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2016

Canada

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2016

doi:10.4095/298816

This publication is available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

Recommended citation

Frey, S.K., Berg, S.J., and Sudicky, E.A., 2016. A Feasibility Study of Merits and Development Strategies for a Regional Water Resources Modelling Platform for Southern Ontario – Great Lakes Basin; Geological Survey of Canada, Open File 8021 46 p. doi:10.4095/298816

Publications in this series have not been edited; they are released as submitted by the author.

Foreword

The Geological Survey of Canada (GSC) Southern Ontario Groundwater Project 2014-2019 is working at a synoptic scale to support an enhanced framework for sustainable groundwater resources management in Southern Ontario. The project is an initiative of the Groundwater Geosciences Program in collaboration with the Ontario Geological Survey (OGS). GSC work in Ontario is completed as a supporting contribution of Natural Resources Canada (NRCan) to responsibilities of the Canadian government supporting the International Joint Commission (IJC), The Canada – US Great Lakes Water Quality Agreement (GLWQA), Canada-Ontario Agreement on Great Lakes Water Quality and Ecosystem Health and as mandated by the Canadian Senate (2005) to complete work on 30 Key Canadian Aquifers and to develop a national database of groundwater information.

In March 2015 the GSC and OGS held a gap analysis of groundwater geoscience needs relative to the Ontario Geological Survey Mandate (Russell et al., 2015). Following up on issues raised in the 2015 gap analysis and a previous assessment in 2012, the GSC coordinated a workshop on November 24th 2015 to initiate a discussion on a groundwater data framework for Ontario. This workshop had three themes: i) data management framework; ii) accessibility and analytical accessibility to data; iii) the feasibility and interest in a regional groundwater modelling platform (Agenda available on GIN: http://gin.gw-info.net/service/ngwds/pdf/workshop20151104/program.pdf).

To support objectives of this workshop Aquanty was contracted to complete a review and compilation of the state of the art of regional groundwater modelling internationally and regarding the technical, science and data support issues within an Ontario context.

This report is an unedited release of the contract deliverable received by the GSC. The publication of this report is not an endorsement by Natural Resources Canada, Earth Science Sector, Geological Survey of Canada, of the views expressed in this report by the authors.

Comments can be addressed directly to the authors or to the contract science authority Hazen Russell at hazen.russell@canada.ca

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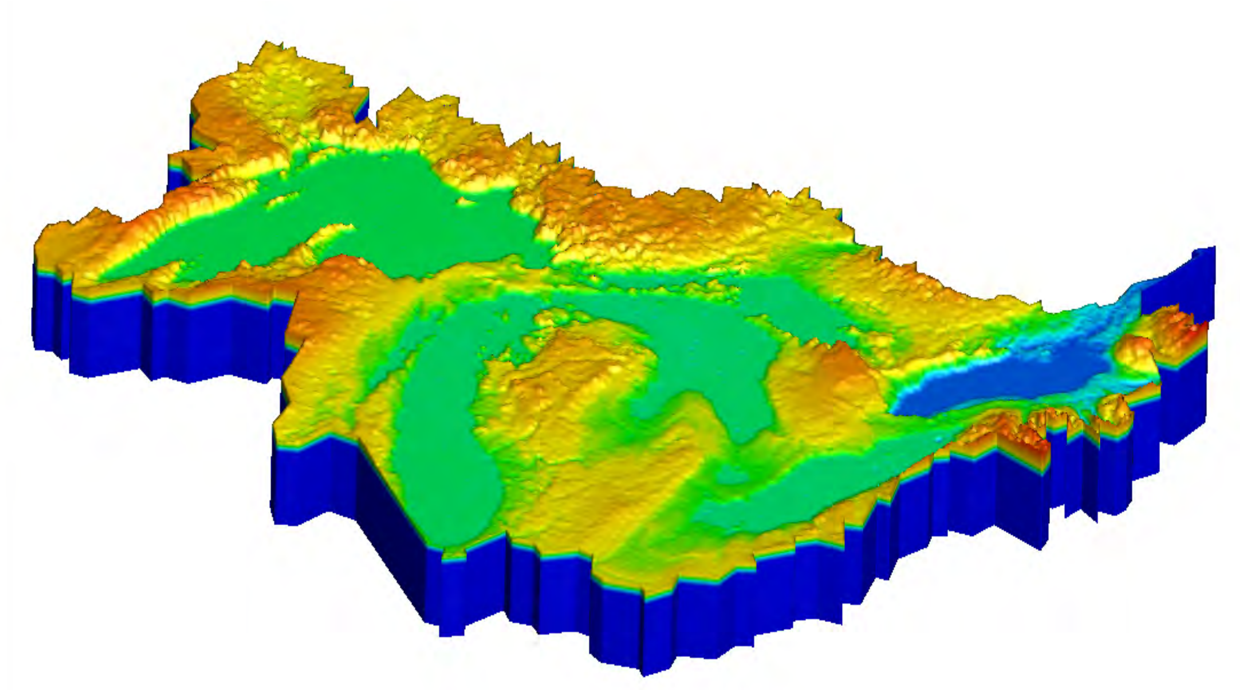
Russell, H.A.J., Priebe, E.H., Parker, J.R., 2015. Workshop Summary and Gap Analysis Report: Unifying Groundwater Science in Southern Ontario. Ontario Geological Survey, Open File Rep. 6310 64 p.



A Feasibility Study of Merits and Development Strategies for a Regional Water Resources Modelling Platform for Southern Ontario – Great Lakes Basin

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Natural Resources Canada

Contract No.: 3000590060

Funding provided by the Groundwater Geoscience Program, Natural Resources Canada

April 13, 2016

Abstract

Water resources within Southern Ontario and the Great Lakes Basin (GLB) are a focal point for a wide range of stakeholders who are faced with addressing climate change impacts and resiliency, surface water and groundwater sustainability, and Great Lakes water quality. Because of the complexity of these challenges, modern science-based decision support tools are required. As demonstrated by water resources management projects underway in the Canadian Prairies and Europe, fully-integrated groundwater-surface water models are increasingly being used as multi-stakeholder decision support tools for demanding hydrologic problems. The centralized high-performance modelling platforms and associated databases are being developed through a collaboration of platform end users and requisite specialists. The multi-stakeholder functionality of this next generation of water resource simulation tools is primarily possible because fully-integrated hydrologic models seamlessly couple surface water (SW) and groundwater (GW) flow systems, including the unsaturated zone, and are driven by spatio-temporal precipitation events that are either derived from observational data or climate system projections. As such, traditional groundwater-only and surface-water-only models can now be replaced by single simulation platforms that employ holistic physics-based approaches for emulating the entire terrestrial water cycle, with full accounting of water balances within and between the various hydrological compartments. Furthermore, fully-integrated physics-based modelling provides additional benefit when simulating hydrologically complex settings such as the GLB because crucial GW-SW interaction processes are inherently captured. While fully-integrated models have been commonly employed on local-scale academic problems (10's to 100's of km^2) for more than 10 years, their application to 3D water resources problems at the scale of Southern Ontario or the GLB has only been recently demonstrated. This increase in model scale, as well as complexity and spatial resolution has evolved because of a number of factors, including the mainstream accessibility to high-performance computing resources, improved numerical techniques, and the increasing availability of the large spatially-distributed datasets required to construct these models. While the movement towards open data is recognized as a major impetus for basin-scale model development, some of the datasets required to construct large-scale integrated models are still not widely available. Based on a preliminary investigation of data availability for the GLB and Southern Ontario, it is apparent that the principle data gap relates to the lack of spatially extensive and vertically resolved hydrostratigraphic characterization within the Phanerozoic and Quaternary sedimentary units. Accordingly, a GLB or Southern Ontario focused integrated hydrologic modelling initiative would need strong collaborative support from specialists familiar with the regional geology.

Contents

1. Introduction

The Geological Survey of Canada (GSC), which is part of the Earth Sciences Sector of Natural Resources Canada (NRCan), has a mandate to complete thematic groundwater studies and mapping of 30 key Canadian Aquifers. As part of the Groundwater Geoscience Program, this theme has a 5-year time frame (2014-2019) with expectations to deliver new, innovative science on aquifers to support economic prosperity for Canada.

The long term viability of the Canadian economy is dependent on access to a sustainable water supply. In the 21st century, increasingly intense land use associated with population growth combined with multiple and often conflicting demands on water resources, necessitates an increased awareness and understanding of water from the local to national scale. There is also increasing awareness of the need to balance consumptive water use (i.e. municipal, agricultural and industrial) with the water requirements of healthy and sustainable ecosystems that include wetlands, and aquatic and riparian habitats that are dependent on surface water baseflow levels. In the Canadian context, this requires collaboration from all levels of government from municipal to federal, as well as agricultural and industrial interests.

Within North America, the Laurentian Great Lakes are widely recognized as a crucial water resource facing pressure from a number of stressors, including population growth, agriculture, and climate change. The Great Lakes Basin (GLB) catchment area covers approximately 766,000 km^2 including 244,000 km^2 of water (EPA, 2015), and approximately 80,000 km^2 of the GLB lies within the Phanerozoic Basin in Southern Ontario (Figure 1). The Great Lakes are an extremely important global resource as they contain approximately 21 % the earth's fresh surface water (GLERL, 2014) and 33 million inhabitants, including 9 million Canadians. The GLB is also an important agricultural region as it accounts for approximately 7 % and 25 % of the respective annual US and Canadian agricultural production (GLCR, 2013).

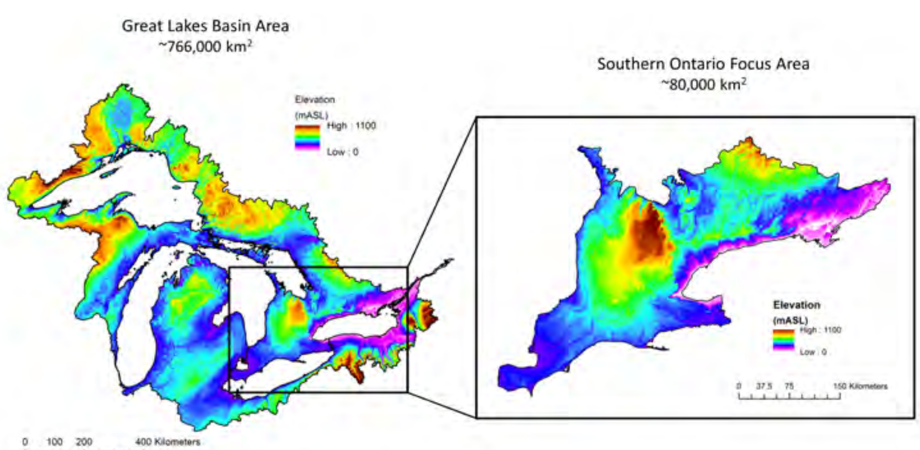

Figure 1. Spatial extent and topographic profile of the Great Lakes Basin (GLB), and the Southern Ontario Phanerozoic Basin that lies within the GLB.

Across the GLB there are a wide range of geological landscapes in which the relative impacts of groundwater-surface water (GW-SW) interactions on water supplies, surface water quality, and ecosystems are of great importance, and are yet poorly understood. In fact, the need for better information regarding the role of GW-SW interactions in the GLB was underscored by the addition of Annex 8 to the Great Lakes Water Quality Agreement (IJC, 2012). Annex 8 requires the identification of groundwater impacts on the chemical, physical and biological integrity of the waters of the Great Lakes, the evaluation of contaminants, and identification of information gaps and science needs.

When considering how to characterize and quantify surface water and groundwater resources within the GLB, the concept of a regional hydrologic model is particularly attractive, whereby in addition to supporting the mandate of NRCan, stakeholders with other interests (i.e. climate change, drought monitoring, ecosystem goods and services, water quality, cumulative impacts, etc.) could also draw decision support information. In fact, the demand for water resources modelling in the GLB was recently highlighted by Stow (2015), who advocated the need and value of modelling to help understand phosphorous loading of the Great Lakes within the context of the Great Lakes Water Quality Agreement (GLWQA). Also, as noted by Kornelsen and Coulibaly (2014), there is a dearth of information pertaining to the overall water budget within the GLB, and large scale modelling initiatives are needed in order to provide water balance information for smaller scale and higher resolution water resources investigations. In addition to developing the many foreseeable applications for a GLB or Southern Ontario scale model, there are also pragmatic issues relating to information management with such large data-driven initiatives, and accordingly, these issues need to be recognized. Prior to the construction of any large scale hydrologic model, careful consideration must be given to the availability of requisite data, and how a lack of key data could potentially influence the models ability to address specific hydrologic questions. In fact, it is not only large-scale modelling projects where data aspects are crucial, and following upon the extensive Source Water Protection (SWP) program, which involved the construction of smaller watershed and local scale hydrologic models for a number of regions within Southern Ontario, there is a recognized need within Ontario to develop a multiagency approach to groundwater data management. In order to achieve this objective, a framework is needed for the storage, integration and access to data that has been collected by provincial ministries, conservation authorities, academia, and municipalities (Russell, 2015; Russell and Priebe, 2015).

With recognition of the aforementioned challenges, this document develops the context, rationale, and technical framework for developing large-scale modelling platforms for both the GLB and Southern Ontario. This document does not overly focus on any one point, but rather attempts to provide a balanced assessment to guide subsequent initiatives.

2. Geologic Setting of the Great Lakes Basin

The GLB is composed of three major geological provinces, including (1) the Michigan Intracratonic Basin and (2) the Appalachian Foreland Basin, which are divided along the Algonquin Arch; and (3) the Precambrian Canadian Shield which composes much of the near surface geology in the Northern region of the basin as well as the basement rock in the Southern region of the basin (Figure 2). Within Southern

Ontario, the geology is dominated by near surface Quaternary deposits that overlay sedimentary rock formations from the Paleozoic era. The Quaternary sediments found across Southern Ontario, which can range in thickness from several meters up to 200 m (Armstrong and Carter, 2010), are quite varied and reflect the actions of several glacial advances and retreats. As a result, landforms commonly associated with continental glaciation can be found across the region, such as till sheets, moraines, drumlins and eskers (Barnett et al., 1991). Below the Quaternary deposits of Southern Ontario is a sequence of Michigan Basin (Figure 3) Paleozoic strata that were deposited in inland seas under tropical conditions. Consistent with this depositional environment, the Paleozoic strata consist of shale/siltstone/sandstone, carbonates, and evaporites. In Southern Ontario, the Paleozoic succession reaches a maximum thickness of 1400 meters (Armstrong and Carter, 2010), and consists of approximately 42 stratigraphic units, which from a regional-scale hydrogeology perspective, can likely be synthesized into 14 major hydrostratigraphic units (Figure 4). The Michigan Basin is centered in the Michigan Lower Peninsula and consists of a conforming sequence of Cambrian (485 – 541 Ma) to Pennsylvanian (299 – 323 Ma) strata.

