleistocene and longer timescales
▪ All of the above. The appropriate scale depends on the question being addressed by the model

What timescales are of greatest interest to you or your organization on this topic (check all that apply)?

33 responses



Briefly describe your organization’s unmet water-budget-related data and information needs, including ecological, socio- economic or legal constraints related to water quantity and use that affect your organization’s decision making. 22 responses

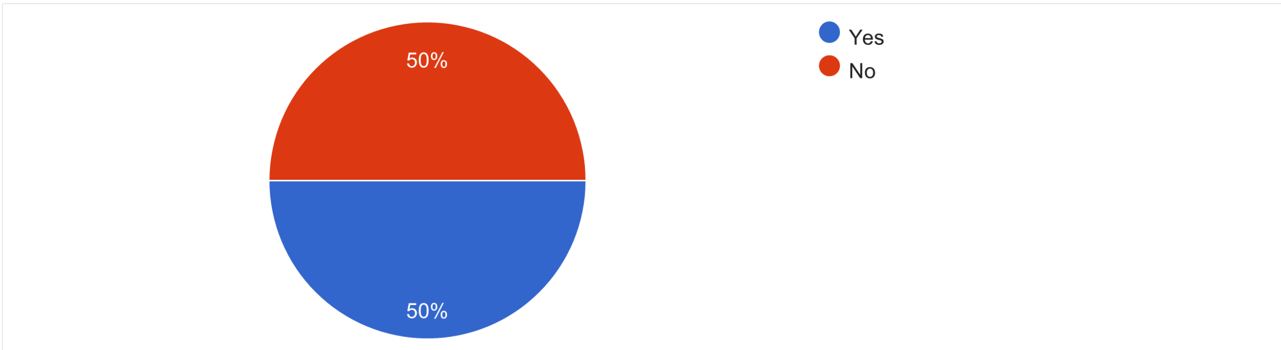
1. Better water use data is always desirable.
2. Very little ecological data to understanding impacts of baseflow/recharge changes. More frequent water use, water level, and water quality data.
3. We were asked to provide Ohio data on GW quality for Lake Erie LAMP purposes, but were not able to round up an adequate data set. We do have GW users on the Lake Erie islands who have been affected by poor GW quality as a supply for their drinking water in the past.
4. Aquanty has already developed a working 3D dynamic SW-GW model of the entire Great Lakes basin, but there still remains data gaps. The paper we have published recently in the Journal of Hydrology can be found at https://doi.org/10.1016/j.jhydrol.2020.12591. The model still needs work because of data gaps but the paper is a working blueprint for integrated model construction and data needs.
5. We need more geologic data for both glacial and bedrock aquifers, and more integration of groundwater/surface water impacts from withdrawals.
6. Complete and consistent 3D geological mapping at multiple levels of resolution.

How do you foresee your organization using output from an operational integrated SW-GW model in the future? 31 responses.

1. Such a model could be used to inform a range of projects done for a variety of cooperators.
2. I see us as the developer, but also the user for further model-driven studies and development.
3. Land- and water-use planning assistance.
4. Initially to understand impacts of groundwater extraction on baseflow, with the goal of minimizing negative impacts.
5. Report out in Ohio's State of the Lake: Lake Erie Quality Index, or for the Lake Erie LAMP.
6. Output from models developed by other organizations would be useful to compare to output from our HydroGeoSphere model mentioned above.
7. With sufficiently high quality data and modeling outputs, we could incorporate this model into a planned state-level hydrologic framework that will connect and coordinate models of different scales into our regulatory water use program.
8. Ongoing clarification of data needs.

Does your organization own hydrostratigraphy data?

32 responses



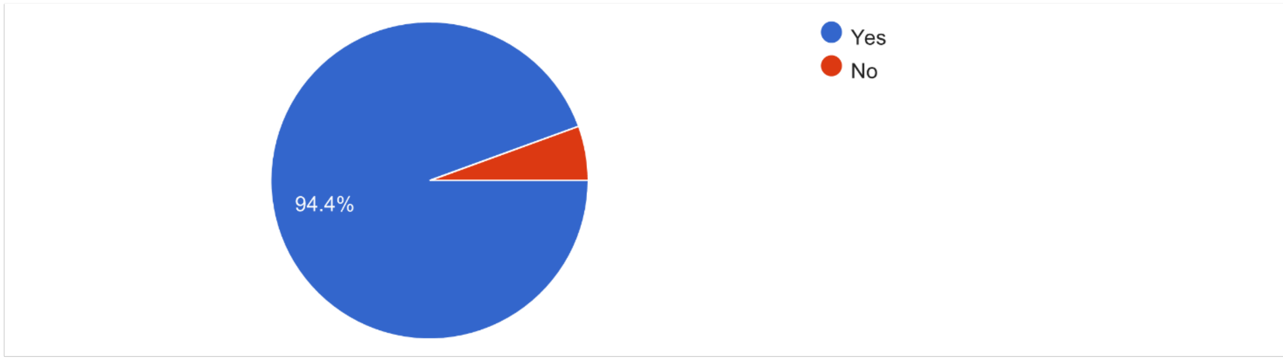
If Data Owner: To identify important/relevant datasets that can provide essential support to a basin-scale integrated GW-SW model, please indicate yes or no and the additional information as appropriate.

If yes, please describe the geographic extent, years of data collection, spatial/temporal resolution. 17 responses.

1. US ONLY: https://pubs.er.usgs.gov/publication/sir20185091; https://pubs.er.usgs.gov/publication/ds1090
2. Data throughout the U.S.
3. Statewide an county level data and maps/models going back to the early 1980s.
4. This is mainly collected by our sister agency, the Illinois State Geological Survey. State-wide (Illinois), for more than a century.
5. D & 3D geological mapping; MN; county and state scale; formal collection since 1872.
6. Variable.
7. We have assembled Quaternary (glacial) layering over a broad part of the Lake Ontario basin - stretching north into the Lake Simcoe basin (Lake Huron). Layers generally interpolated at 100 x 100 m cell size.
8. Provincial scale.

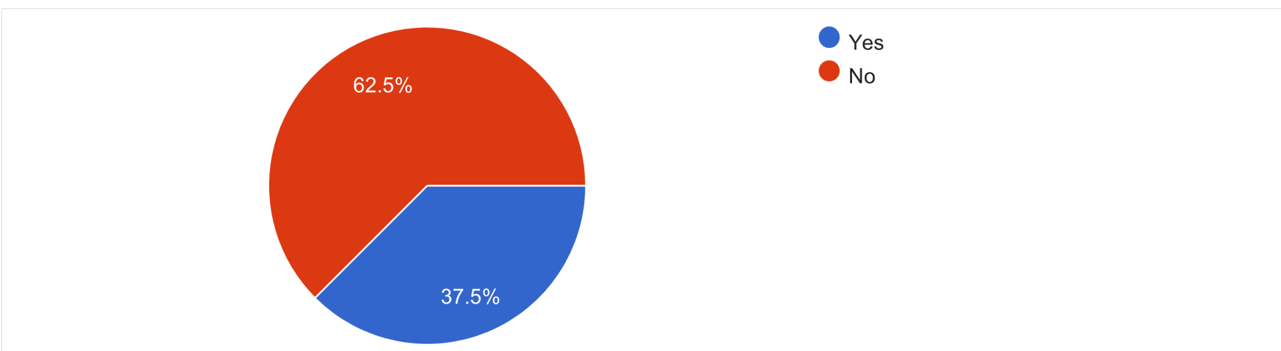
Is this publicly available?

18 responses



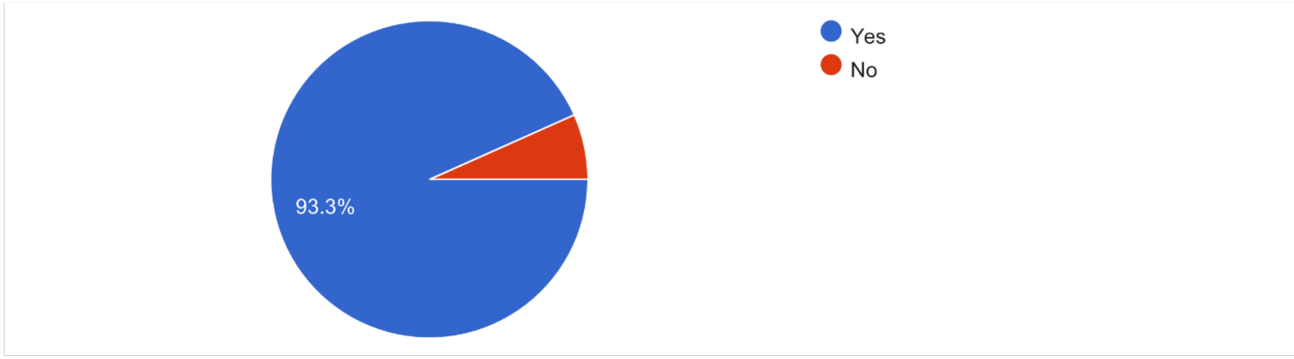
Does your organization own stream flow data?

32 responses



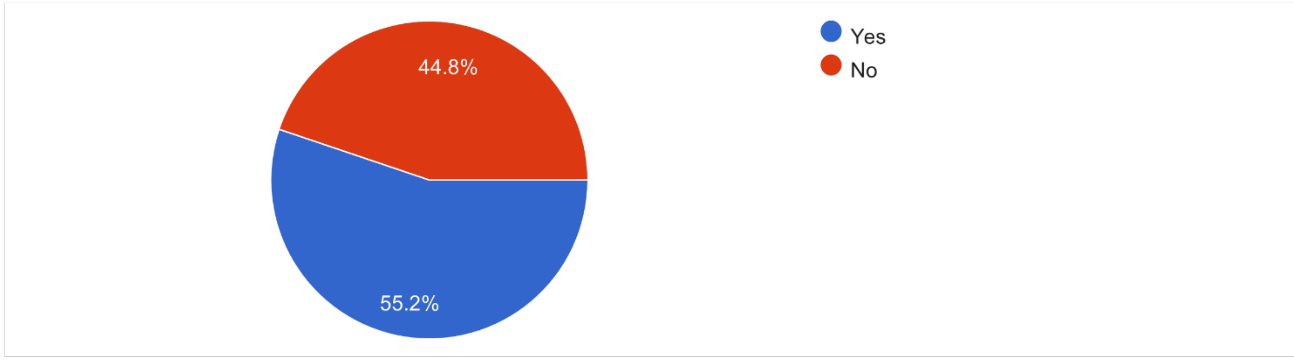
Is this publicly available?

15 responses



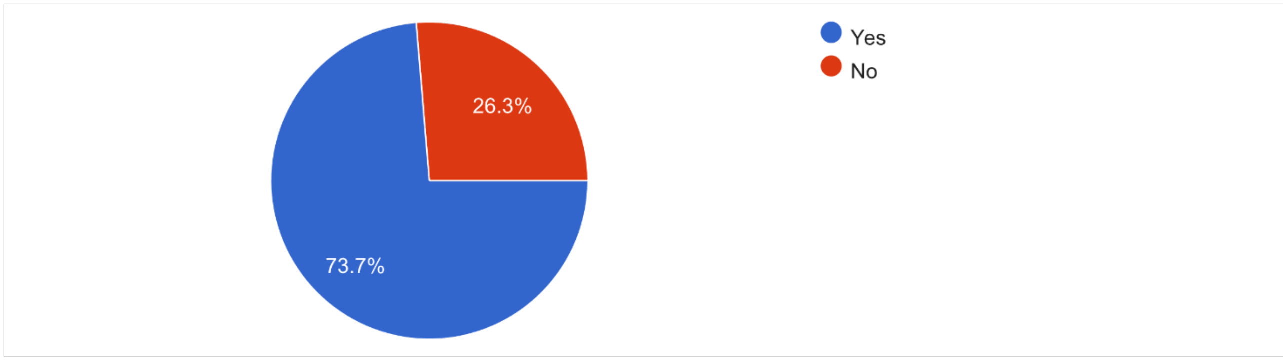
Does your organization own groundwater withdrawal data?

