CAMC/YPDT Technical Report Number 01-06

GROUNDWATER MODELLING OF THE OAK RIDGES MORAINE AREA

York Peel Durham Toronto (YPDT) Groundwater Management Study

Conservation Authorities Moraine Coalition (CAMC)

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Prepared by:

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Earthfx Incorporated

February 2006

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Conservation Authorities Moraine Coalition

Credit Valley Conservation
Nottawasaga Valley Conservation
Toronto and Region Conservation
Lake Simcoe Region Conservation
Central Lake Ontario Conservation
Kawartha Conservation
Ganaraska Region Conservation
Otonabee Conservation
Lower Trent Conservation

February 7, 2006

FORWARD

The enclosed report reflects a large body of hydrogeological work that has been carried out in the Greater Toronto are between 2001 and 2004. The York Peel Durham Toronto Groundwater Management Study is the single most important project being carried out under the direction of the Conservation Authorities Moraine Coalition. The project reflects the interests of six Conservation Authorities and four municipalities that are working together to better understand groundwater issues across the Greater Toronto Area. The project came about as a result of three initiatives that were taking place at about the same time in the late 1990's:

- a planning study undertaken across the Oak Ridges Moraine led by the Regional Municipalities of York, Peel and Durham;
- an initiative by the nine Conservation Authorities across the Oak Ridges Moraine to tackle groundwater issues on the moraine; and
- a project initiated by Toronto and Region Conservation Authority to more closely look at groundwater management issues within York, Peel, Durham and Toronto.

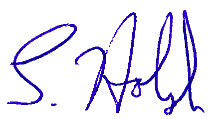
An important theme of the YPDT initiative is that the technical components assembled for the project, specifically: i) the database; ii) the hydrostratigraphical surfaces; and iii) the numerical groundwater model are all designed to be refined and updated on a continual basis. It was the explicit goal of the partnered agencies that the project would be maintained as a long term initiative in order to continually build on the early project work that has now been completed. It is recognized, that despite the high quality of the work undertaken to date, new data and new ideas will come along that will foster constructive improvements to the existing work. Appropriate cautions must be taken when considering the results.

The YPDT Groundwater Management technical steering committee wishes to acknowledge the contributions made to the project in addition to the significant efforts put forth by Earthfx Inc. The work presented in this report reflects contributions from a variety of individuals and corporations. The report was written by Dirk Kassenaar and E.J. Wexler of Earthfx Inc. with significant contributions from: Rick Gerber, Steve Holysh, and Lloyd Lemon. Further technical input was also provided by the Technical Steering Committee. William Snodgrass, Patricia Meyer, Lloyd Lemon and Steve Holysh provided critical reviews of the report. Contributions from the following corporations, either through shared consulting contracts with Earthfx, or through more specific projects, include: Gartner Lee Limited, Golder Associates, Jagger Hims

Ltd., MacViro Consultants Inc., Conestoga Rovers and Associates, and Marshal Macklin Monaghan.

The report meets the requirements of three studies that were partially funded by the Ministry of the Environment through their Municipal Groundwater Studies program. Two of these studies were commissioned through the York Peel Durham Toronto Groundwater Management Program (Regional Oak Ridges Moraine Model & TRCA Watershed Model) while the third was commissioned by the Regional Municipality of York (Yonge Street Aquifer Model).

Financial contributions to the project were made by the Province of Ontario through the Ministry of Northern Development and Mines and the Ministry of the Environment.



Steve Holysh
CAMC – YPDT Groundwater Program Manager

Rick Gerber
CAMC – YPDT Groundwater Program Manager

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Tuesday, February 7, 2006

Steve Holysh
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RE: Groundwater Modelling of the Oak Ridges Moraine Area

Dear Mr. Holysh:

We are pleased to provide our final report on the Ground Water Modelling of the Oak Ridges Moraine Area. The document presents the results of our detailed investigation of the hydrogeologic setting of Oak Ridges Moraine area.

We would like to thank you for the opportunity to work on this project; it has been a journey of challenges and discovery. We have strived to deliver both a numerical model and real conceptual insight into the nature and function of the Moraine.

We would also like to thank both you and Rick Gerber for your active participation and genuine interest in this project. The project would not have succeeded without that commitment.

We trust this report meets with your satisfaction. Please call with any questions.

Yours truly
EarthFX Inc

Dirk Kassenaar, M.Sc., P.Eng.

E.J. Wexler, M.Sc., M.Sc. (Eng)

Groundwater Modelling of the Oak Ridges Moraine Area

Executive Summary

Introduction

The Oak Ridges Moraine (ORM) is a 160-km long ridge of sand, silt and gravel deposits oriented in an approximately east-west direction north of Lake Ontario. To better characterize the hydrogeological conditions of the ORM, a number of regional and local-scale groundwater studies were initiated by the York-Peel-Durham-Toronto (YPDT) Groundwater Management Study and the Conservation Authorities Moraine Coalition in 2001. These projects involved compilation and analysis of the geologic and hydrogeologic data and the creation of computer models of the groundwater and surface water flow systems. This report presents a summary of the findings of these studies.

These projects have produced a number of significant technical products. Although not all a focus of this report, these technical products fall into three categories:

1. Data Compilation: A comprehensive relational database
2. Data Interpretation: A regional hydrostratigraphic framework
3. Numerical Modelling: Regional and sub-regional numerical groundwater flow models

These products were developed using an approach that recognizes that technical understanding is built in a layered manner. The foundation layer is a comprehensive database, followed by interpretation (including conceptual model development) and finally numerical modelling. Each layer depends on the previous, as predictive modelling is only as good as the supporting foundation of data and interpretation.