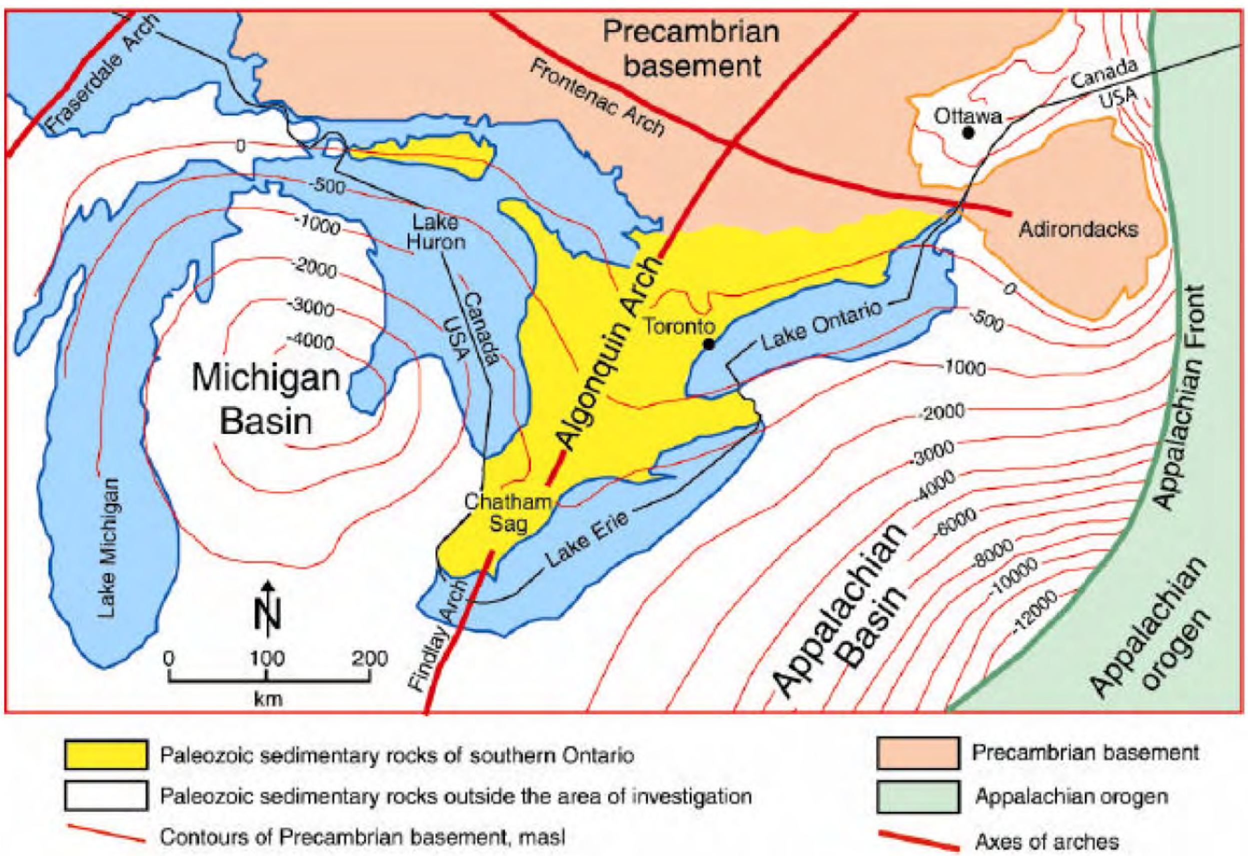

Figure 2. Geological setting of the Great Lakes Basin (from Mazurek (2004)).

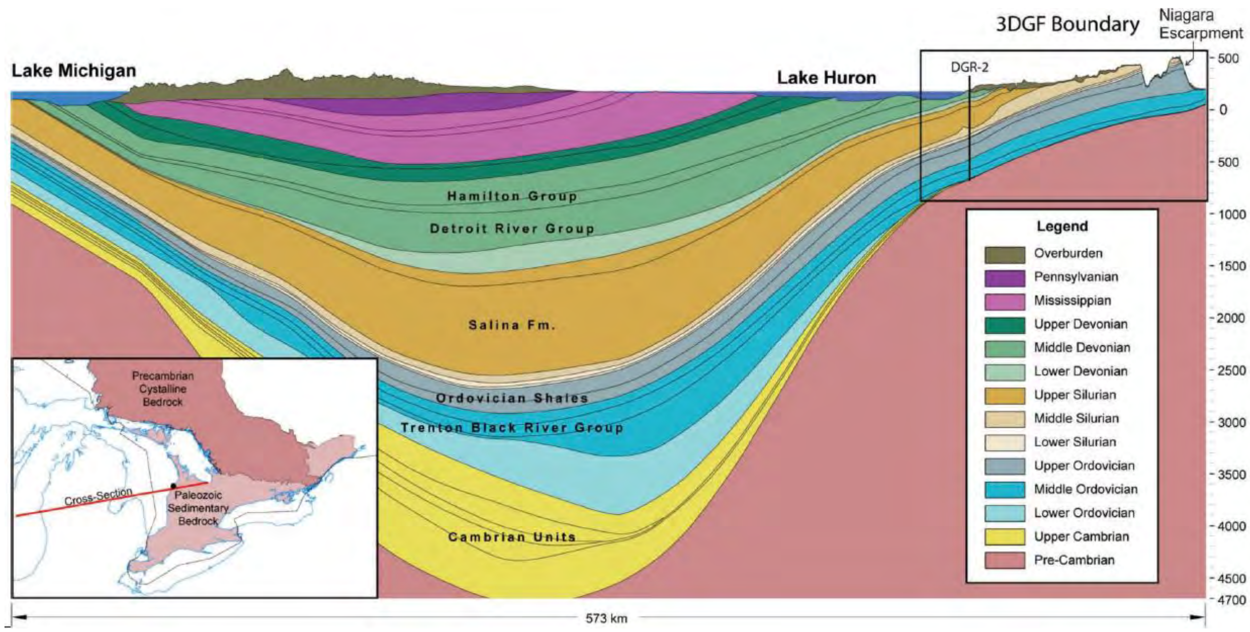

Figure 3. Cross-sectional perspective of the stratigraphic succession within the Michigan Basin (from NWMO (2011)).

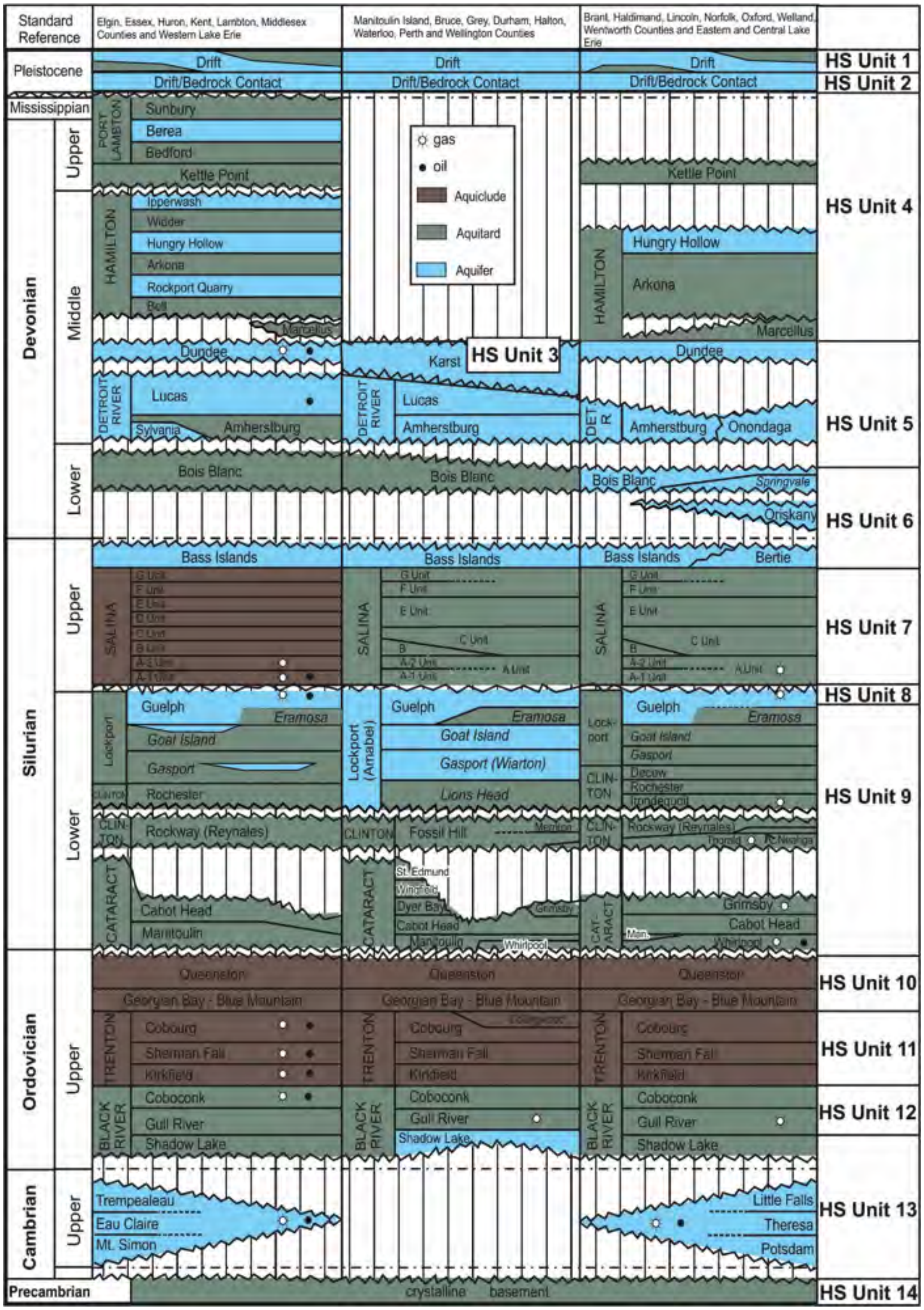

Figure 4. Paleozoic stratigraphic succession in Southern Ontario, with major hydrostratigraphic grouping (from the Geological Survey of Canada, Carter, T., unpublished).

3. Groundwater – Surface Water Interactions in the Great Lakes Basin

Groundwater within the GLB is a large and extremely important resource, with widely varying volumetric estimates of 1900 km^3 to 9200 km^3 in the US portion of the basin alone (Coon and Sheets, 2006). In fact, the highly publicized surface water system in the basin is heavily dependent on groundwater, as groundwater discharge to Great Lakes tributaries is estimated to contribute between 22 % and 42 % of the basin's annual water budget (Holtschlag and Nicholas, 1998). Information regarding the volume of direct groundwater discharge to the Lakes is limited; however, for Lake Michigan alone it is estimated to account for approximately 2 % of the total input, whereas approximately 50 % comes from direct precipitation, and the remainder from tributaries that are often in part fed by groundwater (Grannemann, 2000; Kornelsen and Coulibaly, 2014). It is also important to note that groundwater – surface water interactions within the basin experience significant temporal variability (Kornelsen and Coulibaly, 2014) in response to seasonality, and significant precipitation and snow melt events, with groundwater recharge tending to be highest during the spring and fall periods. Evapotranspiration during the summer is expected to limit groundwater recharge, and reduce groundwater contribution to stream and river baseflow. This is important as many rivers with the GLB are only sustained through the summer months by baseflow. In general, groundwater – surface water interactions within the GLB are known to be an important transient component of the annual water budget (Kornelsen and Coulibaly, 2014), with a high degree of spatial variability, that are inadequately characterized across a range of scales. Capturing the physical processes and conditions that govern groundwater – surface water interactions within a hydrologic model necessitates careful consideration of model requirements, and of how the spatial and temporal resolution employed in the simulation relates to the scale of the question being asked of the model.

4. Fully-Integrated Modelling Rationale

Hydrologic models are applied across a wide range of scales for many different applications. For example, models that are used to support local development and contaminant remediation efforts often encompass less than 10 km^2. Whereas for decision makers seeking to inform water policy at regional, provincial, and national scales, a watershed encompassing a few hundred square kilometers is typically the smallest scale of interest, and depending on the magnitude and scope of the issue at hand, the scale can easily expand to that of a major river basin with well over 100,000 km^2. When considering a hydrologic modelling initiative for a region such as the GLB or Southern Ontario, the scale is obviously large, and for such applications there are conceivably a wide array of models and modelling methodologies available. However, the high physical, temporal, and spatial detail requirements, combined with the need to consider both groundwater and surface-water precludes many potential models from consideration, and it needs to be recognized that many small-scale hydrologic modelling methodologies will not be well suited for modelling at such large scales. In actuality, there are a limited number of modelling options for such an initiative.

As background for a discussion on hydrologic modelling methodologies, Table 1 provides a list of different model classes and examples of common software platforms within each class. When evaluating the different modelling methodologies, it becomes apparent why some models are more appropriate for regional-scale applications than others. For the case of stochastic hydrologic models, which are often used to predict river flow rates under varying precipitation and snow melt conditions, there is a lack of consideration for the underlying physical processes that govern groundwater movement, river flow, and root zone processes, as well as a limited capacity to incorporate spatial variability, that makes them ill-suited for detailed river basin analysis. Groundwater models, while commonly used, do not consider surface water flow processes and are not appropriate for a basin scale analysis where a detailed understanding of surface-groundwater interaction is important. Conversely, stream channel hydraulic models which are commonly used for on-floodplain flood risk assessment, are not appropriate because they strictly consider surface water flow within a river channel – floodplain setting; therefore, by design they do not have the capability to simulate water movement across broad catchment areas. Although it is feasible that separate models from different classes can be explicitly linked (i.e. a groundwater model is coupled to a surface water model) in order to provide a simulation framework that incorporates elements of both groundwater and surface water, such an approach is antiquated given the recent advancements in hydrologic simulation technology.

When considering models that are now commonly used for simulating watershed scale hydrologic behavior, it is important to note the widespread application of distributed hydrologic models. Distributed hydrologic models are commonly used to simulate stream flow, and sediment and nutrient movement in watersheds ranging from tens to thousands of square kilometers, and there are extensive references within the scientific literature of their successful application. It is conceivable that a distributed model (or a series of distributed models) could be constructed for an area the size of the GLB, and while these models would have some utility for assessing sediment and nutrient loading, they would have limited applicability for performing detailed water balance/budget analysis, which is in large part due to their simplistic representation of the groundwater flow system.

As already noted, a regional- or basin-scale analysis of the complex hydrology within the GLB poses a very complex set of challenges to a hydrologic model, which leads to the class of models known as fully-integrated hydrologic models. In comparison to the models mentioned earlier, fully-integrated models are unique in their approach to simulating water movement because they are intended to seamlessly track the movement of water (and in some cases dissolved solutes) between surface water, soil water, and groundwater systems with a physics-based numerical approach. By utilizing the underlying physics to describe water movement, as opposed to the use of empirical or statistical relationships common in the simpler modelling approaches, fully-integrated models are less hindered by the limitations inherent in typical empirical forms of hydrologic process simplification. While historically the strength of the integrated approach towards hydrologic modelling has been well recognized in the scientific literature, these models have also been routinely criticized for their high computational requirements. However, as the widespread availability of high performance computing capabilities continues to increase, so does the applicability of the fully-integrated hydrologic modelling approach towards the 3D dynamical analysis of complex real-world hydrologic problems. As a result, it is now widely regarded amongst the hydrologic modelling community that fully-integrated groundwater – surface water models reflect the 'state of the art' for hydrologic simulation, and that these models are opening up a new frontier in applied hydrological science (Barthel and Banzhaf, 2015). Surface water and groundwater models can be combined in one of two ways to create a integrated model; loosely-coupled, or fully-coupled; where loosely coupled is defined as *"two or more individual models coupled via the exchange of model results, where the output from one model forms the input of the other*"; and fully-coupled is defined as "*equations governing surface and subsurface flows are solved simultaneously within one software package"* (Barthel and Banzhaf, 2015).