29 responses



Is this publicly available?

19 responses

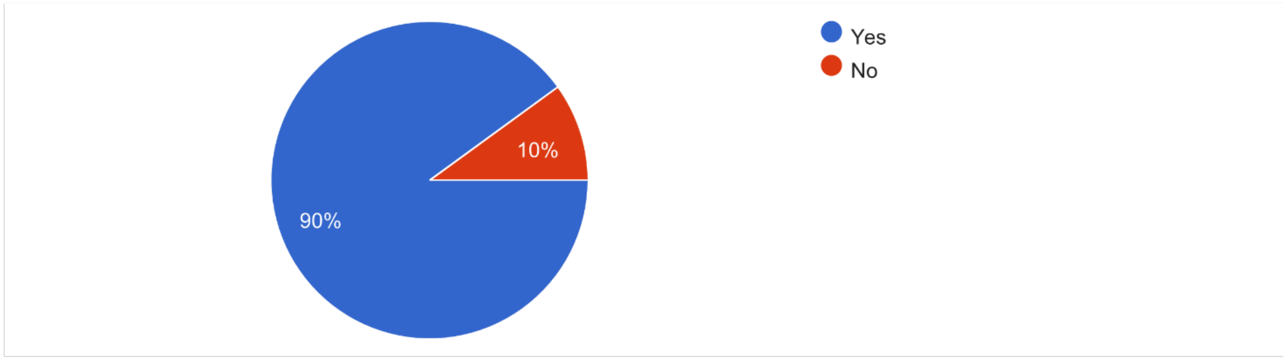


Other dataset_1 - Description:

GW age; GW pH, GW redox
Water well database
Groundwater level data
Geophysics; geochemistry; geological specimens and observations; water wells
Groundwater levels and quality from Ontario Provincial Groundwater Monitoring Network (PGMN)
Data provided by
Surface water withdrawals
Private water wells

Is this publicly available?

10 responses

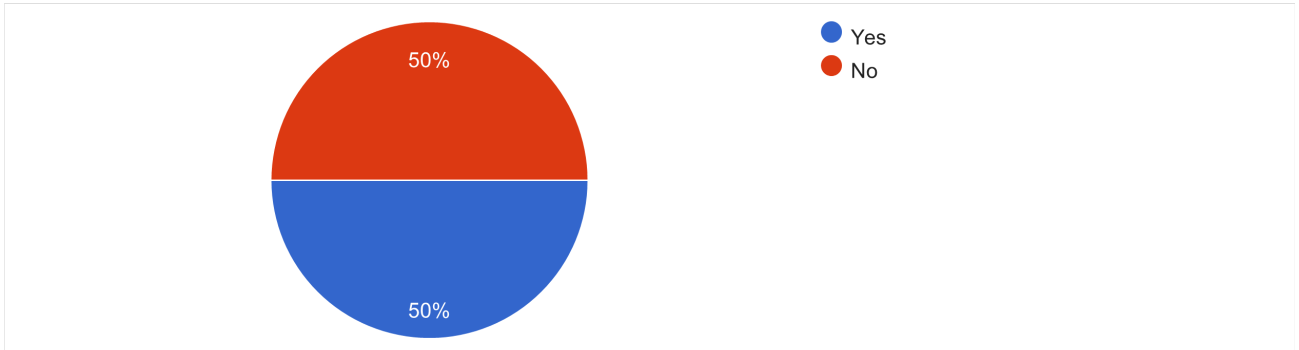


Other dataset_2 - Description: 3 responses

LiDAR
Groundwater quality data
Water well database
ORMGP Program area; various ages and temporal scales of data collection.

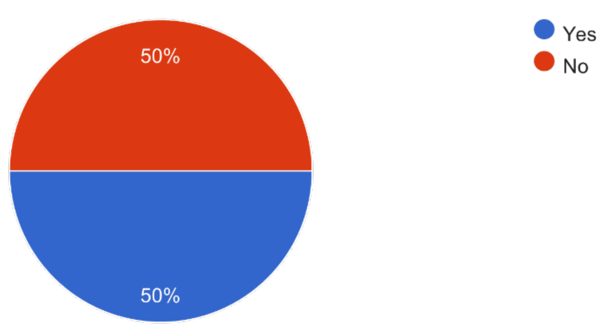
Is this publicly available?

4 responses



Should your organization be considered a potential funder for an integrated basin scale GW-SW model?

26 responses



If yes, please provide the name and email contact information for the appropriate person in your organization with whom to discuss funding or other resources that could be leveraged for the model or models. 11 responses:

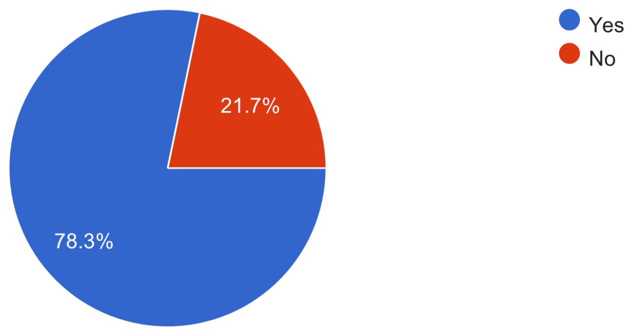
1. Sandy Eberts (smeberts@usgs.gov)
2. Unsure
3. Dr. Steve Frey (sfrey@aquanty.com)
4. Can contact myself
5. David Gochis (gochis@ucar.edu) - lead for the WRF-Hydro development group at NCAR
6. No single person. I can participate in discussions: pfjuckem@usgs.gov
7. The Honourable Jonathan Wilkinson Minister of Environment and Climate Change (ec.ministre-minister.ec@canada.ca)
8. James Clift, cliftj@michigan.gov
9. hazen.russell@canada.ca; eric.boisvert2@canada.ca

Please describe the resources (funding and/or in-kind) your organization could potentially allocate to development and maintenance of an integrated GW-SW basin-scale model. 18 responses:

1. Matching funds
2. Unsure
3. Institutional contributions to the effort.
4. Both groundwater and surface water modelers could contribute their time/expertise.
5. in-kind support for SW-GW model input data assembled by Aquanty
6. Ongoing updating of 3D hydrostratigraphy for MN at county and state resolution
7. Depending on the situation, we may be able to offer in-kind support.
8. I'm not sure we would have funding specifically for this, but it's very possible there could be alignment with existing projects and/or potential funding opportunities we would be interested in pursuing. Our portion of NCAR is almost entirely funded based upon project specific grants and contracts.

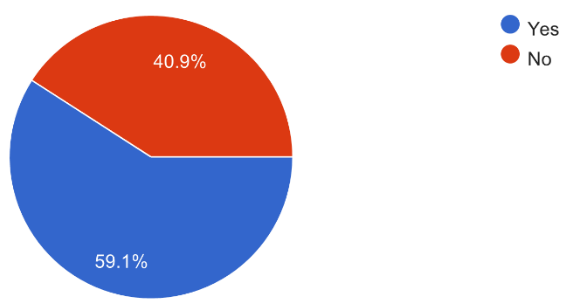
Do these resources include staff with the capacity to develop or advance relevant modeling work?

23 responses



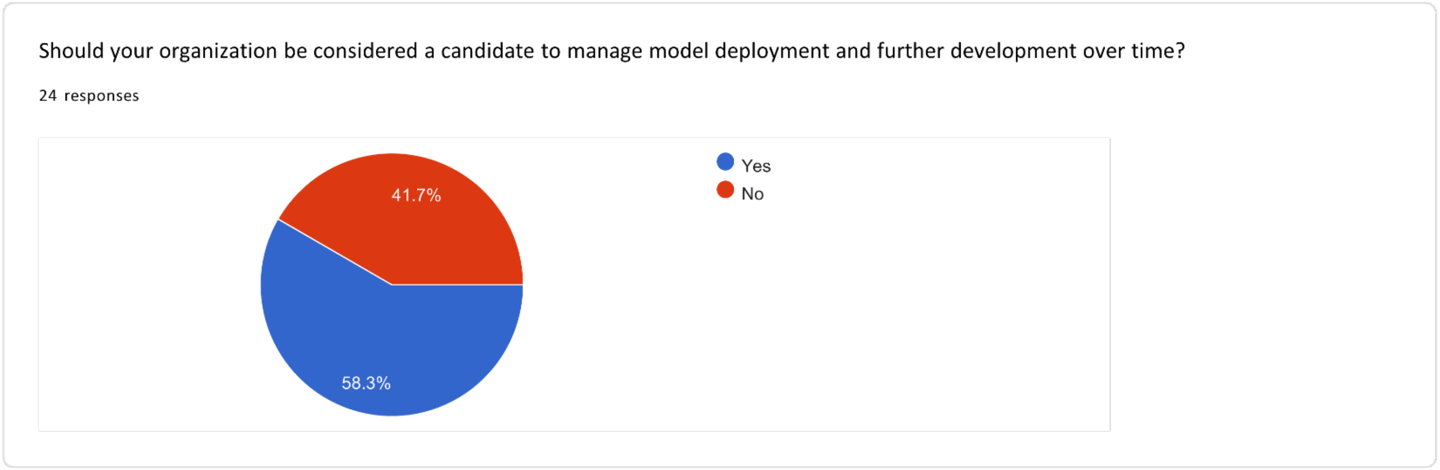
Note that one or more model platforms may be used to advance modeling of GW-SW interactions. Should your organization be considered a candidate to lead model development?

22 responses



If yes, please provide the name and email contact information for the appropriate person in your organization with whom to discuss model development. 14 responses:

1. Sandy Eberts (smeberts@usgs.gov)
2. Jesse Feyen (NOAA)
3. Daniel Abrams: dbabrams@illinois.edu
4. Dr. Steve Frey (sfrey@aquanty.com)
5. Self, Sam Bellamy, David Van Vliet
6. David Gochis (gochis@ucar.edu) and Katelyn FitzGerald (katelynw@ucar.edu)
7. Mason Marchildon
8. Mark Person



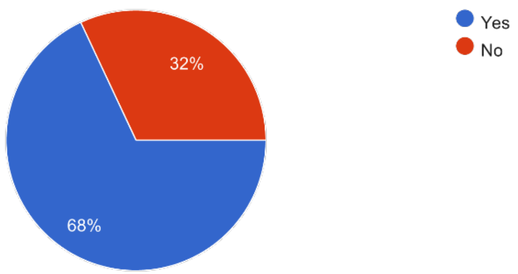
If yes, please provide the name and email contact information for the appropriate person in your organization with whom to discuss model deployment and future development. 12 responses.

1. Sandy Eberts (smeberts@usgs.gov)
2. Jesse Feyen
3. Daniel Abrams: dbabrams@illinois.edu
4. Dr. Steve Frey (sfrey@aquanty.com)
5. same

6. David Gochis (gochis@ucar.edu)
7. Mark Person, mark.person@nmt.edu
8. hwreeves@usgs.gov or pfjuckem@usgs.gov
9. The Honourable Jonathan Wilkinson Minister of Environment and Climate Change (ec.ministre-minister.ec@canada.ca)

Does your organization have expertise relevant to developing a basin-scale integrated GW-SW model for the Great Lakes Basin?