Table 1. Hydrologic model classes and sample modelling platforms representing each class.

Model Class	Representative Modelling Platforms
Stochastic Model	WASMOD (Xu, 2002)
Groundwater Model	MODFLOW (Harbaugh et al., 2000), FEFLOW (Diersch, 2002)
Stream Channel Hydraulic Model	HEC-RAS (Brunner, 1995), Mike-11 (Havnø et al., 1995)
Distributed Hydrologic Model	SWAT (Neitsch et al., 2011), HSPF (Donigian Jr et al., 1995)
Loosely Coupled Hydrologic Models	GSFLOW, MIKESHE (Refsgaard et al., 1995)
Fully-Coupled Hydrologic Models	HydroGeoSphere (Aquanty, 2015), OpenGeoSys (Kolditz et al., 2012), ParFlow (Maxwell et al., 2009)

5. International Perspective on Integrated Model Development

The Denmark Experience

Of the available large-scale hydrologic modelling initiatives of national interest from which to draw insight, the best-in-class examples are currently in Europe. The first case to consider is Denmark, which is similar in size to southwestern Ontario, where a national water resources model has been developed to estimate water budgets and to support a groundwater accounting and inventory exercise (e.g., Højberg and Troldborg, 2011), as well as to help address issues such as conjunctive use and climate change adaptation. The Danish groundwater model (DK Model) links with a national database backed by a management initiative to accommodate new geological, hydrogeological and geophysical data, as well to utilize legacy data available in comprehensive geology, soil, topography, river systems, climate, and hydrology databases (Henriksen et al., 2003; Refsgaard et al., 2010).

The Geological Survey of Denmark and Greenland started construction of the 43,000 km^2 DK Model in 1996 (Henriksen et al., 2003). The DK model is based on a coupling of MIKE SHE and MIKE 11 (Graham and Butts, 2005) and incorporates a simplified vadose zone, 3D groundwater flow, and a river package for stream routing (Refsgaard et al., 2010). The DK Model underwent a major update between 2005 and 2009 in order to improve the hydrostratigraphic representation. Throughout the update process, attempts were made to also improve the links between model input data and the national databases, with input from key stakeholders (Højberg and Troldborg, 2011). As noted by Refsgaard et al. (2010), the national model has provided secondary benefit by serving as a 3D database, and as a result, additional benefits are gained by using it as a platform to enhance conceptual interpretation of the hydrologic/hydrogeologic system.

Similar to Southern Ontario, much of the hydrogeologic data that is collected in Denmark is collected as part of local studies. Incorporation of local-scale data into the regional model is facilitated by a workflow (Figure 5) that allows users to access a particular local model, update the conceptualization, and push the changes back to a central database for review and incorporation into subsequent releases of the regional-scale DK Model (Højberg et al., 2013). This release cycle approach of the national model ensures that as new local knowledge is collected, it eventually finds its way into national model. The process of data and model storage/access/feedback is further illustrated in Figure 6, where the interface methodology between the end-user applications and the central repository is depicted. In order to maintain spatial resolution that aligns with local-scale modelling from which details of the national model are in part derived, the DK model is constructed at a scale of 100 x 100 m, while the simulations are conducted with a 500 x 500 m grid (Refsgaard et al., 2010). Through a connection with the national water well database, the Denmark national model also includes all groundwater abstractions, which amounts to over 40,000 well screens (Refsgaard et al., 2010).

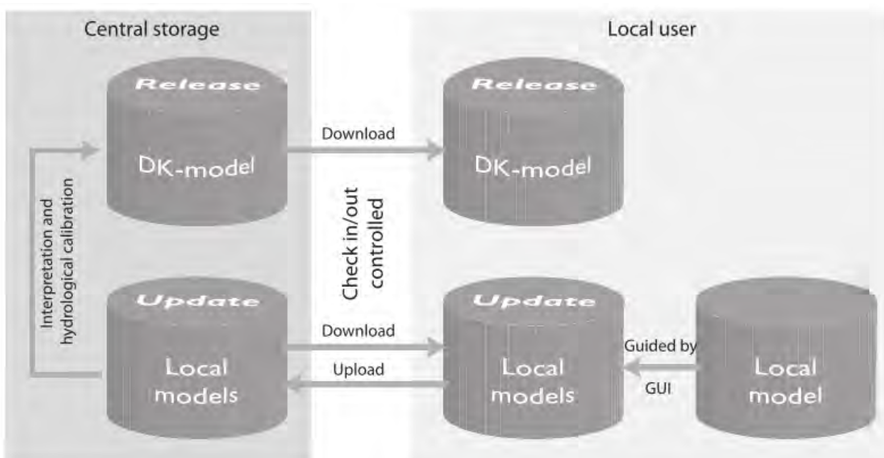

Figure 5. Workflow showing how local updates are pushed to central storage and eventually incorporated in to the Denmark regional model (from Højberg et al. (2013)).

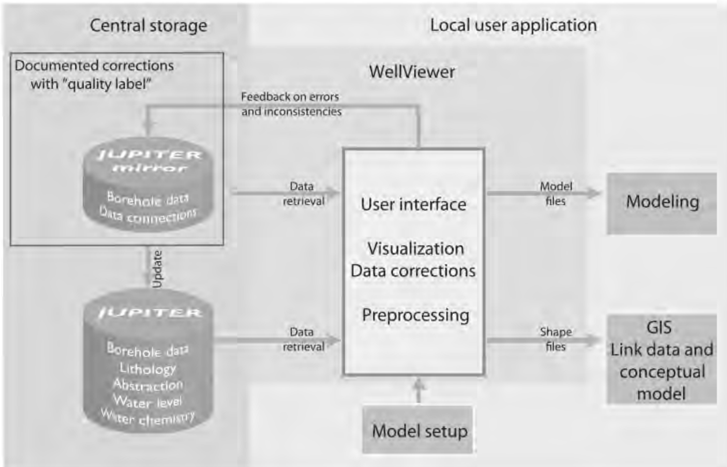

Figure 6. Framework for retrieving data from the central data, setting up a model, and pushing corrections/updates back to the central database (from Hojberg et al., (2013)).

The Netherlands National Hydrological Instrument (NHI)

Probably the earliest conceptual form of a national-scale hydrology model was derived for the Netherlands (Abrahamse et al., 1982; Wegner, 1981) in order to manage issues such as salinity and thermal pollution, as well as to help understand the long-term sustainability of their groundwater resources under competing demands from agriculture, industry and the ecosystem. Since its original inception, the Netherlands model has evolved considerably, and is now a consensus driven national water resources management platform that provides open access to model data, model results and software (De Lange et al., 2014), and is serving additional purpose as a tool to inform policies related to climate adaption measures (Prinsen et al., 2014). Instead of being a fully-integrated hydrologic model, the NHI (Figure 7) comprises a complex coupling of five individual hydrologic models that each represents different components of operational water management, the hydrologic cycle, and salt transport. Because of the extensive database development, linkages to national and regional water authorities, multi-stakeholder applications, and widespread long-term collaboration efforts that went into its development, the NHI is a good example when considering opportunities for the GLB and Southern Ontario. Additionally, because the NHI also considers solute (salt) transport on account of the sea water influences, there is potential insight to be gained on how nutrient issues could be approached within a GLB and Southern Ontario modelling context. The five hydrological models utilized in the NHI function at different temporal and spatial scales, and are explicitly coupled. Per De Lange et al. (2014), the function of the five models (Figure 7) is as follows, with each considering both water flow/balance and salt concentration/balance components:

i) Surface Water model for Optimized Distribution (SWOD): This model comprises the major surface water bodies and is used operationally to manage water redistribution during dry periods.
ii) Surface Water model for Sub-catchments (SWSC): This is a sub-catchment scale water balance model that determines rural water availability and demand.

iii) Soil Vegetation Atmosphere model for the Transfer of Water (SVAT): This is a 1D Richards' equation based model to calculate subsurface - surface water exchange, with consideration for evapotranspiration.

iv) Groundwater Model (GW) - Modflow: This model is used to calculate simple groundwater flow as well as density dependant groundwater flow and salt transport.

v) Surface Water Flow and Transport model (SWFT): This 1D model is used operationally to calculate surface water levels, flow rates, salt concentrations, and temperatures during dry periods.

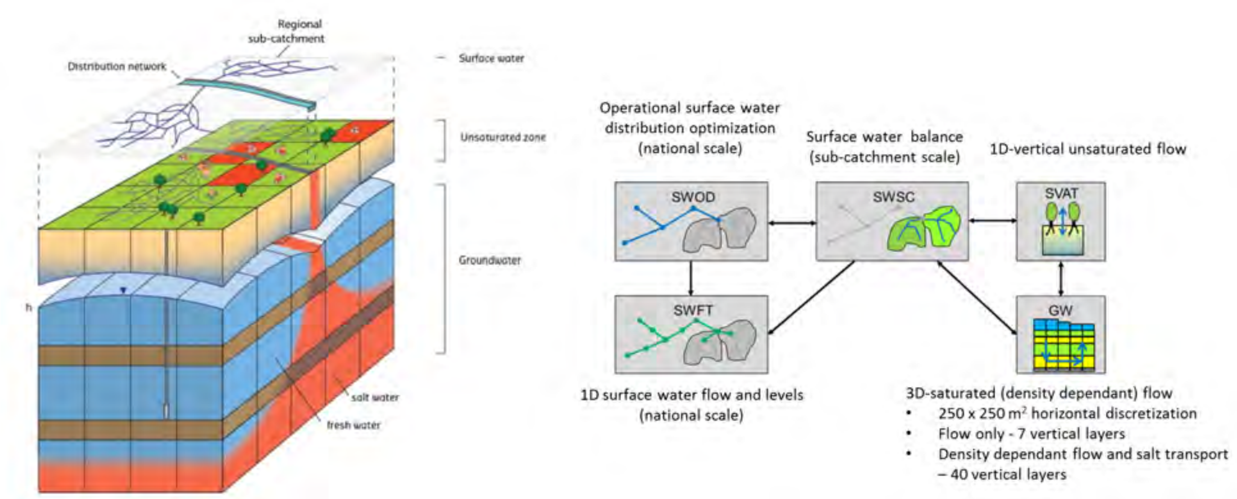

Figure 7. Schematic representation of the different hydrologic compartments considered within the Netherlands Hydrological Instrument and its five individual modelling components (modified from De Lange et al. (2014)).

The New Zealand SMART Portal

As an indication of the growing global interest in creating standardized national-scale water resources assessment platforms, New Zealand has also launched an initiative to harmonize groundwater data collected by different regional management districts into a standardized portal that is OGC and ISO compliant (Kmoch et al., 2012). This portal, known as the SMART project (www.smart-project.info), aims to develop a water resources data management framework that will connect scattered surface water and groundwater data sets and provide easy access. This program, initiated in 2011, is funded by the New Zealand Ministry of Business, Innovation & Employment, and will continue until 2017. In addition to providing access to data, the web-based portal will support 3D and 4D visualization of geospatial data (Kmoch and Klug, 2014). Figure 8 presents the conceptual architecture of the SMART portal.

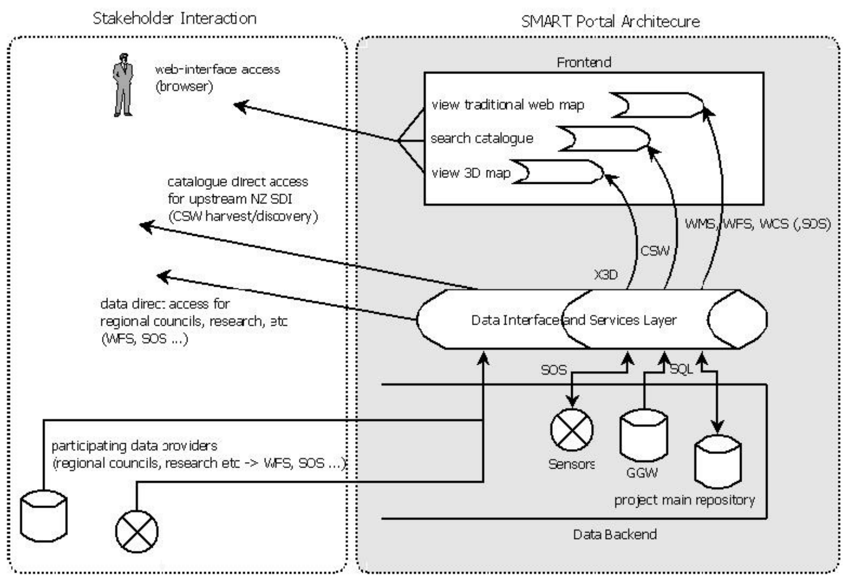

Figure 8. Conceptual architecture of the New Zealand SMART portal (after Kmoch et al. (2012))

Insights from Germany

Although not as far along the path towards a national hydrologic modelling initiative as Denmark or the Netherlands, Germany has also recognized the potential opportunities and benefits of large-scale modelling. In fact, applications for modelling are forefront in the white paper (Teutsch and Krueger, 2010) produced by the Helmholz Center for Environmental Research (UFZ), where priority research needs within the German water research community are identified, and where strong emphasis is placed on building collaboration among multiple centers of excellence and specializations so that the scientific challenges associated with emerging issues in water resources can be met. Within the UFZ synopsis, the utility of models for helping to develop increased science-based understanding is consistently highlighted. One of their six priority research fields is entitled "*A Community Effort Towards Model Development and Data Integration for Water Science*", while applications for integrated hydrologic modelling are interspersed within the other five priority research fields as well. The insight provided by Teutsch and Krueger (2010) clearly shows that within Germany, the leading water resources scientists identify models, and in particular large-scale models, as tools to help assimilate knowledge. In particular, they recognize that common modelling tools utilized across a number of research groups/institutions will strengthen their research community; however, there must be stable ongoing funding in order to ensure the long-term stability of such initiatives. They also identify that managing data in an effective manner is critical for large modelling initiatives to be successful, as data integration and assimilation are becoming increasingly important tasks in the hydrologic sciences. Because the requisite data is often held by a number of institutions and is of variable quality, a centralized database that employs common data formatting along with comprehensive data screening information would be required. From the perspective of hydrologic process consideration, for common modelling tools to be feasible across disciplines and across spatial and temporal scales, it is important that water fluxes related to hydrologic and ecologic functioning are represented. Accordingly, precipitation, evapotranspiration, surface-runoff, infiltration, soil water movement, groundwater, and surface water dynamics all must be considered, which implies a fully-integrated modelling approach.

6. North American Integrated Modelling Initiatives

The scale at which fully-integrated hydrologic models are being applied continues to grow as computational power and numerical methods improve, and two recent very large-scale North America focused demonstrations have been recently completed by Chen (2015) and Maxwell et al. (2015).

In Chen (2015), HydroGeoSphere (Aquanty, 2015) was used to assess the impact of climate change on water resources across the entire Canadian continental landmass by evaluating spatially distributed watertable depths, groundwater recharge-discharge fluxes and flow rates in major rivers under different future climate projections. The 3D model domain, which includes most of Canada and the northern part of the United States, covers an area of approximately 10 million km^2. Since it is not currently possible to explicitly define local-scale subsurface detail at such a large scale, only the major hydrostratigraphic and hydrologic features were incorporated; including unconsolidated sediments, sedimentary rocks, basement rocks, and permafrost. These units were parameterized using available Canadian-scale and regional data sets. Local mesh refinement allowed for representation of streams and lakes while minimizing the overall node count in the finite element mesh. The completed 3D model consisted of approximately 1 million nodes and 1.8 million elements in the unstructured finite element mesh, and Figure 9 shows the spatial extent of both the HydroGeoSphere model and the ensemble of regional climate models that were used to drive the hydrologic simulations.

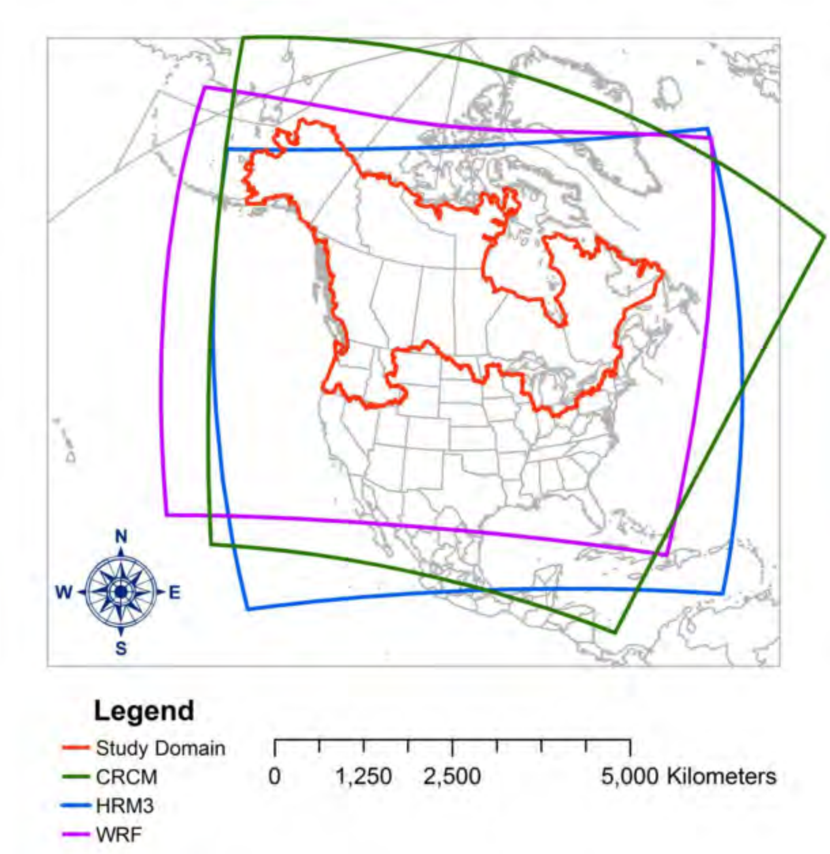

Figure 9. HydroGeoSphere model domain (red) and the regional climate model extents used to drive the HydroGeoSphere simulations (after Chen (2015)).

At a scale similar to that of Chen (2015), an integrated surface and subsurface model for most of the continental United States was developed using Parflow (Kollet and Maxwell, 2006). The Parflow model has a domain area of 6.3 million km^2 (Figure 10), consists of 31.5 million computational elements, and includes spatially-variable subsurface and near surface hydraulic properties. The Parflow model was primarily focused on historic conditions, and simulation results for the historic period were compared to observed stream flows and groundwater levels.

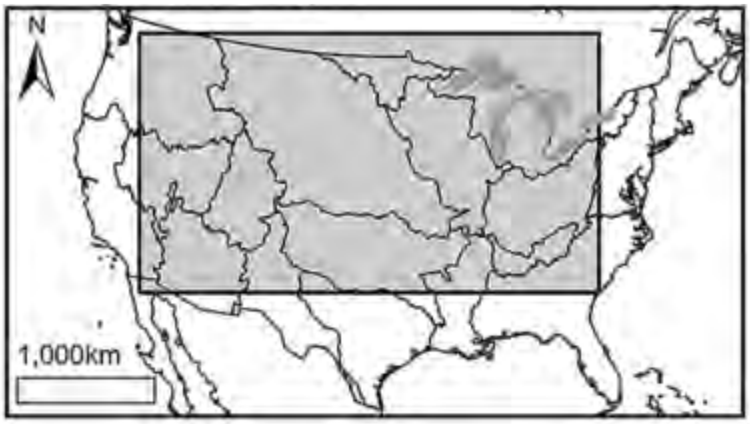

Figure 10. Extent of the continental United States Parflow model domain (from Maxwell et al. (2015)).

Fully-Integrated Regional-scale Modelling Projects Underway in Canada

While there are numerous examples in the scientific literature involving physics-based, fully-integrated hydrologic models being applied at high resolution to watersheds on the order of 10s to 100s of km^2, applications at scales greater than 10,000 km^2 are notably scarce (Barthel and Banzhaf, 2015). Recently however, work in Canada (Figure 11) has been initiated to extend fully-integrated modelling out to scales greater than 100,000 km^2 in order to simulate transient surface water and groundwater dynamics within a number of major river basins as follows:

- Athabasca River Basin (ARB)
    - The focus of the modelling work in the ARB, which entails 159,000 km^2, is to investigate the impact of climate change on surface water and groundwater resources, with a particular focus on base flows in the downstream region. Through the ARB work, a seamless coupling strategy was developed to interface HydroGeoSphere with the Weather Research and Forecasting Model.
- South Saskatchewan River Basin (SSRB)
    - A model of the 146,000 km^2 SSRB is currently under development to assess flood and drought impacts on agricultural sustainability.
- Assiniboine River Basin
    - Modelling of the 155,000 km^2 Assiniboine River Basin commenced in early 2016. This project is currently focussed on understanding the impacts of land-use change on large-scale hydrologic characteristics of the basin including flood and drought resiliency.

High-resolution fully-integrated modelling at these scales has been made feasible largely because of advancements in numerical solution methodologies, including model parallelization, and access to high-performance computational resources. However, there is also a significant level of data required in order to parameterize these models, much of which is becoming increasingly available from federal and provincial institutions. Within Canada, there is also growing interest to utilize basin-scale fully-integrated hydrologic models across a range of different government, academic, non-profit, and private industry stakeholders, and in the case of the SSRB and Assiniboine River Basin projects, the models are being designed for long-term multi-stakeholder functionality.

Figure 11. Geographical extent of the three major Canadian river basins for which fully-integrated hydrologic models are currently under development.

7. Drivers for a Regional or Basin Scale Integrated Hydrologic Modelling Platform

The drivers for developing integrated hydrologic models for Southern Ontario and/or the GLB relate to the needs of a wide variety of stakeholders that include provincial, US state, and federal agencies that are mandated to understand and protect water resources within the basin. Within Ontario, a regional platform could serve the Ministry of Environment and Climate Change (MOECC) in their efforts to provide science-based guidance to the provincial government on water resources related issues pertaining to climate change (Expert_Panel, 2009) and large-scale groundwater and surface water issues (e.g. management of water permits). For the Ontario Ministry of Natural Resources and Forestry (MNRF), a regional modelling platform could support the drought and flood forecasting provided by their Surface Water Monitoring Centre (Kenny et al., 2015). For the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), a regional modelling platform could be used to assess long-term agricultural sustainability, potential cropping and agronomic trends under different future climate scenarios, and to support basin scale irrigation management decisions, as well as to help guide large-scale beneficial management practices targeting off-field nutrient losses. For the Ontario Geological Survey (OGS) as well as the GSC, a regional-scale model could become a platform to store large-scale hydrostratigraphic data and to evaluate large-scale groundwater flow and storage characteristics, as well as groundwater – surface water interactions across Southern Ontario. For the Canadian and American federal governments, a GLB-scale model could help serve their obligations to the Great Lakes Water Quality Agreement (GLWQA) in a number of ways that are concomitant with the needs of the other potential stakeholders; as such, a regional- or basin-scale modelling effort could provide far reaching benefits. Because these benefits stem from a singular collaborative effort, there is also a strong economic incentive to develop a large-scale model to serve as a standardized multi-user platform, as the development and maintenance costs could be shared amongst many groups, duplication of efforts could be minimized, and best-in-class science could be capitalized on in order to provide a broad public benefit. Some of the key obligations/initiatives that a GLB model could contribute towards are as follows:

- Provide an impetus to develop a central publically accessible database for geological, groundwater and surface water related information for Southern Ontario (regional scale) or the entire GLB.
- Serve as a common adaption and mitigation planning tool for water resources related risks, including those from climate change, and to provide best-in-class science to support policy and decision making.
- Provide a platform to generate hydrologic scenarios for which extreme weather events such as floods and droughts can be assessed for their regional- or basin-scale impacts.
- From a hydrologic modelling perspective, a model at the scale of Southern Ontario or the GLB could be used to provide external boundary condition information to smaller scale watershed or sub-watershed models developed to serve local water resources investigations.

With respect to the GLWQA, a basin scale model could be used to support:

- Annex 4 – Nutrients, by evaluating loading characteristics and cumulative impacts on water quality.

- Annex 8 – Groundwater, by providing a large-scale platform to assess information gaps and science needs, as well as to investigate climate change impacts on groundwater.
- Annex 9 – Climate change, by providing a hydrologic modelling platform to test the impact of different regional climate projections on surface and groundwater resources at different spatial and temporal scales.
- Annex 10 – Science, by serving as a standardized platform to assess emerging environmental concerns, help identify science priorities, and foster bi-national collaboration on science efforts.

8. Science and Technical Challenges

There are a number of challenges that will need to be addressed when planning and constructing a multi-stakeholder hydrologic modelling platform, and an associated standardized data repository at the scale of the GLB or Southern Ontario. When assessed both individually and collectively, these challenges are by no means insurmountable; however, due diligence will be required to ensure a successful outcome is not hindered by hurdles that may be viewed as inconsequential early on. It goes beyond the scope of this document to delve into great detail for each of the potential issues, and accordingly the following discussion should be viewed as a high level overview. For the sake of classification, we have grouped the issues in three broad categories relating to modelling, data, and stakeholder acceptance and utilization. It is also important to note that there is tremendous insight to be gained from the efforts and visions in both Denmark (Højberg et al., 2013; Refsgaard et al., 2010) and the Netherlands (De Lange et al., 2014), and that some of the highlighted technical challenges are currently being addressed in the integrated modelling initiatives underway for Western Canada.

Modelling Issues

Perhaps one of the most significant issues related to the actual model development is associated with spatio-temporal resolution, and ensuring that the model applications are commensurate with model resolution, and the objectives of individual stakeholders. For instance, a model constructed at the scale of the GLB would have adequate spatial resolution to address large-scale issues relating to climate change, and basin/sub-basin scale water balance and groundwater – surface water interaction; however, it may not have adequate resolution to address water resources issues at the scale of individual well fields or sub-catchment areas. Furthermore, it may not be feasible nor warranted to incorporate the full level of hydrostratigraphic or near surface soil and land use detail into a basin-scale model, while local-scale modelling applications would most likely require such detail. At what scale water abstractions become relevant to the modelling results would also need to be considered, as incorporating each individual abstraction characteristic in a GLB scale model could prove to be an arduous and expensive task with little net benefit. On the other hand, at the scale of Southern Ontario (or smaller), such detail could be important. The spatial scale and level of complexity of potential solute/chemical transport applications is also a question to be addressed, as transport at the basin scale could prove problematic, while at progressively smaller scales (i.e. sub-basin – watershed – catchment), increasing levels of transport complexity could be incorporated if adequate source characterization and geologic (perhaps even hydraulic property heterogeneity) detail is available. With respect to the aforementioned issues, it is important to note that development efforts are currently underway to facilitate multi-model nesting within a single fully-integrated hydrologic modelling platform. Model nesting, once developed and implemented, will facilitate the sharing of model input data across multiple sub-basin/watershed scale models that are contained within a basin-scale model, and will allow boundary condition information (such as regional groundwater heads and surface water flow rates) to be shared across models of different scales.

Data Issues

Dealing with the issues surrounding data requirements and data management will require a strong collaborative effort and commitments amongst the different stakeholders, and would also likely benefit from involving external specialists who could manage or advise on issues relating to database management and cloud-based resource utilization in order to minimize costs while maximizing efficiency and flexibility. There are many significant organizational and technical issues related to managing a wide range of datasets originating from multiple organizations. For example:

- Direct links would need to be established between the model database and external databases maintained by different agencies, or a new organization that holds responsibility for data management could be created. Either way, strong long-term institutional support for data contribution, management, and updating will be required.
- Standardized data processing and quality assurance processes would be required to translate raw data into model data.
- The model database would need to be reviewed and updated at some regular interval, and testing would need to be conducted in order to assess the overall significance of such updates.
- It may make sense to maintain a central public domain hydrostratigraphic data model that is separate from the integrated hydrologic model.
- A standardized raw-data and model-data visualization portal would be required that perhaps incorporates customized dashboards designed for individual stakeholder objectives.

In addition to the aforementioned points of consideration, there are a number of more detailed questions relating to data processing, platform design, and end user application that would need to be answered, for example:

- Would a multi-user interface be required that allows concurrent users to run multiple scenarios?
- Would future climate projection and historic weather databases need to be developed and then linked to the modelling platform for multi-user access?
- Are all the public domain datasets that could support such a modelling platform available (i.e. physical characterization, observational/monitoring, and anthropogenic influences)?
- What software and service options are available to support such a platform?
- What type of computational resource would be required to host the platform and run the simulations?

Acceptance and Utilization Issues

As per Refsgaard et al. (2010), credibility of large-scale multi-user hydrologic models is an important consideration, and therefore quality assurance, geologic and parameter uncertainty (both qualitative and quantitative) analyses, and stakeholder participation are key considerations for building widespread confidence. Furthermore, these types of large, multi-objective modelling platforms need to be viewed as living projects that are continuously updated, with ongoing calibration and validation efforts, and with continued scientific development in order to ensure their long-term relevance. It can also be envisioned that by having a GLB or Southern Ontario scale hydrologic modelling platform out in the public domain and supported by key government agencies that hold surface water and groundwater related mandates, there could be an increased level of acceptance and utilization within the larger water-resources community, as such a platform would be considered non-proprietary, standardized, and well supported.