25 responses

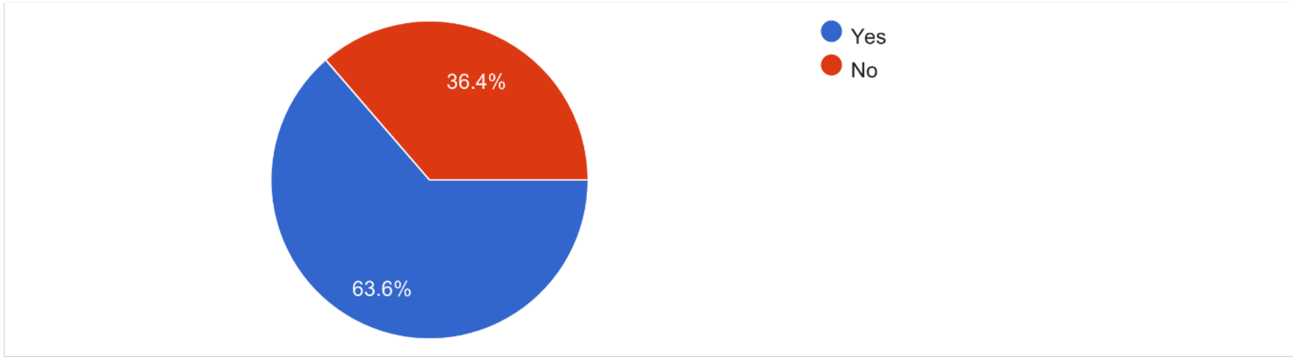


If yes, please briefly describe the qualifications/nature of your organization's expertise in basin-scale modeling. 18 responses.

1. Numerous USGS hydrologists have the skills to develop new code, as well as apply existing code to basin-scale water quantity problems
2. The USGS has conducted basin-scale modeling throughout the U.S. over many years.
3. NWM, etc.
4. Conceptual framework development.
5. We are already involved in developing and using regional groundwater and surface water models, primarily to inform water supply planning decisions.
6. Aquanty is a company that specializes in 3D integrated SW-GW model development and application at local to regional to basin scales. Aquanty has also developed a real-time SW-GW hydrologic forecasting platform based on its HydroGeoSphere software that is driven by an ensemble of weather forecasts. It is a SaaS cloud-based platform currently undergoing final testing for the Southern Ontario portion of the Great Lakes Basin. The short- and long-term hydrologic forecasts include stream flows, water depths, soil moisture, SW-GW interactions, groundwater levels and groundwater recharge.
7. We have been involved in developing integrated modelling since 2009 in Ontario, including developing the Integrated Water Budget.

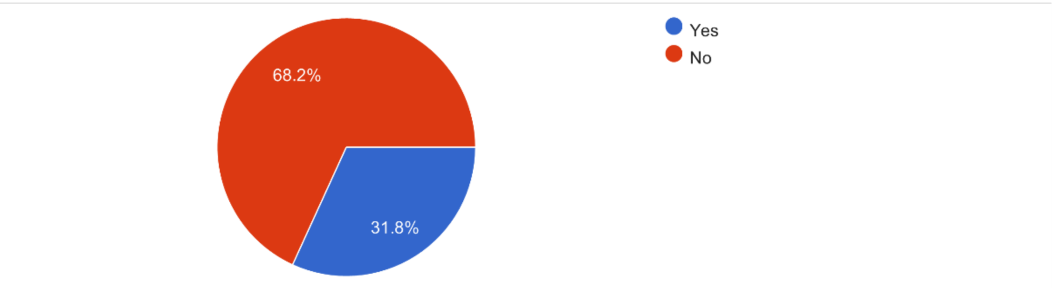
Does your organization have the capacity to run the model operationally over the long term?

22 responses



Has your organization developed, or is your organization in process of developing, one or more models that could be used as a platform for a basin-scale GW-SW integrated model for the Great Lakes (including scientific development, software development, conceptual model development)?

22 responses



If yes, please provide the following information on each initiative that is on-going or planned for basin-wide work that could advance an integrated GS-SW integrated model:

Name of Initiative_1: 6 responses:

1. Aquanty has developed working SW-GW models of the Southern Ontario portion of the Great Lakes Basin, and the entire Great Lakes Basin GLB). As mentioned earlier, the preliminary results for the GLB model have recently been published in a peer reviewed journal and input data gaps needed model refinement details are discussed.
2. Development and application of WRF-Hydro as the NOAA National Water Model (NWM)
3. Lake Michigan Basin model.
4. Michigan Hydrologic Framework
5. Coupling of SUMMA (hydrology) to OpenWQ (biogeochemistry). Partnership between ECCC and UofS
6. See Web site

Duration of the work of Initiative_1 (approximate year of initiation and planned completion). 6 responses:

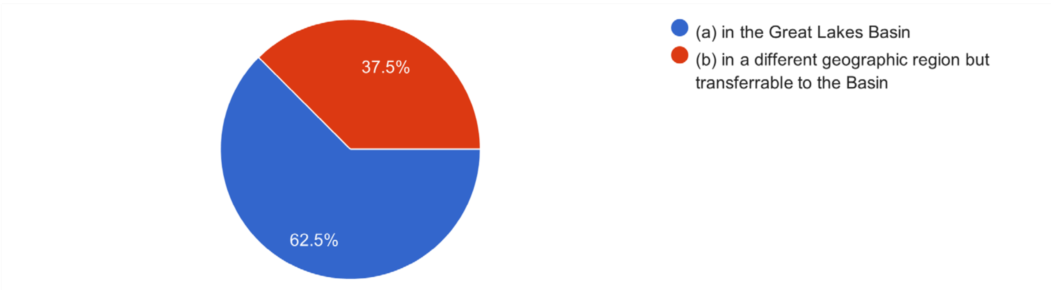
1. ~2017-present; GLB model development to date was largely an internally funded project by Aquanty
2. Ongoing
3. Already completed. A MODFLOW model of GW flow in the Lake Michigan basin.)
4. 2021-2023
5. 4 to 5 years (2025/26)
6. See Web site.

Contact name(s) and email addresses for Initiative_1: 7 responses

1. Dr. Steve Frey (sfrey@aquanty.com)
2. Sandra Eberts
3. David Gochis (gochis@ucar.edu)
4. hwreeves@usgs.gov or pfjuckem@usgs.gov
5. David Hamilton, dhamiltonnc@gmail.com
6. Myself
7. Robert Breault, Director NY WSC rbreault@usgs.gov

Is the work of Initiative_1 focused – (a) in the Great Lakes Basin or (b) in a different geographic region but transferrable to the Basin?

8 responses



List the planned products of Initiative_1: 6 responses

1. A peer-reviewed journal article in Journal of Hydrology
2. too many to list. limitations include minimal representation of groundwater.
3. Usable model and reports (already completed and published)
4. A hydrologic framework that will house nested models on various scales; house climatological, geologic, hydrologic, hydrogeologic data.
5. Continental-scale model for Canada (both hydrology and water quality). Also, a model for the Thames River Watershed
6. Publications and NWIS

Name of Initiative_2: 2 responses

1. Coupling of WRF-Hydro and ParFlow
2. flopy

Duration of the work of Initiative_2 (approximate year of initiation and planned completion): 2 responses

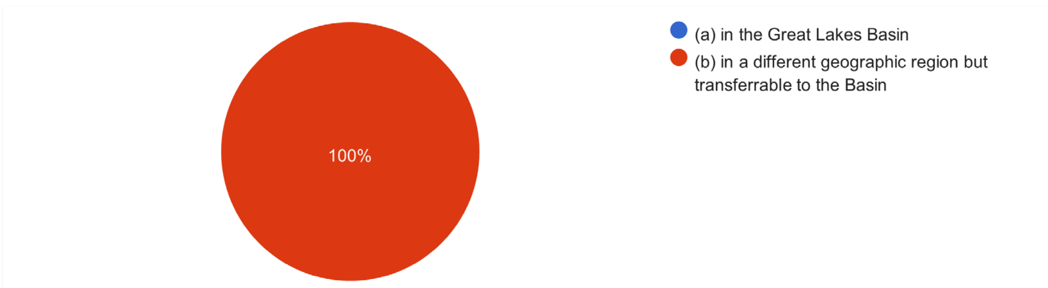
1. estimated implementation end of FY2021
2. Ongoing. This is a suite of software designed to facilitate model creation and use.

Contact name(s) and email addresses for Initiative_2: 2 responses

1. Katelyn FitzGerald (katelynw@ucar.edu)
2. hwreeves@usgs.gov or pfjuckem@usgs.gov or aleaf@usgs.gov

Is the work of Initiative_2 focused – (a) in the Great Lakes Basin or (b) in a different geographic region but transferrable to the Basin?

3 responses



List the planned products of Initiative_2: 2 responses

1. coupling infrastructure and demonstration
2. software and reports

Name of Initiative_3: 2 responses

1. other initiatives to improve subsurface representation and channel coupling / connectivity in WRF-Hydro
2. Nitrate Decisions Support Tool

Duration of the work of Initiative_3 (approximate year of initiation and planned completion): 2 responses

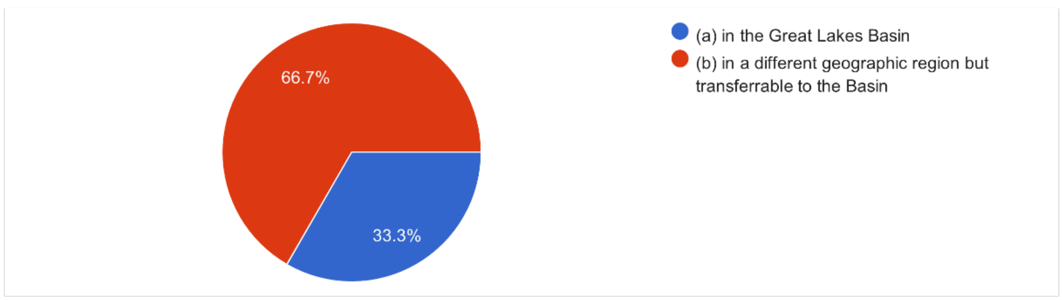
1. ongoing
2. 2019-2021 with planned continuation A tool for forecasting nitrate in wells (expandable to surface water) and changes in concentration due to land management change.

Contact name(s) and email addresses for Initiative_3: 2 responses

1. Katelyn FitzGerald (katelynw@ucar.edu)
2. pfjuckem@usgs.gov

Is the work of Initiative_3 focused – (a) in the Great Lakes Basin or (b) in a different geographic region but transferrable to the Basin?

3 responses

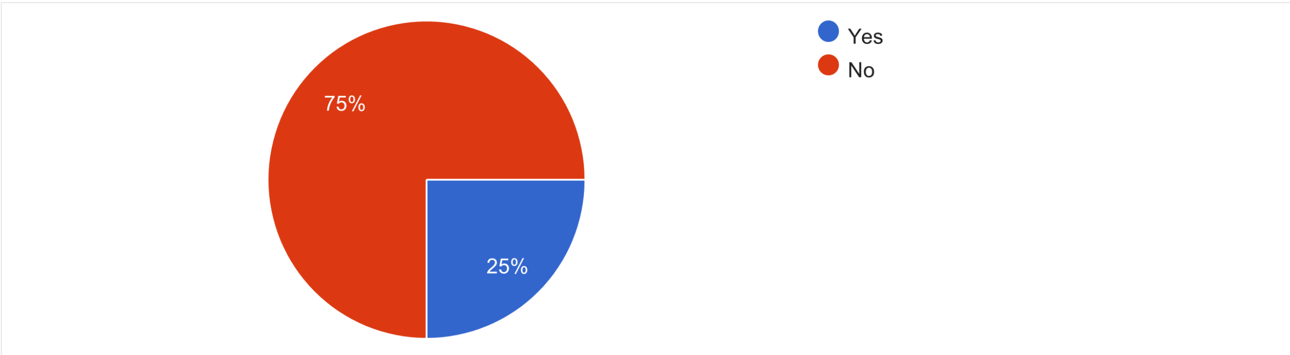


List the planned products of Initiative_3: 2 responses

1. Improved model physics options for subsurface representation
2. software and papers

Are there more than 3 initiatives?

4 responses

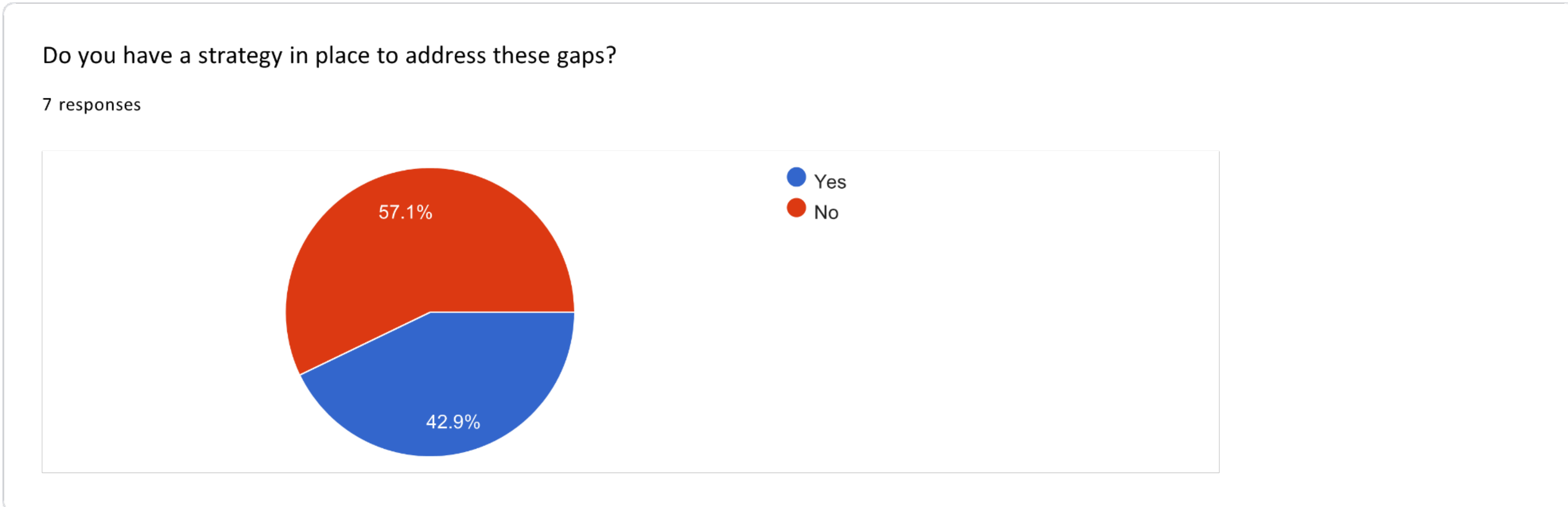


If yes, please indicate how many and a contact name for more information: 1 response

1. Many GW related projects previously and currently developed. hwreeves@usgs.gov or pfjuckem@usgs.gov

What are the most critical data gaps, if any, your organization faces in developing a basin-wide integrated GW-SW numerical model? 7 responses.

1. Not sure. Would have to discuss with the modelers.
2. More refined contiguous hydrostratigraphy, additional time-continuous groundwater monitoring data that have been QA/QC'd, major pumping well completion info and extraction rates
3. Depends upon the level of sophistication / representation desired.
4. hydrostratigraphic 3D surfaces.
5. Many (see GLWQA Groundwater Annex report)
6. Lack of 3D glacial geology mapping; streambed conductance data; streambed characteristics; inland lake level & bathymetry data; vertical & horizontal groundwater flow directions; aquifer transmissivities & storage coefficients; groundwater recharge data; identifying gaining & losing stream reaches; degree of hydraulic connection between glacial & bedrock aquifers and inland lakes & streams.
7. not sure, I am still in the model development phase, so I haven't looked into the available data yet



If yes, please briefly describe the data sources/ approach planned to fill the data gap. 3 responses.

1. Ontario Ministry of Environment, Conservation and Parks, conservation authorities, Ontario Geological Survey, Geological Survey of Canada, etc.
2. Use maps and well information combined with GIS and expert knowledge to develop surfaces. This method has been applied routinely in our workflow.
3. MI Geological Survey doing glacial geology mapping; pilot project to collect inland lake bathymetry data; project specific data collection efforts

Please identify proprietary software and tools your organization could make available to an integrated GW-SW basin-scale model as part of a collaborative effort. 7 responses.

1. For groundwater generally use publicly available platforms (MODFLOW based). For surface water have developed accounting models (ILSAM) for various watersheds in the state.
2. The 3D SW-GW model HydroGeoSphere is Aquanty's proprietary software available under license.
3. Our software and tools are largely open-source.
4. Not sure
5. Water Withdrawal Assessment Tool and related databases and analytical models used by the tool; regional groundwater level GIS mapping; web portals and GIS frameworks;
6. I am not planning to use any proprietary software

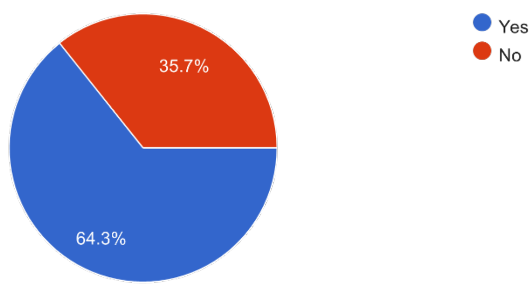
7. Datamine and Leapfrog- for geological model development, we don't have active in-house numerical groundwater modeling.

Please identify the name(s) and email contact information for the appropriate person(s) in your organization with whom to discuss expertise, software and tools for model development. 6 responses

1. Groundwater: Daniel Abrams: dbabrams@illinois.edu; Surface Water: Jason Zhang: zhang538@illinois.edu
2. Dr. Steve Berg, President & CEO (sberg@aquanty.com); Dr. Steve Frey, Senior Scientist (sfrey@aquanty.com)
3. hwreeves@usgs.gov or pfjuckem@usgs.gov
4. Kevin McKnight, mcknightk@michigan.gov; Jill Van Dyke, vandykej1@michigan.gov
5. Myself
6. elizabeth.priebe@ontario.ca

Does your organization have staff with unique skills to apply and/or run models for GW-SW integrated modeling in the Great Lakes Basin?

28 responses



If yes, please briefly describe the unique nature of the skills and provide the name and contact information of a person with whom to discuss deploying the skills to the development of a basin scale model. 16 responses.

1. Philip Chu
2. Jason Thomason jthomaso@illinois.edu

3. Aquanty's technical staff are uniquely skilled and highly experienced in all aspects of sophisticated SW-GW model development and application. The team includes Doctorate and Masters level specialists in hydrogeology, hydrology, soil physics, geological modelling, atmospheric physics, mathematics and numerical methods. Dr. Steve Frey can provide further details.
4. See previous answers. Can contact me.
5. Large group of surface water and groundwater modellers focused on integrated water resource for more than 15 years. 6 of the 20 modellers' specific expertise in the application of integrated models for water balance assessments.
6. David Gochis (gochis@ucar.edu)
7. Diogo Costa (diogo.costa@canada.ca)
8. Expertise in PRMS/Hydrogeosphere Modelling.

Comments

Provide any general comments or observations on a GW-SW integrated model and its relevance for your organization. 13 responses.

1. Test
2. Information on groundwater/surface water relations throughout the basin would be useful for any future USGS work related to water quality or ecological health.
3. I am not in a position to know about organizational plans for basin-wide modeling the Great lakes basin. I know we have the capability, and that we do similar projects elsewhere. I'm sure others in the USGS will provide more detailed insights.
4. This is a priority for our organization, primarily to help understand impacts on water supply planning
5. Definitely useful
6. Integrated SW-GW modelling is the core business of Aquanty. Aquanty has developed HydroGeoSphere models in a number of basins across Canada.
7. Linking groundwater and surface water interactions could be very important and represent the next step in managing water use by allowing full accounting of water budgets and potential impacts from withdrawals.

Additional narrative text for truncated fields

Please identify up to three key questions that an integrated GW-SW model for the Great Lakes on a basin scale should answer.	Which of these questions is the highest priority in terms of investment of resources for your organization? You may response "not applicable" or leave blank if appropriate.
What is the relation between GW levels / GW storage and lake levels? How have GW levels / GW storage changed over time? What is the relation between groundwater supply and groundwater demand and how might it change in the future given projected climate change and groundwater demand forecasts?	N/A
What is the stream baseflow contribution to chemical loads to the Great Lakes? How does the contribution of stream baseflow change seasonally and annually? How does land use affect groundwater quality?	The first question
(1) What is the groundwater contribution to the water budget? (2) What is the groundwater impact on surface water and lake hydrodynamics?	What is the groundwater impact on surface water and lake hydrodynamics?
What is the vulnerability of aquifers to potential contaminants that might discharge into streams or discharge in the lakes themselves?	The answer requires 3D mapping and modeling, which we are capable of performing.
What are the impacts of changes in baseflow on aquatic ecosystems? How do groundwater extraction activities influence changes in baseflow and recharge in streams and wetlands?	How do groundwater extraction activities influence changes in baseflow and recharge in streams and wetlands?
To what extent does GW quality affect SW quality; is GW quality and quantity sufficient for drinking water use in those areas where it is a critical resource; where are the GW sources to SW	
1) Direct groundwater input; 2) groundwater discharge to streamflow entering lakes; 3) nutrient inputs to lakes from 1) and 2); 4) deleterious lake levels	Are are connected and equally important

Please identify up to three key questions that an integrated GW-SW model for the Great Lakes on a basin scale should answer.	Which of these questions is the highest priority in terms of investment of resources for your organization? You may response "not applicable" or leave blank if appropriate.
What data and parameters will go into the model's assessment of groundwater and surface water interaction and impacts from withdrawals? How will the model be validated and at what scales will it operate? How will this model be shared with state and federal agencies with responsibility to manage water quantity and use and what expectations are there for its incorporation or implementation?	All three questions are important to our organization. Michigan's water withdrawal regulatory program depends on the ability to provide accurate assessments of the impact of withdrawals, so the data feeding models, their validation and scalability, and their implementation are all very important to farmers who both are committed to responsible water use that protects natural resources and depend on access to water for livestock watering and crop irrigation.
Storage; flux; chemistry	Flux
I'm not certain that a level of detail (particularly in the sub-surface) can be included in a basin-scale model that would support answering questions that are being asked of numerical models these days - that being said, the 3 major questions I see are: sustainability of existing and future water uses; ecologic dependencies on sw/gw interactions and their inter/intra-annual variability; and how climate change may impact the two previous questions.	
What are the areas of infiltration, recharge linked to discharge areas that support aquatic habitat? What are the seasonal characteristics of recharge and discharge areas. What is the effectiveness of source control stormwater (source control) management in protecting groundwater quality from salt and other contaminants. What is the appropriate time-scale of the simulation for each decision?	
1) increased understanding of overall water budget; 2) role of GW in nutrient and contaminant transport within the basin	
Where, when and on what spatiotemporal scales is groundwater important for fluxes and stores of water in the Great Lakes Basin (and what is the uncertainty)? Where should future observational data collection be focused? Where should future model development and implementation (including calibration, data assimilation, model physics, parameterization, etc.) be focused?	"Where should future model development and implementation (including calibration, data assimilation, model physics, parameterization, etc.) be focused?"

Please identify up to three key questions that an integrated GW-SW model for the Great Lakes on a basin scale should answer.	Which of these questions is the highest priority in terms of investment of resources for your organization? You may response "not applicable" or leave blank if appropriate.
Water balance, climate change impact, nutrient pathways in streams and the lakes	climate change impacts and nutrient pathways
1. What is the Great Lakes basin water budget comprised of, especially the role that the groundwater component plays and its spacial and temporal dynamics? 2. Will a basin-wise GW-SW model be able to provide critical information (e.g., data, model structures, boundary conditions, modeling results) for local water management projects?	
1. What are the quantities and patterns of groundwater and stream water contribution to the Great Lakes and the inland water systems, the associated contaminant loadings, and the effects to water quality dynamic change? 2. How will the hydrological system (surface, soil and ground water) of the Great Lake basins respond to future climate change scenarios? 3. Gain a better understanding, on a basin wide and regional basis, of: a) Whether water is available and sustainable to meet demands for agricultural and industrial use, drinking water and healthy ecosystems b) Nutrient pathways through the watershed and nutrient loadings to the lakes c) The role of groundwater in sustaining nearshore and tributary ecosystems	Number 1. above. Helps most to deliver on GLWQA Annex 8 and Draft COA Annex 9
How much direct input to the lakes comes from Groundwater (ie. not into streams and then into the lakes)? How much does this input change every month?	The change in groundwater input into the lakes.
not in my field of expertise	
Can Canada's high level nuclear waste be safely stored within the Michigan Basin proximal to the Great Lakes as proposed by the NWMO? To what extent is deep (> 1km) groundwater flow contributing the hydrologic budget of the great lakes?	