9. Administration and Funding

The experience gained through the Source Water Protection program in Ontario, as well as other international regional modelling exercises (e.g. Højberg et al. (2013)) highlights that an appropriate administrative and funding framework needs to be in place at the initiation of the project. Having these resources in place from the outset ensures the long-term success and sustainability of the program. As identified by Refsgaard et al. (2010), the driving force behind the Denmark model was multiple levels of water management authorities, policy makers, and legislators, who provided substantial funding. The Denmark motivation was in part led by their belief that best-in-class science and innovation should be applied to water resources issues. Similarly, the Netherlands National Hydrologic Instrument is a collaborative funding and technical effort from their national research institutes and regional water authorities, and is funded on the order of about 1M€/y (De Lange et al., 2014). Some of the key administration challenges are identified as follows:

How will the project be funded in the short-, and medium-term?

- Reviewing the geographic extent and the key stakeholders involved should drive the decisions surrounding funding. For example: the GLB model could potentially be funded by Federal, Provincial and State level agencies from both Canada and the United States, whereas a Southern Ontario model is perhaps more appropriately funded by Canadian Federal and Provincial government sources.

How should data and model results be managed?

- At the outset of the project, a comprehensive data management framework should be established for both input data, as well as model results. As noted above, responsibilities and procedures for data/results compilation and management need to be recognized. Adherence to this framework is of utmost importance to ensure consistency of model results.

- Where applicable, international standards, such as those developed by the Open Geospatial Consortium (http://www.opengeospatial.org/) should be adopted. An example of such implementation in Canada is the Groundwater Information Network (GIN).

Managing the model updating process

- Diligent tracking and documentation during the model update process is critical so that it can easily be determined which model was used to generate a particular set of results. This process of tracking model updates could be managed using version control software.

Long-term platform funding and management

- Who would handle the data management and modelling platform over the longer term, and who would be able to commit stable long-term funding to the initiative in order to ensure its long-term success? With this question in mind, there would need to be careful consideration given to the respective roles of government agencies (federal, provincial, and state), and private industry over the longer term, given that government commitment and funding will be invariably required to ensure long term success, and that some level of ongoing support from private industry specialists will be required. With the previous point in mind, it is also important to note that it will be the government participants who are best positioned to deliver the platform into the public domain, and as such it could appear logical that a government agency (or government led consortium) would lead long term management.

10. Data Availability for a Great Lakes Basin Integrated Modelling Initiative

One of the largest challenges associated with constructing regional- or basin-scale integrated hydrologic models revolves around identifying and obtaining suitable datasets, which are often sourced from a variety of different organizations. With the push to make government data publically available within Canada (e.g., Ontario Open Data Initiative) and around the world, it is becoming increasingly feasible to gather requisite data for large-scale trans-border hydrologic models from internet sources. Within Canada, a number of data portals exist for access to data pertinent to groundwater and surface water modelling, which are maintained by provincial and federal agencies respectively. The primary Ontario example is Land Information Ontario (LIO) which is maintained by the Ministry of Natural Resources and Forestry. LIO is a site that supports partners across Ontario to create and provide access to a suite of data. Provision of data to LIO is open to public organizations willing to become part of the Ontario Geospatial Data Exchange, with 656 members as of September 2015, and include participants from municipal, provincial or federal government, First Nations, conservation authorities, public health units, non-profit organizations, academia, and public utilities. In addition, geological data products for Ontario are made available by the Ontario Geological Survey through Geology Ontario and OGSEarth (http://www.geologyontario.mndm.gov.on.ca). OGSEarth is a website for accessing OGS geoscience data using applications compatible with Keyhole Markup Language (e.g., Google Earth). At the Canadian Federal Government level, a pertinent website is the Groundwater Information Network (GIN) which is the primary portal for data collected by the Groundwater Geoscience Program of the GSC. GIN also reserves water well data, monitoring well data and a variety of geological data from provincial ministries and the United States Geological Survey (USGS).

The following provides an overview of the current availability of data required to construct a GLB scale hydrologic model where both the surface water and groundwater flow systems are considered. For modelling at the scale of Southern Ontario, it is important to note that there are a number of additional provincial level datasets that could be considered.

Topography

The Shuttle Radar Topography Mission (SRTM) is noted for its global topography data coverage. Prior to 2014, uniform SRTM coverage for the GLB was available at approximately 90 m spatial resolution (30 m in US and 90 m in Canada) (Figure 12); however, since, 2014, 30m resolution data has been made available almost worldwide.

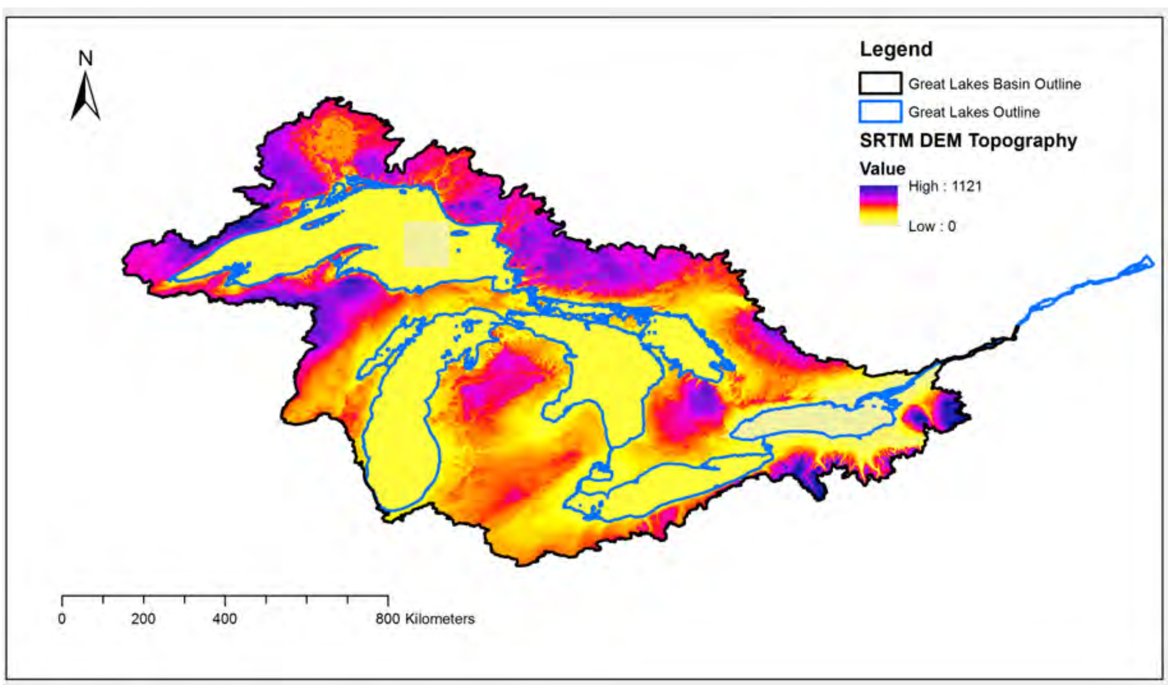

Figure 12. SRTM 90 topographic representation for the GLB, with elevation in meters (Jarvis et al., 2008).

One of the challenges in working with SRTM data in hydrologic models is that surface water body characteristics may be such that artificial water bodies and drainage networks form in the simulations due to artifacts in the digital topographic representation. Accordingly, SRTM data is commonly subject to a series of automatic and manual corrections in order to create a digital topography that can realistically emulate natural drainage. For large-scale hydrologic modelling applications, there are publically available digital elevation models that incorporate hydrologic correction algorithms, of which HYDRO1k (which is derived from the USGS GTOPO30 30 arc-second DEM) and HYDROSHEDS (Lehner et al., 2008) (Figure 13) which is primarily derived from the SRTM 90 m DEM are two widely recognized products.

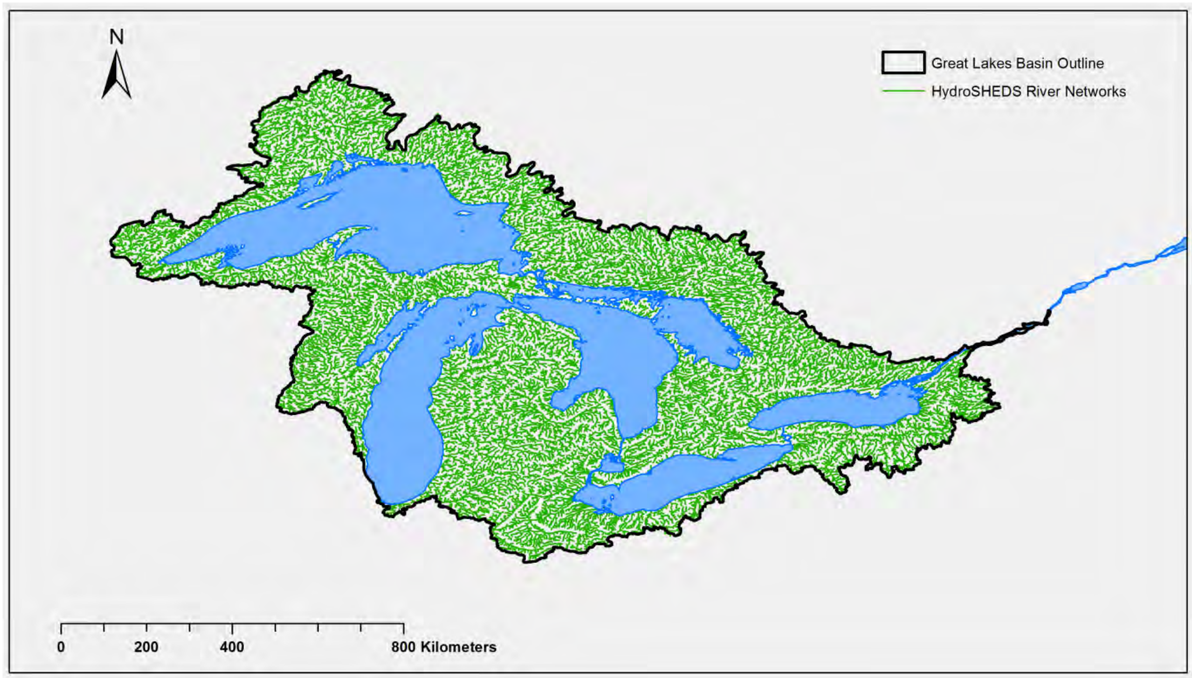

Figure 13. HYDROSHEDS river network for the GLB (Lehner et al., 2008).

Upon a cursory evaluation of both HYDRO1k and HYDROSHEDS in the Grand River Watershed, a 7000 km^2 watershed within Southern Ontario that drains into Lake Erie, it is evident that HYDROSHEDS provides superior resolution (Figure 14) and should therefore be the DEM of choice for a GLB hydrologic model. As noted in the HYDRO1k documentation (https://lta.cr.usgs.gov/HYDRO1KReadMe), the resolution of the HYDRO1k drainage network is constrained to a minimum catchment area of 1000 km^2, which is a limiting factor for hydrologic modelling in regions such as the GLB where surface water-groundwater interactions controlled by local topography are a very important component of the water balance.

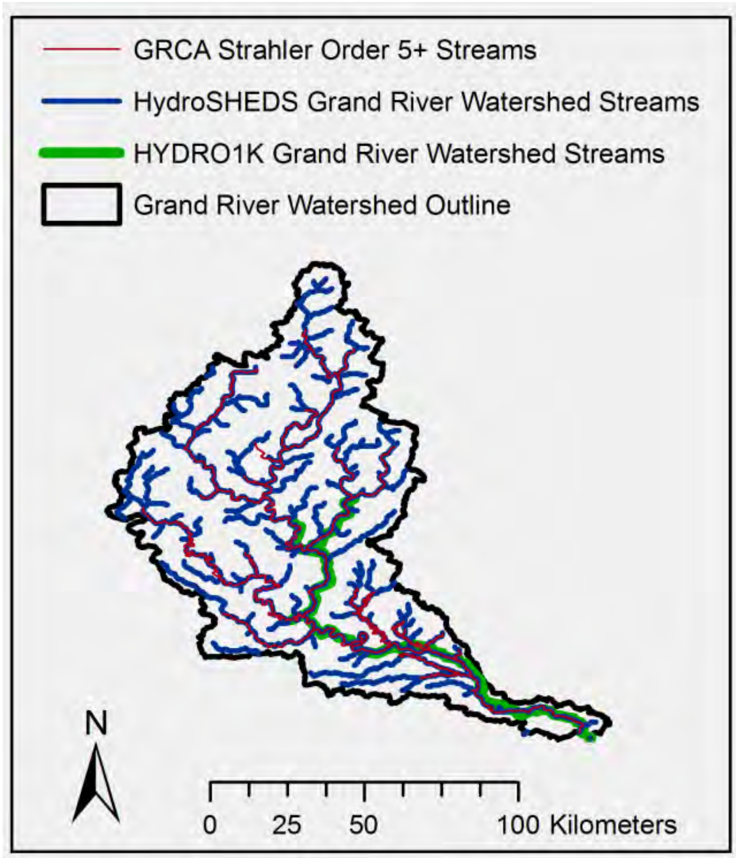

Figure 14. Visual comparison between the stream networks defined by the Grand River Conservation Authority (Strahler order 5+), and the HYDROSHEDS, and HYDRO1k datasets.

Bathymetry

Bathymetric detail (Figure 15) of the Great Lakes is imperative for realistically simulating the surface water system within the GLB, and especially for simulation objectives that pertain to lakes levels. Bathymetry data would need to be stitched into the HYDROSHEDS DEM in order to create a top surface for a GLB integrated model.

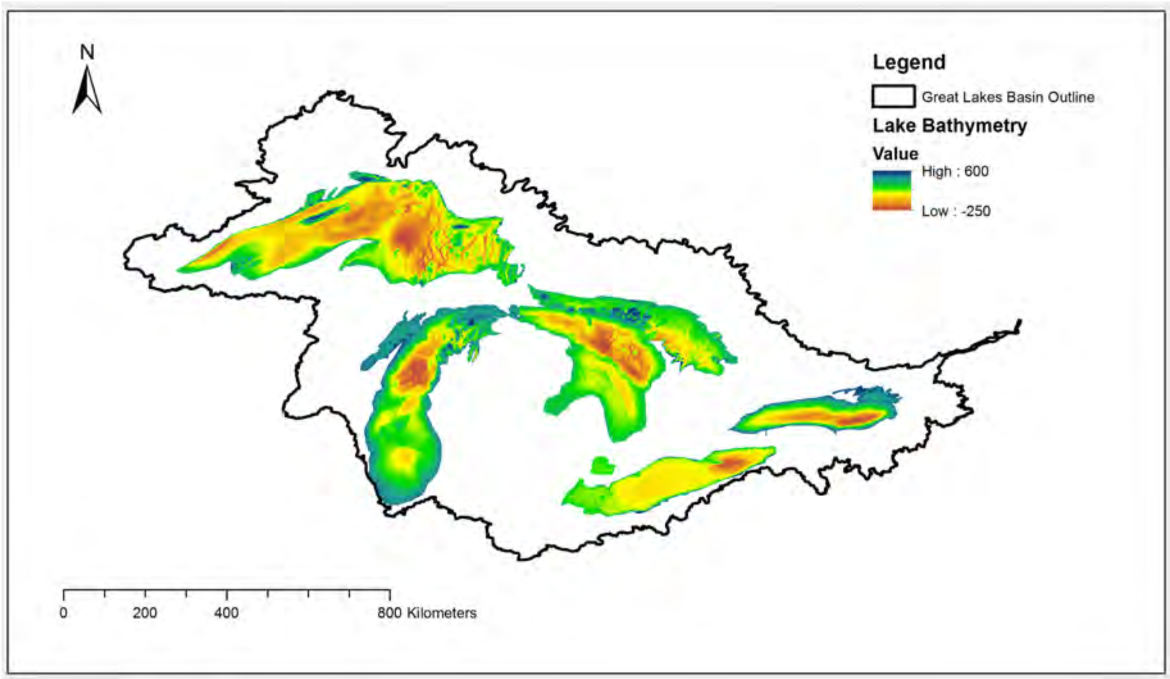

Figure 15. Great Lakes bathymetry (GLIN, 2012).