Please identify up to three key questions that an integrated GW-SW model for the Great Lakes on a basin scale should answer.	Which of these questions is the highest priority in terms of investment of resources for your organization? You may response "not applicable" or leave blank if appropriate.
Role of GW-SW model in nutrient transport, overall water budget and ecosystem services	Nutrient transport
What percent of the water budget is from GW? What is the role of GW in nutrient (&other chem) transport & loading to the lakes and tribs?	Need the water budget first.
1. Have enough support (HR) to allow for development, calibration, maintenance; 2. Be focused on "priority/ key/indicator areas/watersheds; 3. Be able to simulate the various water "fractions" and their interactions (e.g. surface runoff/overland flow/channel flow; subsurface flow; shallow drainage, shallow and deep groundwater), the contaminant concentrations, loads, fate, attenuation, etc.	
climate effects on GW and SW levels	
1. Influence of large-scale (e.g., major municipal) GW withdrawals on GW/SW dynamics. 2. Identify and locate contaminant risks to primary source aquifers. 3. Develop long-term aquifer trends.	Identifying and locating contaminant risks to primary source aquifers.
1) Create a hydrologic framework for the Great Lakes that includes climatological data, surface water hydrology, groundwater, and hydrogeologic data. Identify key gaps. 2) Water budgets at the Basin scale, individual Great Lake scale, major watershed scale, sub-watershed scale, and aquifer scales, that includes providing information on precipitation, groundwater recharge, groundwater discharge to surface water, interconnections between shallow and deeper aquifers. Identify key data gaps. 3) Surface water and groundwater resource sustainability, including climate change impacts. Identify key data gaps.	Creating a hydrologic framework for nesting models at various scales that will incorporate all of the existing climatological, geologic, hydrogeologic, and hydrologic data and make that data available for use by all interested parties.
Define in-basin groundwater vs. out-of-basin groundwater; identify areas of direct/immediate GW/SW interconnection; identify areas where groundwater resource availability is stressed/limited.	

Please identify up to three key questions that an integrated GW-SW model for the Great Lakes on a basin scale should answer.	Which of these questions is the highest priority in terms of investment of resources for your organization? You may response "not applicable" or leave blank if appropriate.
role and influence of groundwater in water budget	same as above
What will be the impact of climate change on groundwater water quantity and quality? What will be the combined effect of climate change and land use changes (i.e., agriculture and urbanization) on groundwater water budget? What mitigation, remediation or adaptation measures should be taken to protect groundwater in the future?	not applicable
Role of groundwater in maintaining stream baseflow, impact of ground quality on surface water	not applicable
Existing and future potential water scarcity	
1. What is the contribution of groundwater to each Great Lake water budget 2. What are changes in the deep aquifer cone of depression in Wisconsin and Illinois 3. Quantifying water loss and impact to groundwater/surface water interactions.	N/A
What is groundwater flux at various temporal and spatial scales? What settings, landforms and geological features are associated with groundwater discharge? What scale of characterization/mapping of these features is necessary to support model development? How can we use an integrated SW-GW model to test and improve our conceptual model?	Our priority is tailoring our geoscience mapping and characterization to support model development.
Quantity of water available (in sub-basin) for groundwater water-taking permits and surface water water-taking permits / Spatially distributed annual recharge of aquifer / Climate change effects on these quantities	

What water budget-related decisions are currently being made by your organization within the Great Lakes basin (briefly describe or indicate not applicable)?
1. The province makes water management decisions that are divided here into three categories in terms of scale for discussion purposes. These scales and examples of MECP decision making related to water budget include: (1) Site scale For example, Permits to Take Water; (2) On an area / regional scale; For example, source protection, watershed management, proposed water quantity area-based management, Oak Ridges Moraine and Niagara Escarpment Area decisions, stream and wetland management etc. (3)Provincial/Basin Wide scale; developing and implementing provincial water policy or province wide guidance, Great Lakes Water Quantity Agreement, Canada Ontario Agreement, province wide climate change assessment (water resources aspects) 2b. All of these activities and ministry quality related decisions, no matter what scale, depend on some level of understanding of provincial basin wide conditions and an understanding of water budget.
1. WDNR reviews high capacity well applications for impacts to surface waters statewide, including the Great Lakes Basin 2. WDNR reviews water withdrawal applications (groundwater or surface water) with a proposed water loss of 2 MGD or more for impacts surface waters 3. WDNR reviews diversion application proposals that can include an alternatives analysis for groundwater versus surface water supply source. 4. WDNR reviews and contributes to the cumulative impacts assessment conducted by the Great Lakes Compact Council and Regional body that assesses water budgets for each Great Lake over the past 5 years.
allocating research funds under COA, some are water budget related.
Based on policy developed by farmers statewide, we make recommendations to our state environmental agency and the Legislature on improvements in data collection, modeling, conservation and efficiency measures, and other topics to improve our state's water withdrawal regulations. We also support education and outreach on water conservation and efficiency in partnership with Michigan State University Extension.
Data needs
Feature-based water balances pre and post development for wetlands. Recharge and discharge area linkages and travel time. Can recahrge distribution be changes and still support seasonal discharge function.
Impacts to SW/GW features (i.e. wetlands, coldwater watercourses) caused by land use modification; sustainability of water takings.
none for now
None in terms of policy or governance, but we do make decisions regarding model development priorities for various applications and research efforts.
Not not directly applicable to Aquanty; decisions are made by Ontario Conservation Authorities and Provincial Ministries
NYSDEC currently has regulatory authority to issue withdrawal permits for water use (both surface and groundwater withdrawals).
Our group is heavily involved in water supply planning activities, providing the technical expertise. While most of these activities are technically outside the Great Lakes Basin, activities in the Chicago region will impact Lake Michigan. An example is the decision of Joliet to switch from deep groundwater to Lake Michigan as their water source due to unsustainable pumping.
Permit to take water and source water protection
Risks related to high and low water levels

What water budget-related decisions are currently being made by your organization within the Great Lakes basin (briefly describe or indicate not applicable)?
sub-watershed scale permitting decisions for proposed new withdrawals based on predicted impact to river/stream flows
The Water Withdrawal Assessment Tool has a regression model that estimated stream index flows (50% exceedance during lowest flow month) on a sub-watershed scale everywhere in Michigan based on an existing USGS stream gage network with long-term flow records. Those index flow value estimates are revised by EGLE Water Resources Division hydrologists during site-specific reviews. EGLE & U.S. Geological Survey have joint funding agreements to install & operate stream gages and collect one-time stream flow measurements. Gage sites are a mix of high flow & low flow sites. One-time stream flow measurements are primarily low flow sites. This stream flow data is used to monitor stream flows, help guide regulatory decisions about whether to authorize proposed new or increased large quantity water withdrawals, and to detect whether an adverse resource impact is happening to stream flow and fish populations.
USGS is currently inventorying and compiling data in Superior watershed that will facilitate model calibration.
Water Survey of Canada is responsible for water budget from the Canadian federal perspective. Our research group works with model development, and some small scale ground water related contaminant and nutrient transports
Water taking autorizations
Water withdrawal permitting (surface and groundwater).
We assist municipalities to make decisions regarding groundwater based Water Taking Permits for municipal supply.
We look at all aspects of the water budget to try and get the best estimate of the components of the water budget based on a statistical model.

What data sources and information are being used to inform water budget-related decisions described in the previous question?
1. Site scale decision making is supported by data collected by project proponents, local municipal and Conservation Authority data and in some cases where available provincial monitoring networks data and modelling. 2. Area / Regional Scale and Provincial / Basin Wide projects, programs and policy development are supported by data collected from provincial monitoring networks, source protection and watershed assessments and models and where available, consolidation of key local scale information.
1. WDNR uses streamflow data, water table maps, lake level data, and available hydrogeological information to assess groundwater surface water interactions for high capacity wells or water loss approvals. Additionally, WDNR uses or reviews groundwater flow models, when available for proposed wells in locations with a high density of wells or groundwater withdrawal with high water loss. 2. WDNR uses best available information for reviewing diversion application. For the recent Waukesha diversion application WDNR used, the SEWRPC groundwater flow model, the USGS Lake Michigan groundwater flow model and an Illinois water survey assessment of the deep sandstone aquifer in the review of the deep sandstone aquifer as a water supply alternative for the City of Waukesha. 3. The Compact Council and Regional Body use best available information for the Great Lakes cumulative impacts assessment.

What data sources and information are being used to inform water budget-related decisions described in the previous question?
Annual water withdrawal reports, water withdrawal permits/applications, groundwater pumping tests.
climate data, streamflow data, groundwater levels, water well/boreholes and their associated stratigraphy, land cover, topography/DEM, water takings (locations and withdrawal volumes)
climate models, groundwater monitoring networks, shallow piezometers at surface water features, bathymetry. spot flows and baseflow
Data from ECCC, NOAA, USACE.
For groundwater withdrawals, aquifer tests (72-hour constant rate pumping tests) are required.
Geoscience surveys; drillhole databases
mainly based on needs identified by current research completed by practical communities.
Monitoring and modelling studies by various levels of government, industry and academia
Ordinary high water mark, USACE water levels
ORMGP database and website.
Provincial Groundwater Monitoring Network, streamflows and provincial and federal climate data
Results of "PACES" regional hydrogeology studies
stream gages, aquifer performance test data, well drilling log geology, organizational geologic mapping
The Center's streamflow and GW level networks
USGS stream gage records, EGLE & USGS one-time stream flow measurements, groundwater elevations in monitor wells and other wells, hydrogeologic evaluations based on water well logs, 3D glacial and bedrock geologic mapping, aquifer pumping test and slug test data, groundwater/surface water model predictions.
Water level data from monitoring and production wells, collected by us and water plant operators. Geological information from Illinois State Geological Survey and USGS for model development. Water quality data. Pump test data. Stream stages (USGS). Water demands, including amounts extracted.
We source information from our state environmental agency, the Michigan and U.S. Geological Surveys, Michigan State University, and from industry professionals conducting data collection and modeling projects around the state.
We work primarily with publicly available datasets (e.g. USGS streamflow observations) having some level of quality control and significant spatiotemporal coverage given the nature of our primary applications and timelines for development work with some exceptions for more specific research efforts where there's more time for data processing and integration.
WL in wells and streams, aquifer maps, base flows, maps (geology), others.
WSC gauge network, MESH and CaPA model and analysis

Briefly describe your organization's unmet water-budget-related data and information needs, including ecological, socio-economic or legal constraints related to water quantity and use that affect your organization's decision making.
1) additional stream flow data (ungauged streams); 2) improved access to water taking data.
A nested hydrologic framework; 3D glacial geology; areal extent and volume of aquifers; effects of high-capacity wells on nearby stream flow & inland lakes; groundwater flow, recharge, & discharge in shallow & deeper glacial aquifers & bedrock aquifers; inland lake level data; inland lake bathymetry; you name it & we need it.
Aquanty has already developed a working 3D dynamic SW-GW model of the entire Great Lakes basin, but there still remains data gaps.The paper we have published recently in the Journal of Hydrology can be found at https://doi.org/10.1016/j.jhydrol.2020.12591. The model still needs work because of data gaps but the paper is a working blueprint for integrated model construction and data needs.
Better water use data is always desirable.
Biggest gap would be considering ecological and socio-economic values of water in a water budget. Water quality is also typically not considered in a water budget excercise.
Complete and consistent 3D geological mapping at multiple levels of resolution
empirical data on effects on SW from GW pumping, and long-term effects on GW levels
groundwater levels, in areas of needed due to site access, permission
Having enough measurements of the different water budget components.
How much water is available for water-taking? How to consider environmental needs?
Information regarding groundwater surface water interactions and overall water budget for model development, calibration, assimilation, and evaluation purposes.
Know of no information for Lake Erie on the connection between groundwater and Lake Erie
More paired groundwater - surface water - climate monitoring stations; improved mapping of baseflow contribution to streams; more soil moisture data; mapping of groundwater dependent aquatic ecosystems.
N.A.
not aware of the activities in my group in this area
NYSDEC doesn't have access to modeling software; also our staffing capacity is pretty thin so we would have a limited ability to build models in-house.
Very little ecological data to understanding impacts of baseflow/recharge changes. More frequent water use, water level, and water quality data.
Water use and groundwater levels & base flow
Water-budget for the Great Lakes is not complete without including ground water

Briefly describe your organization's unmet water-budget-related data and information needs, including ecological, socio-economic or legal constraints related to water quantity and use that affect your organization's decision making.
WDNR has limited groundwater flow models or other tools in areas with high densities of high capacity wells to assess the cumulative impacts of proposed new wells. Hydrogeological data is dispersed from different sources and in different formats, continuous streamflow measurements, particularly in headwater reaches are limited. Existing tools for calculating streamflows in ungaged streams have high error in some areas of the state, lake level data is limited, information on assessing the ecological impact to wetlands and lakes and determining thresholds for impacts is limited. The deep aquifer cone of depression in southeast Wisconsin/NW Illinois has been studied extensively, but the system is a dynamic system and existing assessment will be outdated.
We need more geologic data for both glacial and bedrock aquifers, and more integration of groundwater/surface water impacts from withdrawals.
We were asked to provide Ohio data on GW quality for Lake Erie LAMP purposes, but were not able to round up an adequate data set. We do have GW users on the Lake Erie islands who have been affected by poor GW quality as a supply for their drinking water in the past.

How do you foresee your organization using output from an operational integrated SW-GW model in the future?
1. The information being collected and the model being proposed will provide ministry staff with a fulsome understanding of the hydrological system within the Great Lakes basin, and help them identify vulnerable areas, so that studies and resources could be directed to these areas of priority. 2. An improved understanding of climate change effects, currently and in the future, will help deliver on these activities and support policy makers in drafting climate change adaptation and mitigation plans for the province.
A regional hydrologic framework will provide a framework for nesting models at various scales. Improving decision making about authorizing proposed large quantity water withdrawals. Improving assessments of the impacts of large quantity water withdrawals. Improving sustainability decisions about groundwater and surface water resources, including planning for private and public water supplies.
Being downstream (in Quebec) and mostly interested abourt groundwater, I'm not sure...
Decision related to availability of water, and role of groundwater in nutrient transport, stream water quality, nutrient loading, impact of climate change
Depends, some outputs may be used for overall synthesis of water balance, climate change impacts on the basin. If water quality is integrated, more applications are possible from the GLWQA perspective.
Developer and technical and scientific support
for example for monitoring if the nutrient targets for GL are met
help in our geoscience research activities and 3D modelling
I don't foresee a need for this scale of model in our work.
I see us as the developer, but also the user for further model-driven studies and development.

How do you foresee your organization using output from an operational integrated SW-GW model in the future?
If there was better mapping and acknowledgement of the groundwater and lake interfaces that would be helpful. I worked on a landfill issue in the 1980's and found the groundwater connection here in Wood Lucas County Ohio was over near Canada. Researchers also said that groundwater levels directly corelated with fluctuating lake levels. Understanding this would be important for those with groundwater well users
Initially to understand impacts of groundwater extraction on baseflow, with the goal of minimizing negative impacts.
Land- and water-use planning assistance..
Modifying where we are conducting regional and/or provincial scale work to fill data gaps, or target sensitive areas that require more detailed work.
Most likely for comparison purposes and/or guiding future model development efforts. Could potentially be used for DA or boundary conditions.
Ongoing clarification of data needs
Output from models developed by other organizations would be useful to compare to output from our HydroGeoSphere model mentioned above.
Primarily to inform policy and regulatory decisions with regard to ensuring safe and sustainable municipal water supplies and identifying any emerging threats to these supplies.
projects initiated and funds allocated could be prioritized to the areas with the greatest needs.
Report out in Ohio's State of the Lake: Lake Erie Quality Index, or for the Lake Erie LAMP.
Such a model could be used to inform a range of projects done for a variety of cooperators.
The model could be used to access management options
To answer questions at the local level regarding impacts from an anthropogenic change (e.g. land use change, water taking or climate change), on a specific natural feature.
to guide setup of subwatershed, local models
to help "close" the water budget, or at least get the best estimates we can of the different components.
To meet the needs of our State and local cooperators
Water quality analyses over large areas; Foundation for inset models; many options
water resources management, new withdrawal permitting decisions
Water withdrawal permitting decisions.
WDNR would likely use a regional scale model for boundary conditions for developing local scale models. Such a model would be used for understanding changes in the deep sandstone aquifer in SE Wisconsin, and used the Great Lakes Compact Council and Regional Body cumulative impacts assessment that is conducted every 5 years.
With sufficiently high quality data and modeling outputs, we could incorporate this model into a planned state-level hydrologic framework that will connect and coordinate models of different scales into our regulatory water use program.

Please describe the resources (funding and/or in-kind) your organization could potentially allocate to development and maintenance of an integrated GW-SW basin-scale model.
Matching funds
Cooperative matching funds
Both groundwater and surface water modelers could contribute their time/expertise.
Could maybe offer modelling assistance (review or techncial advice)
Depending on the situation, we may be able to offer in-kind support.
don't know
EGLE would need to request appropriations from Michigan's legislature.
funding, in-kind, HR, infrastructure
Funding, staffing, technical support, data
funding, steering expertise
I'm not sure we would have funding specifically for this, but it's very possible there could be alignment with existing projects and/or potential funding opportunities we would be interested in pursuing. Our portion of NCAR is almost entirely funded based upon project specific grants and contracts.
in kind support for developing a supporting conceptual model
in-kind support for SW-GW model input data assembled by Aquanty
Institutional contributions to the effort.
Matching for any dollars that come to USGS (if $100 for USGS to complete work; USGS contributes <=$50; often $25)
Ongoing updating of 3D hydrostratigraphy for MN at county and state resolution
Provided by others
unsure

If yes, please briefly describe the qualifications/nature of your organization's expertise in basin-scale modeling.
Aquanty is a company that specializes in 3D integrated SW-GW model development and application at local to regional to basin scales. Aquanty has also developed a real-time SW-GW hydrologic forecasting platform based on its HydroGeoSphere software that is driven by an ensemble of wether forecasts. It is a SaaS cloud-based platform currently undergoing final testing for the Southern Ontario portion of the Great Lakes Basin. The short- and long-term hydrologic forecasts include stream flows, water depths, soil moisture, SW-GW interactions, groundwater levels and groundwater recharge
Cohen, D., Person M. , Wang, P. Gable, C. Hutchinson, D., Marksamer, A. Dugan, B. Kooi, H. Groen, K., Lizarralde, D. and R. L. Evans, Origin and Extent of Fresh Paleowaters Beneath the Atlantic Continental Shelf, 2009, Groundwater, Volume 48 Issue 1, p. 143 â€“ 158. Person, M., Raffensperger, J., Ge. S., and G. Garven, 1996, Basin-Scale Hydrogeological Modeling, Reviews of Geophysics, 34, 61-87 Swenson, J.B. and M. Person, 2000, The role of basin-scale transgression and sediment compaction in stratigorm copper mineralization: implications from White Pine, Michigan, USA, Journal of Geochemical Exploration, v. 69-70, p. 239-342. Neuzil, C. E. and M. Person (2017), Reexamining ultrafiltration and solute transport in groundwater, WRR, 53, 4922â€“4941. Micallef, A., Person, M., Haroon, A., Weymer, B. A., Jegen, M., Schwalenberg, K., et al. (2020). 3D characterisation and quantification of an offshore freshened groundwater system in the Canterbury Bight. Nature Communications, 11, 1372.
Conceptual framework development.
developed or implemented many regional or local models including hydrodynamics, surface water, groundwater
Geology specialists with experience in creating and calibrating numerical groundwater/surface water models at the project specific and county level scales.
have develop models for most watersheds in southern ontario. Using groudnwater and integrated modelling tools. Have completed water use and water balance studies at watershed and basin scale.
I have created a series of models/tools suitable for basin-scale simulations suitable for Canada. You can see more information about these models/tools from this link: https://demos-lab.weebly.com/
national USGS expertise across multiple scales
Numerous USGS hydrologists have the skills to develop new code, as well as apply existing code to basin-scale water quantity problems
NWM, etc.
Provided by others
Staff have built and maintain over 70 local scale numerical models in ORMGP. No basin wide modelling - but could contribute modelling expertise.
The hydrometerological applications program at NCAR has significant experience with hydrologic model development and applications including WRF-Hydro and the development of NOAA's National Water Model (NWM).
The USGS has conducted basin-scale modeling throughout the U.S. over many years.
USGS developed MODFLOW and GSFLOW. We have many staff who have used these tools and developed software to facilitate the creation and utilization of these models and others.
We are already involved in developing and using regional groundwater and surface water models, primarily to inform water supply planning decisions

If yes, please briefly describe the qualifications/nature of your organization's expertise in basin-scale modeling.
We are the Nation's premier agency water-related data collection and interpretation
We have been involved in developing integrated modelling since 2009 in Ontario, including developing the Integrated Water Budget Modelling Guide for MNR in 2011. We have since developed numerous integrated models, ranging in size from small to 1000 sq km. The level of discretization required to answer the questions being asked typically limit integrated models from being >10,000 km2.

Please provide any general information about related projects that you or your organization has recently completed, are currently active, or are planned or proposed for the future with approximate timeframe of implementation. Please include citations for recent publications if appropriate.
I recently completed a study of groundwater age distributions throughout the glaciated U.S. https://doi.org/10.1029/2020WR027335
State of the Lake: Lake Erie Quality Index report. Next issuance expected fall 2021.
I have provided above some key citations relevant to SW-GW modelling in the Great Lakes Basin. Aquanty publishes frequently in peer-reviewed journals. Our HydroGeoSphere model is being used under license by academia, industry and government in numerous countries.
The Michigan Water Use Advisory Council has made recommendations to the state Legislature for funding of projects identified in this report: https://www.michigan.gov/documents/egle/egle-wrd-wateruse-WUAC_2020_council_report_711968_7.pdf
Minnesota County Geologic Atlas program
Integrated watershed-lake models (SWAT) for 3 tributaries as part of Great lakes protection Initiative, GEM-MESH-NEMO for the Great lakes
Michigan Hydrologic Framework planned for 2021-2023. USGS & MI DNR published reports documenting the Water Withdrawal Assessment Tool are available via links at http://www.michigan.gov/wateruse. Google MI Groundwater Inventory & Mapping (GWIM) project also associated with developing the WWAT, aquifer properties, & using well log info.
The most relevant work for the GLB is the full coupling of SUMMA to OpenWQ for continental scale simulations across Canada. We have initiated the coupling and expect it to be completed, tested and validated within the next 2 to 3 years.

Appendix C.2 Stakeholder questionnaire

Great Lakes Groundwater Modeling Stakeholder Registry Questionnaire

Background: The impact of groundwater on the water budget and water quality of the tributaries and waters of the Great Lakes, although assessed partially at the regional scale, has not been fully assessed at the scale of the basin. Understanding the groundwater component of the water cycle is necessary to obtain a complete picture of the Great Lakes water budget and to improve water management strategies. Tributary base flow and direct discharge of groundwater can strongly impact the health of the ecosystems of the Great Lakes. Although there is an undisputed relationship between surface water and groundwater, they are commonly treated as two separate resources. An integrated water model is needed to better represent surface and subsurface hydrological processes impacting water within the binational Great Lakes basin in terms of water quantity, water quality, ecosystem health, and projected climate change impacts.