Land Use

Land use description is another important feature of large-scale integrated hydrologic models due to its strong influence on both evapotranspiration and surface water runoff characteristics. Within both Canada and the United States, there have been concerted efforts to characterize land use distribution at a high level of spatial resolution. The Canadian effort is being led by Agriculture and Agri-Food Canada (AAFC) and has resulted in annual land use distribution maps for most of the agricultural area within Canada since 2011, at 30 m resolution, which is ideal for model domains that lie entirely within Canada. For the United States, 30 m generalized land cover data is available from the USGS National Land Cover Database. For full coverage of the GLB, homogenized land use data (Figure 16) is available for years 2005 and 2010 at 250 m resolution (NALCMS, 2005), which is more than adequate for a basin-scale integrated hydrologic model.

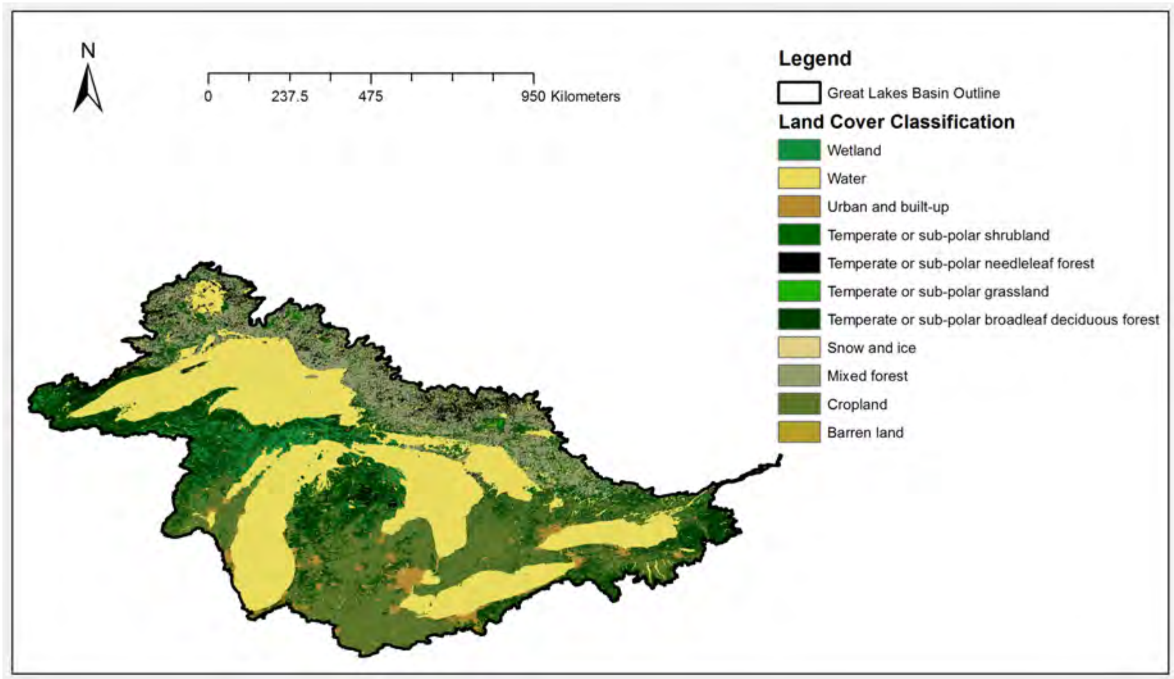

Figure 16. Land cover description for the GLB at 250 m resolution (NALCMS, 2005).

Soils

Soils data are another key component for parameterizing the near-surface region of integrated hydrologic models, as soil physical characteristics often play a significant role in infiltration/surface runoff relationships and the evapotranspiration process. Furthermore, from an agro-chemical and nutrient transport perspective, the physical and chemical properties of soil combined with land use can have a strong influence on the potential risk that agriculture poses to surface and groundwater resources. For the agricultural regions within Canada, soils data are available from AAFC in the Detailed Soil Survey dataset (map scale of 1:50,000 to 1:100,000) and the Soil Landscapes of Canada (SLC) dataset (map scale of 1:1 million) which is at a scale well suited for a basin-scale hydrologic model (Figure 17). The U.S. equivalent of the SLC is the STATSGO2 database that is available from the USDA-NRCS that provides a 1:250,000 scale soil inventory for the continental U.S. (Figure 18). In order to facilitate soils-related North American continental-scale investigations, a Unified North American Soil Map (UNASM) has been produced (Figure 19) by combining the SLC and STATSGO2 datasets (as well as their Mexican equivalent); however, the UNASM dataset resolution is only 0.25 degree (Liu et al., 2013). For the purposes of parameterizing the soil layers in a GLB integrated hydrologic model, a homogenized combination of the SLC and STATSGO2 datasets would need to be produced.

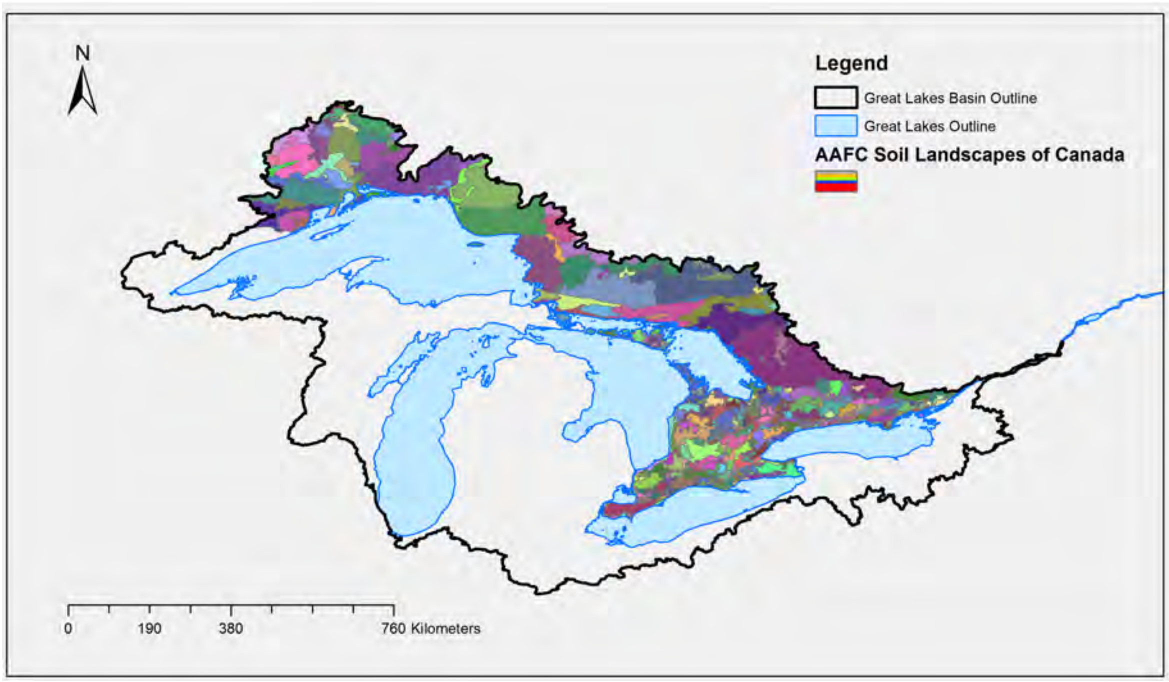

Figure 17. Soil Landscapes of Canada soil class distribution for the Canadian portion of the GLB (SLC, 2010).

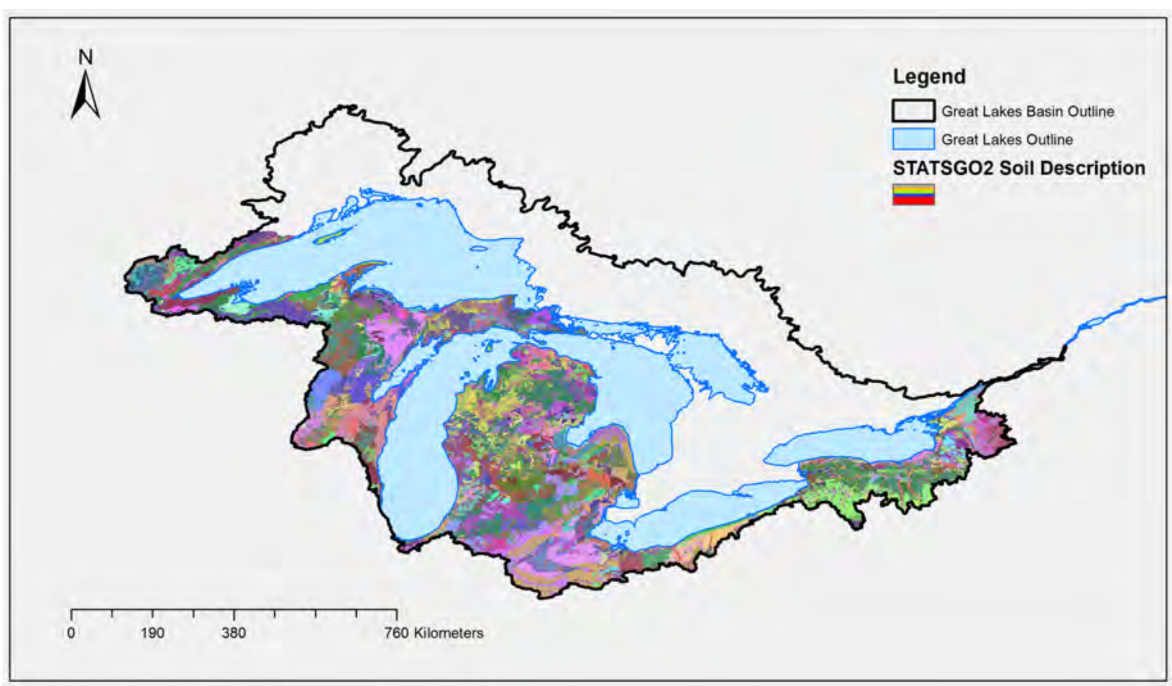

Figure 18. STATSGO2 soil class distribution for the U.S. portion of the GLB (STATSGO2).

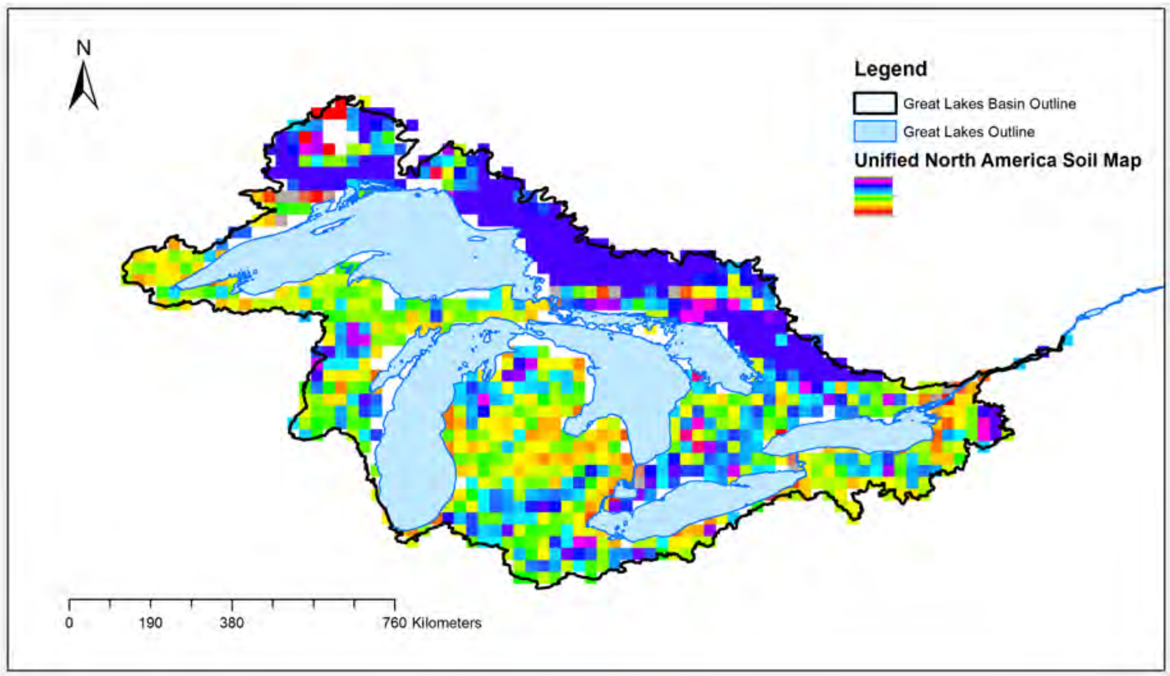

Figure 19. Unified North America Soil Map (UNSAM) soil distribution for the GLB, at 0.25 degree spatial resolution.

Surficial Geology

Surficial geology, including Quaternary/glacial deposits, is another important component of integrated hydrologic models constructed for the Great Lakes region, as these geologic units often contain productive aquifers that are used for municipal, rural, and agricultural water supplies, as well as key aquitard units. In regions with thick quaternary/glacial deposits, these geologic units are often heavily influential on groundwater-surface water interactions, and can be principle contributors of stream/river baseflow, which makes their inclusion in an integrated hydrologic model an important consideration. While practically impossible to capture all of the details pertaining to surficial geology (composition/thickness/depth), nor would it be possible to incorporate such a high degree of three-dimensional detail into a large-scale integrated hydrologic model even if the data were available, some level of surficial geology representation is required in order for the model to capture key large-scale hydrologic behavior characteristics within large-scale hydrologic models. Surficial geology for the GLB region is available from a number of different sources. For the Canadian portion of the GLB, surficial geology mapping is available in the NRCan Surficial Geology of Canada dataset (Figure 20), which is a 1:5 million scale, single layer representation of depositional characteristics (i.e. moraine, lacustrine, off-shore, near-shore, ice-contact etc.). Some expert scrutiny of the NRCan surficial geology map would be required in order to use it as a guide for parameterizing the spatial distribution and the hydraulic characteristics of surficial geology. The Ontario Geological Survey also provides higher resolution 1:1,000,000 scale (Barnett et al., 1991), and 1:50,000 scale (OGS, 2010) coverage for Southern Ontario.