The purpose of this Groundwater Modeling Stakeholder Registry is to:

1. Identify agencies with the capacity to carry out basin-scale groundwater-surface water (GW-SW) integrated modeling work,

2. Identify agencies with the capacity to run such a model operationally over the long term,

3. Collect information on basin-scale water-budget-related decisions currently being made and related unmet decision-support needs,

4. Identify ongoing or planned basin-wide government or university programs or projects that could advance an integrated SW-GW basin-wide modeling effort and delineate related critical data gaps, and

5. Identify potential stakeholder resources that could help support a future basin-wide modeling initiative to address unmet data and information needs.

The information you provide about yourself and your organization will be used to help the IJC workgroup develop a conceptual modeling framework that captures important aspects of groundwater-surface water interaction and meets the needs of those who make decisions based on knowledge of groundwater-related resources in the basin. No statements about your interest or capabilities will be viewed as commitments on behalf of yourself or your institution--this is merely an information-gathering exercise.

After respondent information and general question sections below, additional questions are presented in four role-specific sections, followed by a section with two open fields for general comments. You may skip any questions or sections that do not apply to you or that you do not wish to complete, except for the three marked with an asterisk--name, organization, and email address. The questionnaire should take 15 to 30 minutes to complete, depending on the number of questions that apply to you and your organization. Please plan to complete the survey in a single session, or prepare narrative responses in a separate document and paste them into fields so you do not lose your work. Please feel free to forward the survey to others in your network who would be able to provide useful information. Email John Bratton at jbratton@limno.com with any questions. Thank you for participating!

International Joint Commission (IJC)
Commission Mixte Internationale (CMI)

1. Name*

2. Organization*

3. Unit(s), department(s), or division(s) (include all levels that apply; e.g., Office of Well Data, Department of Groundwater, Division of Water Resources)

4. Title

5. Email address*

6. Phone

7. Personal role and responsibilities in organization

* Required question

8. Website or sites

Following is a summary table describing stakeholder groups for a groundwater-surface water (GW-SW) interaction model for the Great Lakes basin.

Stakeholder Group	Role (note: an organization may have more than one role)
Model owners/responsible agents	-- Contribute funding or in-kind resources -- Accountable for model development and maintenance
Model creators	-- Technical/ scientific development of model(s) -- May create, own or use third-party software and tools
Data owners	-- Collect, store and/or develop data sets essential for model development, model refinement
Model users	-- Skilled group who run models or manipulate model output and understand underlying assumptions, parameters, etc.
Decision-makers and policy advisors, influencers	-- Seek answers to questions about water quantity, quality, and ecosystem health; prioritize investments of resources

9. Please indicate all roles your organization plays in GW-SW interaction modeling for the Great Lakes basin. *Check all that apply.*

    - Model owner/responsible agent
    - Model creator
    - Data owner
    - Model user
    - Decision maker, policy adviser, influencer
    - Other

10. Please indicate all roles in GW-SW interaction modeling that your organization has concrete plans to play within the next five years (within the Great Lakes Basin or in building expertise). *Check all that apply.*

    - Model owner/responsible agent
    - Model creator
    - Data owner
    - Model user
    - Decision maker, policy adviser, influencer
    - Other

11. Provide any additional comments about you or your organization's role(s) that don't fit neatly into the previous categories.

General questions for all respondents

12. Please identify up to three key questions that an integrated GW-SW model for the Great Lakes on a Basin scale should answer.

13. Which of these questions is the highest priority in terms of investment of resources for your organization? You may response "not applicable" or leave blank if appropriate.

14. What water-budget-related decisions are currently being made by your organization within the Great Lakes Basin (briefly describe or indicate not applicable)?

15. What data sources and information are being used to inform water budget-related decisions described in the previous question?

16. What spatial scales are of greatest interest to you or your organization on this topic (check all that apply)?

    - Local
    - County or district
    - Tributary watershed
    - Embayment watershed
    - Great Lakes connecting channel watershed
    - State or provincial scale
    - Watershed of an individual Great Lakes within a single country (U.S. or Canada)
    - Binational watershed of an individual Great Lakes
    - Binational watershed of multiple Great Lakes, but not all five
    - Binational watershed of the entire Great Lakes basin, including Lake Michigan
    - Other:

17. What timescales are of greatest interest to you or your organization on this topic (check all that apply)?

    - Hourly
    - Daily
    - Weekly
    - Monthly
    - Seasonal
    - Annual
    - Decadal
    - Centennial
    - Millennial
    - Other:

18. Briefly describe your organization's unmet water-budget-related data and information needs, including ecological, socio-economic or legal constraints related to water quantity and use that affect your organization's decision making.

19. How do you foresee your organization using output from an operational integrated SW-GW model in the future?

If you are not a data owner, you can skip this section. Scroll down to the bottom and select "next." If you are a data owner:

To identify important/relevant datasets that can provide essential support to a basin scale integrated GW-SW model, please indicate yes or no and the additional information as appropriate.

20. Does your organization own hydrostratigraphy data? *Mark only one.*

- Yes
- No

21. If yes, please describe the geographic extent, years of data collection, spatial/temporal resolution.

22. Contact name and email address for this dataset:

23. Is this publicly available? *Mark only one.*

- Yes
- No

24. Does your organization own stream flow data? *Mark only one.*

- Yes
- No

25. If yes, please describe the geographic extent, years of data collection, spatial/temporal resolution.

26. Contact name and email address for this dataset:

27. Is this publicly available? *Mark only one.*

- Yes
- No

28. Does your organization own groundwater withdrawal data?

- Yes
- No

29. If yes, please describe the geographic extent, years of data collection, spatial/temporal resolution.

30. Contact name and email address for this dataset:

31. Is this publicly available? *Mark only one.*

- Yes
- No

32. Other dataset_1 – Description:

33. What is the geographic extent, years of data collection, spatial/temporal resolution?

34. Contact name and email address for this dataset:

35. Is this publicly available? *Mark only one.*

- Yes
- No

36. Other dataset_2 – Description

37. What is the geographic extent, years of data collection, spatial/temporal resolution?

38. Contact name and email address for this dataset:

39. Is this publicly available? *Mark only one.*

- Yes
- No

40. Other dataset_3 – Description

41. What is the geographic extent, years of data collection, spatial/temporal resolution?

42. Contact name and email address for this dataset:

43. Is this publicly available? *Mark only one.*

- Yes
- No

44. Please identify the name and email contact information for the appropriate person in your organization with whom to discuss access to data for assisting with an integrated GW-SW model at a basin scale.

If you are not a model owner/responsible agent, you can skip this section. Scroll down to the bottom and select “next.”

If you are a model owner/responsible agent:

45. Should your organization be considered a potential funder for an integrated basin scale GW-SW model? *Mark only one.*

- Yes
- No

46. If yes, please provide the name and email contact information for the appropriate person in your organization with whom to discuss funding or other resources that could be leveraged for the model or models.

47. Please describe the resources (funding and/or in-kind) your organization could potentially allocate to development and maintenance of an integrated GW-SW basin-scale model.

48. Do these resources include staff with the capacity to develop or advance relevant modeling work? *Mark only one.*

- Yes
- No

49. Note that one or more model platforms may be used to advance modeling of GWSW interactions. Should your organization be considered a candidate to lead model development? *Mark only one.*

- Yes
- No

50. If yes, please provide the name and email contact information for the appropriate person in your organization with whom to discuss model development.

51. Should your organization be considered a candidate to manage model deployment and further development over time? *Mark only one.*

- Yes
- No

52. If yes, please provide the name and email contact information for the appropriate person in your organization with whom to discuss model deployment and future development.

If you are not a model creator, you can skip this section. Scroll down to the bottom and select "next."

If you are a model creator:

53. Does your organization have expertise relevant to developing a basin-scale integrated GW-SW model for the Great Lakes basin? *Mark only one.*

- Yes

- No

54. If yes, please briefly describe the qualifications/nature of your organization's expertise in basin-scale modeling.

55. Does your organization have the capacity to run the model operationally over the long term? *Mark only one.*

    - Yes
    - No

56. Has your organization developed, or is your organization in process of developing, one or more models that could be used as a platform for a basin-scale GW-SW integrated model for the Great Lakes (including scientific development, software development, conceptual model development)? *Mark only one.*

    - Yes
    - No

If yes, please provide the following information on each initiative that is on-going or planned for basin-wide work that could advance an integrated GS-SW integrated model:

57. Name of Initiative_1:

58. Duration of the work of Initiative_1 (approximate year of initiation and planned completion):

59. Contact name(s) and email addresses for Initiative_1:

60. Is the work of Initiative_1 focused – (a) in the Great Lakes basin or (b) in a different geographic region but transferrable to the basin? *Mark only one.*

    - In the Great Lakes basin
    - In a different geographic region but transferrable to the basin

61. List the planned products of Initiative_1:

62. Name of Initiative_2:

63. Duration of the work of Initiative_2 (approximate year of initiation and planned completion):

64. Contact name(s) and email addresses for Initiative_2:

65. Is the work of Initiative_2 focused – (a) in the Great Lakes basin or (b) in a different geographic region but transferrable to the basin? *Mark only one.*

    - In the Great Lakes basin
    - In a different geographic region but transferrable to the basin

66. List the planned products of Initiative_2:

67. Name of Initiative_3:

68. Duration of the work of Initiative_3 (approximate year of initiation and planned completion):

69. Contact name(s) and email addresses for Initiative_3:

70. Is the work of Initiative_3 focused – (a) in the Great Lakes basin or (b) in a different geographic region but transferrable to the basin? *Mark only one.*

    - In the Great Lakes basin
    - In a different geographic region but transferrable to the basin

71. List the planned products of Initiative_3:

72. Are there more than 3 initiatives: *Mark only one*.

    - Yes
    - No

73. If yes, please indicate how many and a contact name for more information.

74. What are the most critical data gaps, if any, your organization faces in developing a basin-wide integrated GW-SW numerical model?

75. Do you have a strategy in place to address these gaps? *Mark only one.*

    - Yes
    - No

76. If yes, please briefly describe the data sources/ approach planned to fill the data gap.

77. Please identify proprietary software and tools your organization could make available to an integrated GW-SW basin-scale model as part of a collaborative effort.

78. Please identify the name(s) and email contact information for the appropriate person(s) in your organization with whom to discuss expertise, software and tools for model development.

If you are not a model user, you can skip this section. Scroll down to the bottom and select "next."

If you are a model user:

79. Does your organization have staff with unique skills to apply and/or run models for GW-SW integrated modeling in the Great Lakes basin? *Mark only one*.

- Yes
- No

80. If yes, please briefly describe the unique nature of the skills and provide the name and contact information of a person with whom to discuss deploying the skills to the development of a basin scale model.

Comments

81. Provide any general comments or observations on a GW-SW integrated model and its relevance for your organization.

82. Please provide any general information about related projects that you or your organization has recently completed, are currently active, or are planned or proposed for the future with approximate timeframe of implementation. Please include citations for recent publications if appropriate.

End of survey – thank you!

Appendix D Expanded description of scientific elements of the conceptual framework

This appendix provides more detailed descriptions of **Table 5** (page 32) entries.

D.1 Climate forcings

Precipitation

Precipitation presents changes in intensity in the order of minutes. Aggregating minute observations of precipitation to longer time steps allows model simulations at those longer time steps. Some models, as the Sacramento model, which uses six-hour time steps for the NWS river forecasts, compute the nonlinear infiltration process in steps of 5 mm, essentially reducing internally the computational time step. The spatial resolution of the precipitation is also an important consideration in modeling.

Temperature and potential evapotranspiration

These two forcings have an important influence on evapotranspiration, and snow and ice melt, and are the most frequently used forcings to model those processes.

D.2 Other forcings

Some models, particularly physically-based and some conceptual models, require additional input to temperature for snow and ice melt and evapotranspiration, such as solar radiation, cloudiness, relative humidity and wind speed and direction. These forcings are not as commonly available as precipitation and temperature

Hydrologic processes

This group includes hydrologic processes and their characteristic times **specific** for the Great Lakes basins.