For the US portion of the GLB, the USGS has been conducting large-scale mapping (Soller et al., 2012) of quaternary sediments (Figure 21) east of the Rocky Mountains that has resulted in detailed 1:1 million scale representation of composition and thickness (Figure 22). From the perspective of constructing an integrated hydrologic model, the surficial geology data for the U.S. portion of the basin is currently much more workable than that for the Canadian portion.

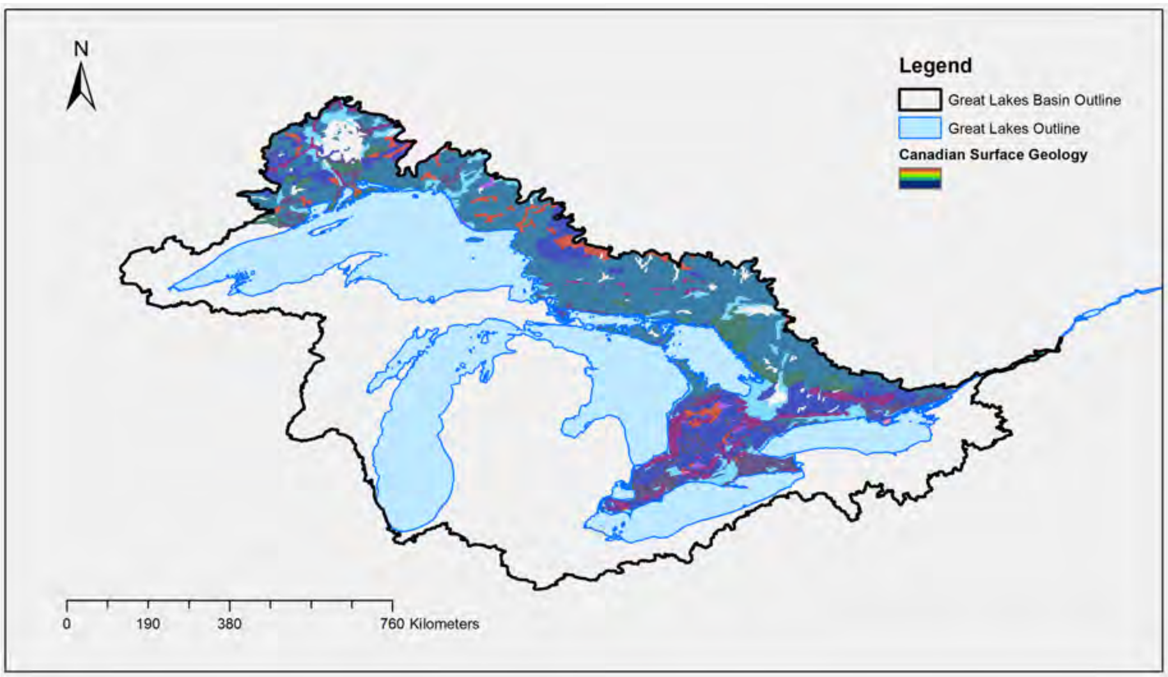

Figure 20. Surficial geology distribution within the Canadian portion of the GLB (GSC, 2014).

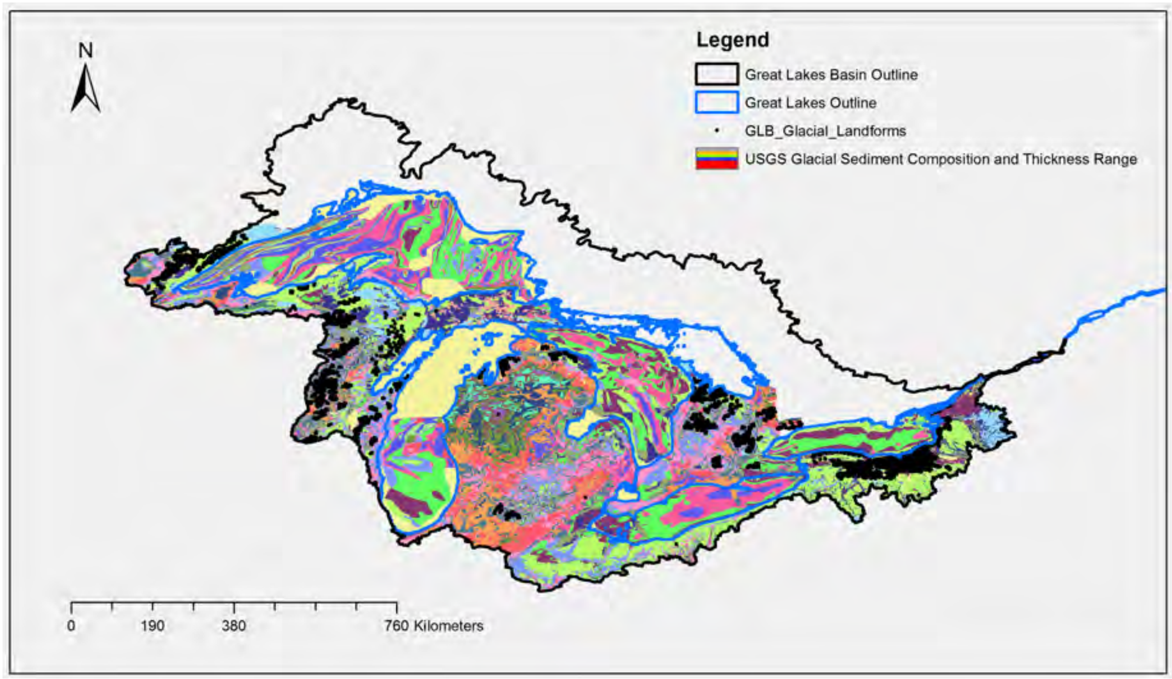

Figure 21. Quaternary sediment distribution within the U.S. portion of the GLB (Soller et al., 2012).

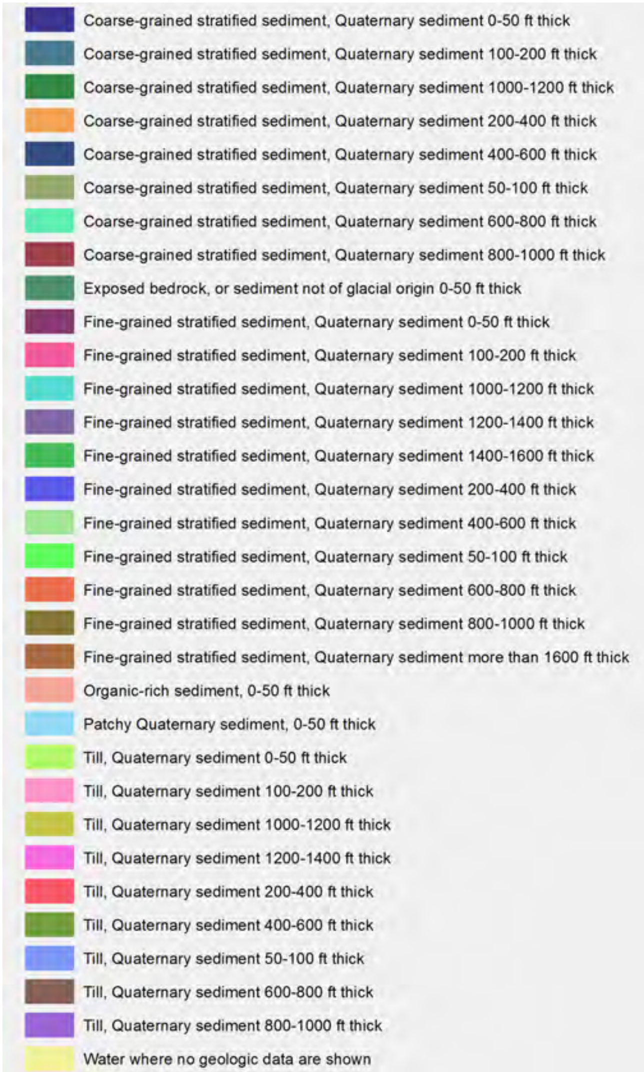

Figure 22. Representative descriptive information for the quaternary sediments within the U.S. portion of the GLB (Soller et al., 2012).

Bedrock Topography

Bedrock topography is typically another key physical characteristic for basin-scale integrated hydrologic models, as it defines the contact between surficial/glacial/Quaternary sediments and underlying bedrock. Because there is often sharp contrast in the hydraulic properties between the materials above and below this key contact surface, it can be an especially important consideration when defining the subsurface hydrostratigraphy within the model domain. However, there is no spatially homogenous bedrock topographic surface data available for the entire GLB and therefore a data amalgamation exercise would be required. For the Canadian portion of the GLB, a uniform bedrock topographic surface exists for the Southern Ontario region (Figure 23) (Gao et al., 2006), and for the U.S. portion of the GLB an approximate bedrock topographic surface could be readily interpolated from the Quaternary geology dataset depicted in Figure 21, using the spatially-distributed sediment depth intervals in conjunction with surface topography (Figure 12). The limiting factor in producing a continuous bedrock topographic surface for the GLB would be the apparent lack of data in Northern Ontario (Figure 23); however, across much of Northern Ontario bedrock is known to be very close to ground surface.

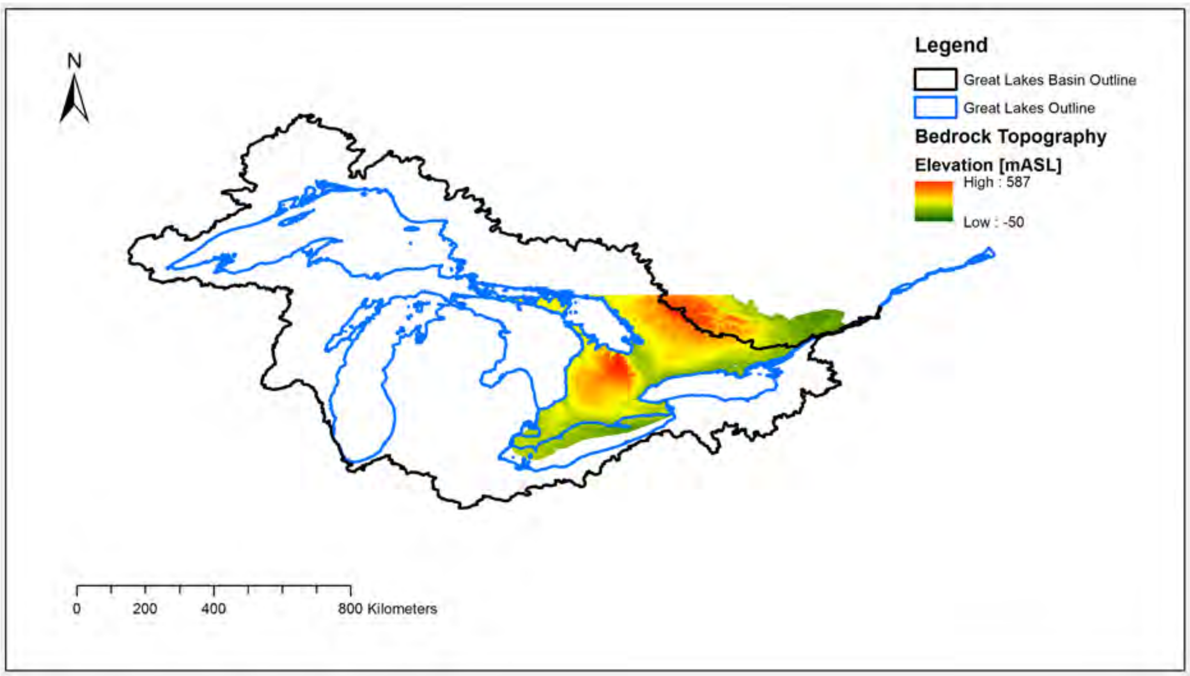

Figure 23. Bedrock topography within the Southern Ontario portion of the GLB (Gao et al., 2006).

Bedrock Geology - Sedimentary

As previously mentioned, sedimentary rock within the Paleozoic Michigan Basin stratigraphic succession compose the bulk of the sedimentary rock within the GLB, with regional presence of Mesoproterozoic and Paleoproterozoic units in the Eastern and Northern portions of the basin (Figure 24). While a spatial distribution of the sedimentary bedrock is available from the Generalized Geology of the World (Chorlton, 2007) digital dataset which is itself primarily derived from paper-form maps at 1:1 million to 1:10 million scale, there is little contiguous data describing the three-dimensional geometry of the sedimentary rock units within the GLB. There is, however, work underway at the GSC to develop three-dimensional geologic models for key sedimentary formations within the Canadian portion of the GLB (Figure 25); however, this is not a basin-wide initiative. The GSC geological modelling is supported for the subsurface Palaeozoic geology by a well-structured petroleum borehole data structure and database maintained by the Ontario Oil Salt and Gas Resources Library (http://www.ogsrlibrary.com) in London Ontario. While constructing a three-dimensional model of the key sedimentary rock units within the GLB at a scale/resolution suitable for a GLB integrated hydrologic model is indeed feasible, this effort would require collaboration with a number of research groups and agencies. For Southern Ontario focused hydrological modelling, additional detail on the Paleozoic geology can be found in Armstrong and Dodge (2007).

In addition to characterizing the three-dimensional spatial distribution, there would also need to be a concerted effort to define the hydraulic properties for the sedimentary rock units, which could be largely completed through a literature review process. Furthermore, the level of detail with which the Paleozoic hydrostratigraphy needs to be described for a GLB or Southern Ontario focused hydrologic modelling initiative should also be considered. Given that much of the water within the Paleozoic strata can be considered to have high TDS levels (which will also impart density influences on flow), and little interaction with fresh (i.e. low TDS) water resources, it is foreseeable that flow within much of the deep Paleozoic will be of little interest for the majority of potential stakeholders in a GLB or Southern Ontario modelling initiative.