Baseflow

Baseflow is the contribution of groundwater to the Great Lakes, either directly to the lakes, or through the river network. Its characteristic time is considerably longer than that of the surface processes, whereby significant changes to the groundwater states, and, hence to the baseflow, are only noticeable over time steps of a month or more.

Intricately connected with baseflow are the concepts of bank storage and bank flow. When a river receiving baseflow rises, due to flooding for instance, some of the water in the river channel infiltrates the riverbank and is stored there until the river level decreases. After the river level returns to normal the water in storage supplements the natural baseflow.

Baseflow is a fundamental component of the hydrologic cycle. Yet, the difference in characteristic times between baseflow and the other surface fluxes complicates the practical issue of having an integrated **tightly-coupled** surface and groundwater model.

Direct runoff

Direct runoff is comprised of precipitation falling directly on river and lake surfaces. It is driven by precipitation and is not capacity-limited as is the case of surface runoff.

Impervious runoff

This flux is generated by rain falling on impervious areas of a basin, such as roofs, pavement in urban areas, and rocky outcrops in rural areas. In contrast to direct runoff, it does become part of the surface runoff routing

Infiltration

Rainfall not captured by interception, in addition to snowmelt, infiltrates into the soil at a rate that is a function of the soil saturation. It is a fairly slow process with time constants on the order of hours to days. Beyond that time horizon, infiltration would appear as a constant for models with time steps of weeks or longer. Infiltration can also refer to the direct recharge of water from lakes or streams into underlying aquifers based on elevated heads in surface water relative to groundwater.

Interception

Interception refers to water and snow trapped in the canopy and not released to the ground to be part of the surface and subsurface hydrologic processes. It is, of course, driven by precipitation but it has a limited capacity, which is a function of surface cover and land use.

Interflow

Interflow is a temporary flow from the normally unsaturated soil layer, which happens when infiltration fills the soil layers to capacity.

Streamflow

Water in a river channel has a velocity that is rarely constant. Given the short length of rivers in the Great Lakes basin, it is unlikely that any of those rivers take more than one week to move water from the headwaters to the lakes except where large riparian wetlands may be present. There are two families of river routing: hydraulic and hydrologic. Hydraulic routing requires noticeably short computational times and extensive river channel cross-section information. They are computationally expensive, and their use would be required only for very short simulations. Hydrologic routing, on the other hand, is used in quite simple models which, due to their simplicity, cannot consider certain hydraulic cases and, therefore, may not yield accurate results in some cases. For models using time steps of one week or more, river routing processes will be invisible. In general, hydraulic models could be one-, two- or three-dimensional, and computational and data requirements increase exponentially with the dimensionality of the model. For simulations of horizons of the order of one week or more, hydraulic models are rarely required. For shorter time frames, and depending on the objective of the simulation, one-dimensional models may be used. Cases in which these models may be required include those in which it is desired to know water surface elevations at cross-sections between stream gauging sites. two-dimensional models may be required when studying the extent of surface flooding, although in many cases one-dimensional models are suitable. Some modern models allow a combination of one-dimensional and two-dimensional models which only switch to two-dimensional mode when the conditions require, thus saving a considerable amount of computational time. For most of the studies in the Great Lakes basin undertaken with a GW-SW model, a much simpler hydrologic routing model will be sufficient.

Snow accumulation and snow melt

These fluxes track the rate at which snow accumulates and melt, respectively. Characteristic times of snow melt depend on the season.

Surface Runoff

This flux refers to the runoff caused when the top layer of the soil reaches saturation, and rain intensity or snowmelt are above the soil's saturated infiltration capacity.

Anthropogenic changes to the hydrologic cycle

Anthropogenic changes to the water cycle present some of the most difficult processes to consider in hydrologic simulations, given the uncertainty and, sometimes, the total lack of knowledge as to how some of those alternations will manifest.

Streamflow alteration

River regulation refers to the modification of the flow regime by reservoir operations. In many instances, for example, hydropower generation, planned reservoir operations or even reservoir operations policies are considered corporate proprietary information. Short-term simulations (less than one month) are affected by reservoir operations, even small reservoirs with regulating capacity of a week or so. Long-term simulations, such as those carried out to assess the impact of climate change, are only affected by the operation of reservoirs with large regulating capacity (more than a season). In the Great Lakes basin, all reservoirs are of modest regulating capacity and, therefore, long-range simulations would not be affected.

Large-quantity withdrawals of water from rivers and lakes

Large-quantity withdrawals for public supply, irrigation, and other uses occur throughout the Basin. We define large-quantity withdrawals as withdrawals of 100,000 gallons per day or greater because these are the amounts that states and provinces must track under the Great Lakes-St. Lawrence River Basin Sustainable Water Resources Agreement and Compact.

Extractions from and returns to aquifers due to irrigation and water supply

Large-scale irrigation and water supply from the Great Lakes aquifers have a major impact on the overall water cycle. On one hand, there is groundwater extraction that affects surface water baseflow. On the other hand, some of the water is lost to evaporation from plants and the upper soil layer, and the rest of the water used for irrigation is returned to groundwater. The partitioning of the irrigated water into those components is a function of the crop type, the soil and the climate. Short-term simulations may be carried out with the current conditions, but long-term outlooks should consider the pumping-irrigation return cycle, especially keeping in mind the increase in evaporative losses due to an increase in temperature from climate change. Some fraction of the water supply for domestic or industrial use from either surface or groundwater is returned to surface water via wastewater treatment plants, or to groundwater via septic systems. Some fraction of the irrigation taken from surface water, similar to that from groundwater sources, is also returned to the groundwater regime.

Tile drains

Farmers in Canada and the United States have been installing thousands of miles of tile drains in agricultural lands. Tile drains allow farmers to work their land after precipitation or snowmelt earlier in the spring than is possible with land without tile drains. Tile drains modify the water cycle by intercepting water that would normally run off or infiltrate to the water table. In some areas, tile drains are being installed in well-drained soils where irrigation occurs. The impacts of tile drains on the natural water cycle need to be explicitly considered. The tile drains row in **Table 5** refers to the installation of tile drains, not to their operation. Tile drains present another difficulty: while the drainage of the soil is done automatically, the discharge of the drained water may be controlled by the farmer. Only a few water management agencies in the United States keep track through permitting of the actual size and location of tile drains. Tracking in Ontario is much better, although still imperfect. Recently, researchers have been using remote sensing techniques to map out the location and extent of tile drains in high resolution. Some recent references are Cho et al. (2019), [1] Giglierano (2018), [2] Gökkaya et al. (2017), [3] Tilahun and Seyoum (2021) [4] and Valayamkunnath et al. (2020). Urban storm sewer systems present a similar situation of enhanced drainage, artificial lowering of the water table and altered stream hydrology in some areas due to infiltration and interception, although the water cycle here is also complicated by impervious surfaces, leakage from water distribution systems, irrigation of landscaping and dewatering by sump pumps.

---

[1] Cho, E., Jacobs, J.M., Jia, X., Kraatz, S., 2019. Identifying subsurface drainage using satellite Big Data and machine learning via Google Earth Engine. Water Resour. Res. 55(10), 8028-8045. DOI: 10.1029/2019WR024892.

[2] Giglierano, J., 2018. Identifying and mapping tile drainage tutorial Wright County, Iowa. 24 p. Accessed at: iowaview.org/wp-content/uploads/2018/03/Tutorial_3_TileMapping.pdf, February 9, 2022.

[3] Gökkaya, K., Budhathoki, M., Christopher, S.F., Hanrahan, B.R., Tank, J.L., 2017. Subsurface tile drained area detection using GIS and remote sensing in an agricultural watershed. Ecol. Eng. 108(B), 370-379. DOI: 10.1016/j.ecoleng.2017.06.048.

[4] Tilahun, T., Seyoum, W.M., 2021. High-resolution mapping of tile drainage in agricultural fields using unmanned aerial system (UAS)-based radiometric thermal and optical sensors. Hydrol. 8(1), 2. DOI: 10.3390/hydrology8010002.

Land use change

Changes to land use (current land use is shown in **Figure 13**) are typical during extended simulations. Anthropogenic changes are those resulting from urban growth, changes to crops, deforestation and reforestation, and wetland drainage. Those changes are only visible in time intervals of months and seasons.

Canals, intra-basin and inter-basin connections

There are canals and anthropogenic intra-basin and inter-basin connections in the Great Lakes basin. By intra-basin connections we mean those between Great Lakes. For instance, the Trent-Severn waterway is a series of lakes and stream, with locks, which connects Lake Ontario and Lake Huron. By inter-basin connections we mean those between the Great Lakes basin and another basin. The primary inter-basin connections are the two diversions into Lake Superior (Long Lac and Ogoki) and the diversion from Lake Michigan at Chicago. An example of a canal is the Welland Canal, which provides navigation between Lake Erie and Lake Ontario at Niagara Falls. During long simulations it is likely that there will be changes to land use that are not anthropogenic. For instance, land formerly used for source wood for paper mills that are no longer operating may be restored to its natural condition either by forest management (anthropogenic) or by letting the natural process of reforestation take its place. Another likely natural change in land use is that caused by climate change, which may change some of the natural vegetation. Natural changes can also occur due to forest fires and insect infestations that reduce forest cover.

D.3 Hydrologic storage

Surficial aquifers

Modeling groundwater marks a major difference in approaches between surface and subsurface models. Groundwater is highly simplified in surface models precisely to avoid the problem of computational expense resulting from the more physically based groundwater models.

Ice on natural lakes and reservoirs

Ice covering natural lakes and reservoirs reduces lake evaporation and contributes to spring runoff volume. Ice on lakes has the same states as ice on rivers.

Ice on rivers

Like snow on land, ice on rivers is an important factor during the spring runoff. Depth of the ice, the extent of the ice and the temperature of the ice are all factors. Shorter time simulations may also need to consider the effect of ice dams.

Ice on the canopy

It may accumulate as freezing rain or freezing after canopy interception of rain and, therefore, its accumulation follows the characteristic times of snow on the canopy. However, melting takes longer.

Snow on the canopy

Resulting from the net effect of interception minus sublimation or falling to the ground.

Snow on the surface

Snow has several sub-states that describe the snowpack in a matter suitable for modeling:

- **Snow water equivalent:** as the name implies, is the amount of liquid water that snow would produce if it were to melt that instant
- **Snow cover area:** the amount of area covered by snow
- **Snow depth:** although some models explicitly consider snow depth as one of their state variables, many models ignore it since, when comparing with snow water equivalent and snow cover area, it does not have much information useful in the determination of snowmelt
- **Snow temperature:** important in calculations for snow dynamics

Soil moisture

Soil moisture is at the heart of the infiltration process. Some models may divide the soil into several layers, explicitly including the root zone layer, for example. Some other models, essentially conceptual models, simplify the soil column into one or more groundwater ‘reservoirs’ that mimic the increase and decrease of soil moisture throughout the simulation cycle.

Water in natural lakes

Natural lakes do not have a control at the outlet. It is substantially easier to model these lakes because the discharge is a function of the water level only unless affected by backwater effects from downstream water bodies. Many natural lakes have control structures and, therefore, can be modeled as regulated reservoirs.

Water in reservoirs

This state variable could be considerably difficult to model. Many reservoir owners/operators consider their reservoir operations to be confidential and, therefore, they are very reluctant to share their operating plans and reservoir levels. Historical reservoir elevation/volume and discharge may be available from the USGS and State Engineer offices. Long-term simulations make those changes fairly invisible to a model because changes in the reservoir level (state) and discharge (flux) in the Great Lakes basin reservoirs occur within time durations considerably lower than the model time steps. Shorter simulations, in the order of days, do need to consider reservoir operations.

Water in rivers

This is an important state variable for certain types of routing models, such as hydraulic models.

Water on the land surface

Water on the land surface is that which remains in small ponds, potholes behind highway embankments, etc. It may result from precipitation or snowmelt. Some of it will eventually infiltrate and some of it will evaporate.

Water on the canopy

This is a net result of interception and evaporation.