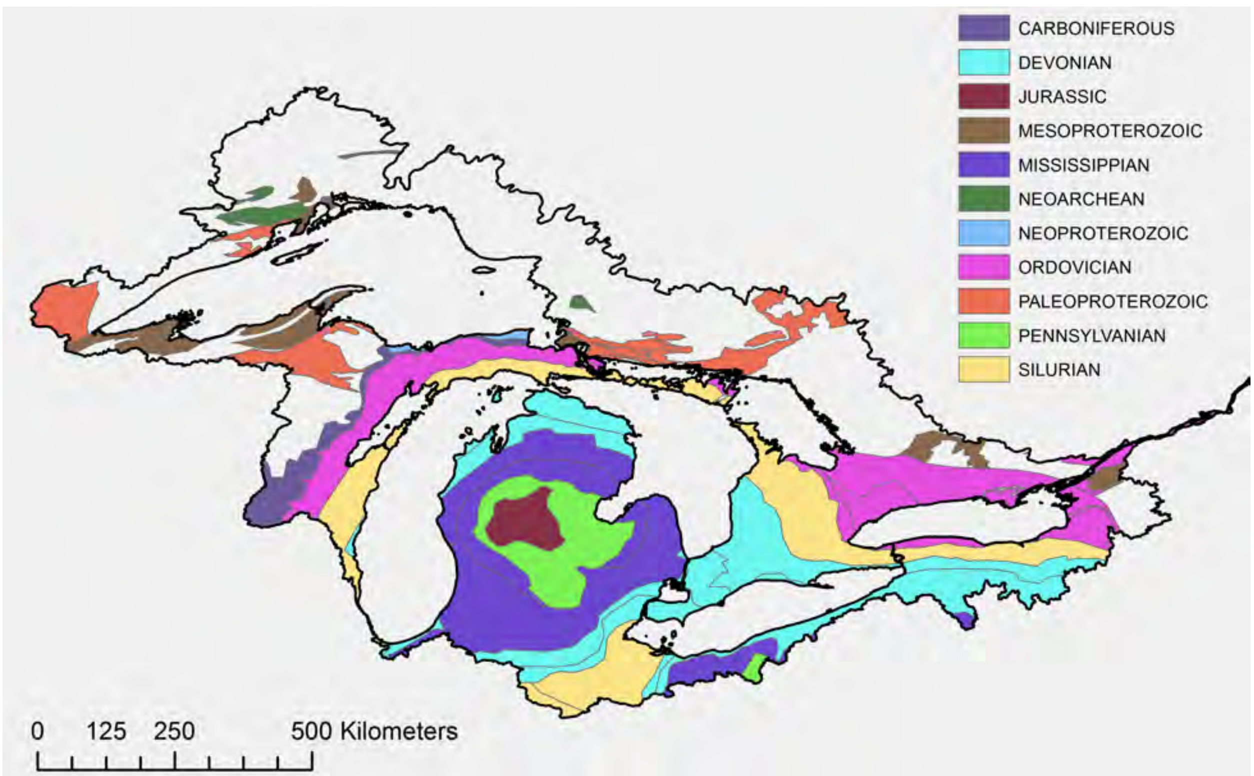

Figure 24. Generalized sedimentary bedrock distribution within the GLB from the General Geology of the World dataset (Chorlton, 2007).

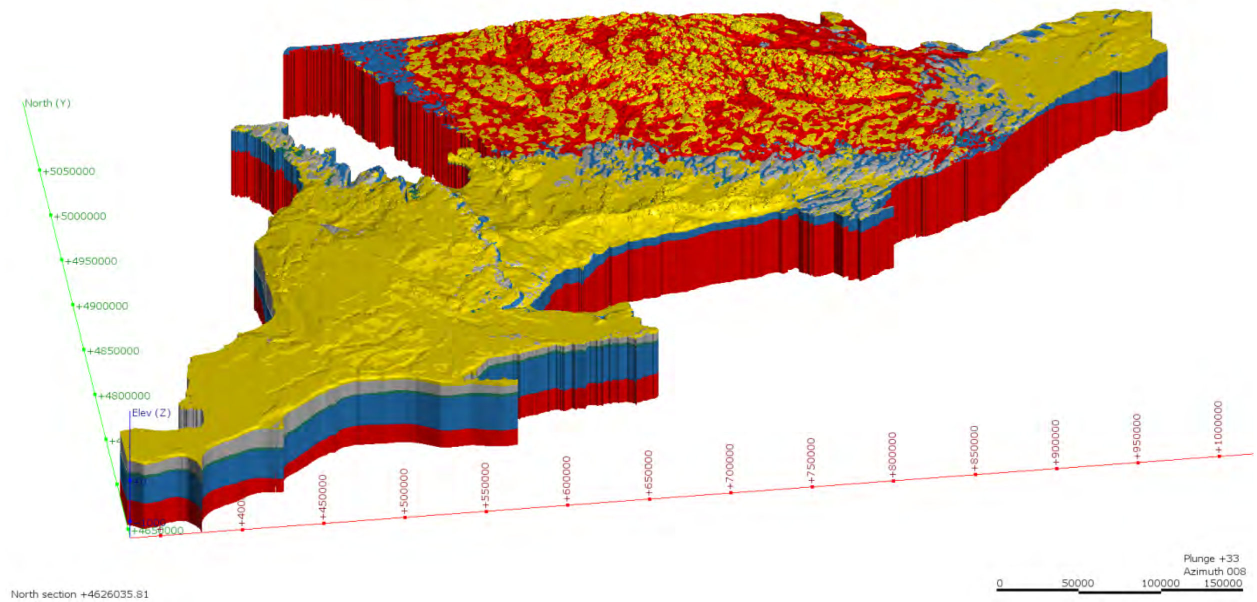

Figure 25. Four layer geological model for Southern Ontario (from the Geological Survey of Canada).

Bedrock Geology – Igneous and Metamorphic

Like the sedimentary geology data, spatially-distributed igneous and metamorphic geology characterization is available for the entire GLB (Figure 26) from within the Generalized Geology of the World dataset (Chorlton, 2007). While characterizing the three-dimensional distribution of the igneous and metamorphic rock would be less intensive than characterizing that of the sedimentary rock due to its vertically continuous nature (relatively), there would again need to be a concerted effort towards characterizing hydraulic properties, which a literature review process could accomplish.

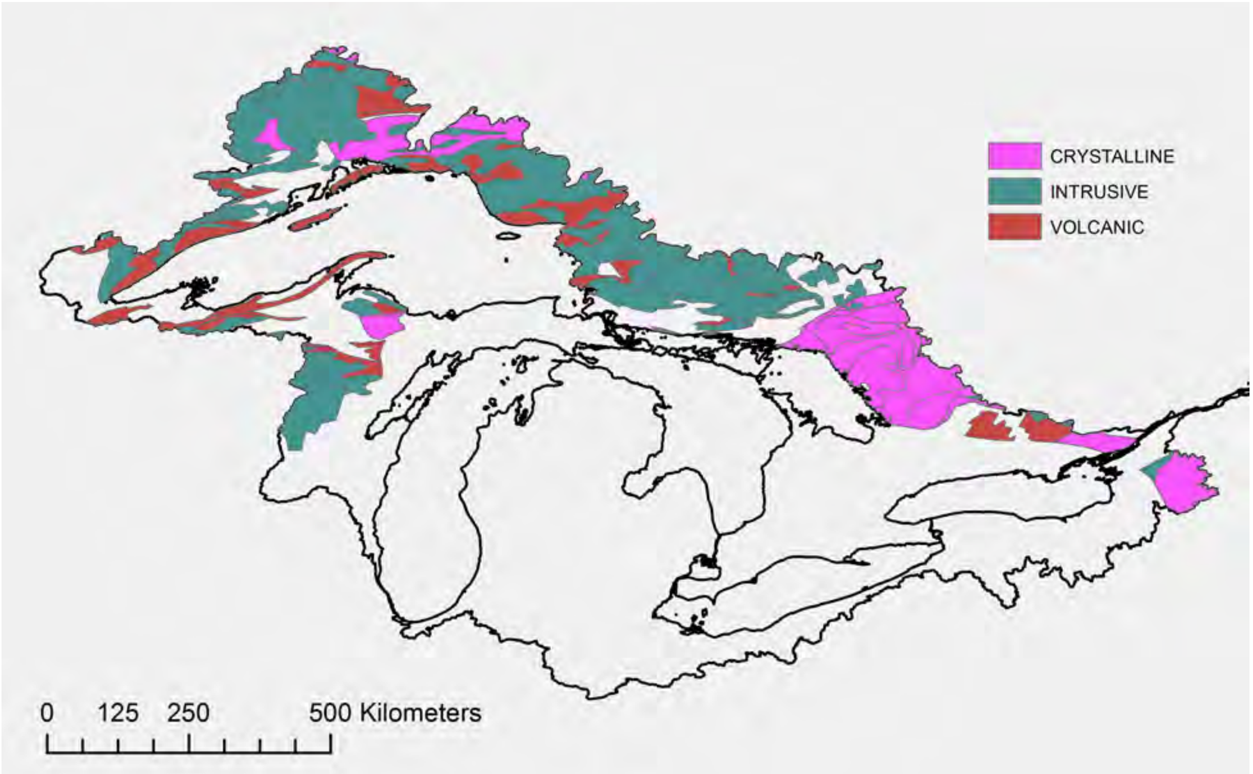

Figure 26. Generalized igneous and metamorphic bedrock distribution for the GLB (Chorlton, 2007).

Primary Data Limitations

From the above discussion regarding potential datasets for use in configuring a GLB integrated hydrologic model, it is apparent that surface and near surface (i.e. soils) data is readily available, and that certain limitations exist in regard to subsurface geologic data. These limitations can be summarized as follows below.

- Quaternary/glacial sediment characterization within the Canadian component of the GLB does not directly support the inference of hydraulic properties.
- Three-dimensional hydrostratigraphic modelling is limited to within Southern Ontario.
- Hydraulic properties for both the sedimentary and crystalline rock formations are not widely available.
- Even the Southern Ontario hydrostratigraphic model is currently limited in the context of vertical resolution.

11. Summary and Conclusions

While there are limitations in the availability of data required for the construction of a hydrologic model at the scale of Southern Ontario or the GLB, these limitations do not preclude a preliminary model from being constructed. In fact, from a hydrologic modelling perspective it is the norm that important data is missing, and in such cases hydrologic models are valuable tools to help inform field-data collection activities so that data with the highest net value for specific applications can be obtained. Using a model to identify data gaps also forces a comprehensive assessment of how structural and parameter uncertainties may impact the model outputs, which is an important part of responsibly using a hydrologic model for decision making purposes.

For surface water and groundwater resources issues relevant at the scale of both Southern Ontario and the GLB, it is evident that a broad range of applications representing the interests of multiple stakeholders could be addressed with a single modelling platform. Through a multi-stakeholder approach, the cost and effort of developing and maintaining the platform could be potentially distributed across a number of different funding bodies, which would in turn make an otherwise unaffordable asset attainable for many organizations. Also, by employing best-in-class resources and scientific capabilities from complementary organizations who are participating in the development and application, a common modelling platform would allow a wide range of stakeholders to capitalize on knowledge and technology that they may otherwise not have direct access. Furthermore, for the GLB, a multi-stakeholder approach towards development could prove valuable when utilizing the platform as a decision support tool in water resources related investigations of bi-national interest, as formal participation of experts from both the US and Canada would help ensure that the science behind the platform is vetted and accepted on both sides of the border. However, as with any highly collaborative initiative, consideration will need to be given to the roles, responsibilities, and interests of the respective groups. Conceivably, the discussion surrounding roles and responsibilities would coincide with a parallel discussion on funding strategies to ensure the initiative has adequate management and financial support over the short, medium, and long term.

While this report focuses primarily on the modelling component of a GLB or Southern Ontario hydrologic simulation platform, it is important to note there are many other facets of such a project. As the conceptual diagram presented in Figure 27 shows, the hydrologic modelling engine can be perceived as one of the core components of such a platform; however, from an operational perspective, the many data management challenges should not be underestimated. Over the longer term it would be expected that maintenance and support efforts relating to data management will dwarf the effort required to maintain and support the modelling engine. Although not discussed in detail here in this document, climate and weather data are another significant component of the overall platform, as these data are the primary drivers for any hydrologic simulation. With proper consideration and design, the weather data will have strong positive impact on model performance metrics. Furthermore, forward looking climate projection data, if carefully selected based on scientific merits and credibility, could help promote the platform as a valuable tool for climate change impact and resiliency analysis pertaining to surface water and groundwater resources. Public accessibility, along with user experience, will both be important considerations during development. In order for the platform to be broadly utilized, it will need to provide a wide array of observed and modelled hydrologic data, hydrostratigraphic data, operational water resources management information, and (potentially) weather/climate data through a single portal in a user-friendly fashion for all stakeholders.

Plotting a path forward for such a complex, collaborative initiative is a non-trivial task; however, in addition to consensus building within the government agency and stakeholder communities, development of a proof-of-concept integrated hydrologic model based on existing data would be a very valuable resource to aid with planning and early development activities. A proof-of-concept model will also serve as an important instrument to define (based on current best-in-class hydrologic modelling technology), the level of spatial and temporal resolution that can be realistically incorporated into the hydrologic model. Only by properly understanding the spatial and temporal scales at which an integrated hydrologic model will operate will it be possible to clearly define the expectations and limitations of the modelling platform.

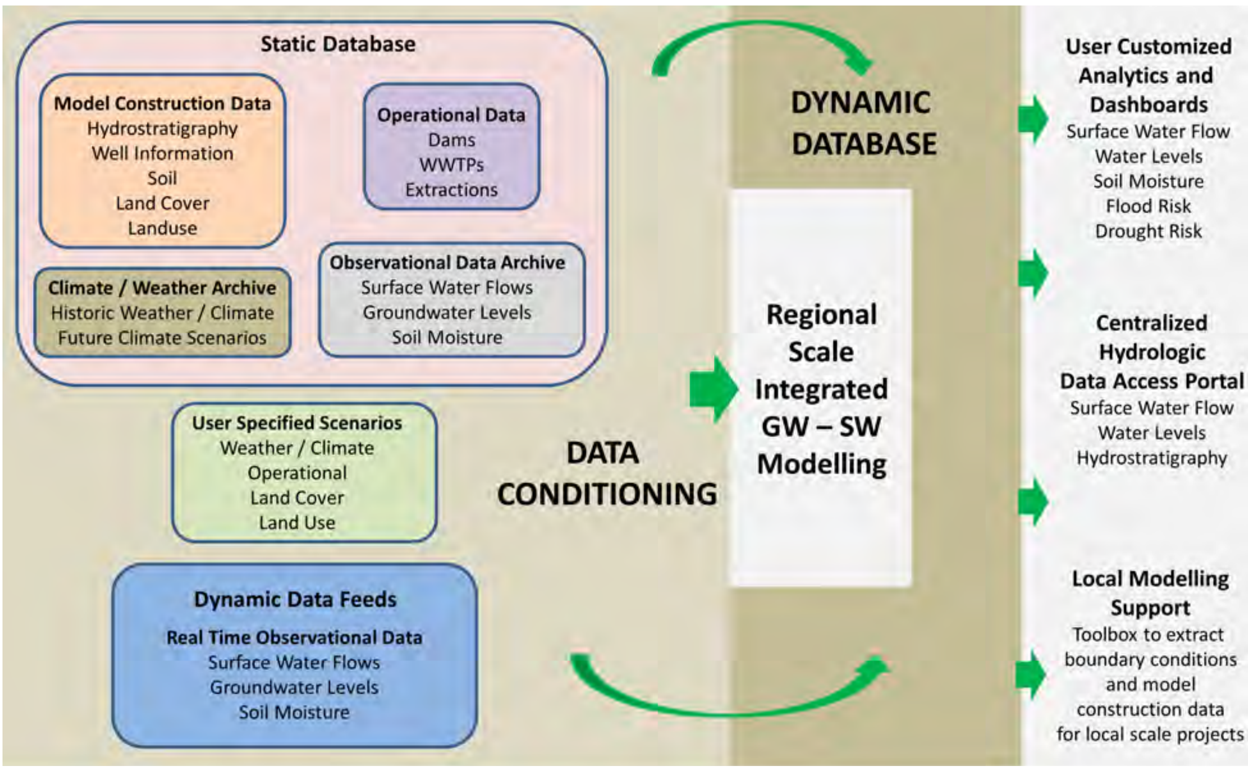

Figure 27. Conceptual overview of key elements required (or for consideration) in a multi-stakeholder water resources data repository and modelling platform for the Great Lakes Basin or Southern Ontario.

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