Data Compilation

Considerable effort was spent in this and related projects to build a relational database that included groundwater, surface water and climate data. Over 140,000 boreholes, 600,000 geologic descriptions, 1.8 million water levels, as well as streamflow records and climate data were compiled and organized into a comprehensive database. This central database serves the needs of a wide range of users, including field staff, data managers, hydrogeologists, and numerical modellers. Data consistency and integration has proven very effective in making the database a useful analysis tool rather than just a storehouse for information. The entire database and report library are available to agency staff online, allowing interactive mapping, retrieval of borehole logs, drawing of cross-sections, and graphing of time-series data.

The entire database has been fully integrated into the interpretation and modelling process. A significant benefit of integration is that all aspects of the database, including geologic logs, aquifer test results, rainfall rates, and pumping data, could be used in construction of both the conceptual and numerical models. The data were also used in model calibration to compare groundwater levels and surface water flows to model results. In turn, the model results helped provide feedback and error checking of the database. We understand that the intent is for the database to continue to be used to store new information as it is collected. These new data can then be used to update and validate long-term model predictions.

Geologic Data Interpretation

Many organizations, particularly the Geological Survey of Canada (GSC), have studied the geology of the ORM. The GSC provided two key elements that formed a starting point for this study; (1) a conceptual regional scale model of the processes that shaped the Quaternary geology of the region; and (2) a five-layer digital stratigraphic model. A regional scale flow model was constructed from the 5 layer GSC stratigraphic model.

While the GSC conceptual model provided insight into the formation and character of the moraine, many of the municipal wells draw water from sediments deep beneath the moraine thus resulting in the need to incorporate deeper systems into the current study. Because the GSC model was focused on stratigraphy and geologic processes, and not hydrogeologic issues, the central portion of the study area (the "Core" area) was re-interpreted to address hydrogeologic issues, better represent erosional channels in the Newmarket aquitard, refine and subdivide the deeper sediment layers, and map interconnected bedrock valley systems. All of these features were deemed important to understanding the overall groundwater flow system and in particular, the capture zones of the deep municipal wells.

Thousands of cross sections were generated and analyzed in the interactive interpretation of the well data. The layer interpretation process identified a number of features and patterns in the well data, including deep bedrock valley systems, erosional glacial channels, and regional aquitard layers that separate the upper water-table aquifers from the lower aquifers. The interpretation provided significant insight into the characteristic lithologic patterns and a comprehensive eight-layer digital hydrostratigraphic representation of the core area.

Over 67,000 layer picks (geological interpretation points) were made during the process of re-interpreting and refining the central portion of the study area. An additional 12,000 3-D polyline vertex constraint points were drawn to guide the layer construction process. This interpretation process was the largest single task in the project and was also the most critical to advancing the understanding of the aquifer systems.

Flow Model Construction

Two numerical groundwater models have been created to represent groundwater flow in the ORM area. The first model, referred to as the ***Regional Model***, covers an area encompassing all watersheds that originate on the Oak Ridges Moraine, while the second, referred to as the ***Core Model,*** covers the TRCA watersheds, York Region, and parts of Durham and Peel Regions with greater resolution. The model layers represent the major aquifer and aquitard layers in the unconsolidated sediment and upper bedrock. The regional model is based on a five-layer stratigraphic model with a nominal cell size of 240 m by 240 m, while the higher resolution core model is based on an eight-layer hydrostratigraphic model with a nominal cell size of 100 m by 100 m (7.1 million cells). Model boundaries have, where possible, been extended to natural flow boundaries (i.e. large lakes (Lake Ontario, Lake Simcoe), watershed boundaries, or rivers) where groundwater boundary conditions might be logically inferred.

The regional model was constructed and calibrated prior to starting work on the core model. Insights gained in developing the regional model provided guidance to the process of refining the core model hydrostratigraphy and calibrating the core model. Development of the core model has generated significantly more conceptual insights into the connections between geology, groundwater flow, and groundwater/surface water interaction.

The core region flow model was constructed using eight hydrostratigraphic layers. The model simulates flow through five main water-bearing units as well as groundwater discharge (baseflow) to the many streams and tributaries that originate on the flanks of the ORM. The model was calibrated to match observed water levels and stream baseflow measurements. This high level of resolution provides sufficient detail to address a variety of regional and local water resources issues such as municipal wellhead protection area delineation, well interference, and impacts of urban development on stream baseflow.

The streams and rivers in both the regional and core model study areas were represented in great detail within the model. The 100-m cell size of the core model was selected so that each small tributary would be separated from other tributaries by several model cells. This allowed local groundwater flow patterns to develop between the streams and provided a significantly more realistic representation of the interaction between the groundwater and surface water systems.

Conclusions and Recommendations

The modelling has demonstrated, in a quantitative manner, the importance of the ORM as a regionally significant recharge area. Model results suggest that the recharge rates through the coarse grained sediments at the top of the ORM are more than four times greater than recharge on the sloping till plains north and south of the moraine. Recharge through the fine-grained sediments that cover the ORM in places is significantly higher than for similar sediments on the till plains because the hummocky topography in these areas tends to capture precipitation and surface runoff.

Sensitivity analysis simulations show that the system is very sensitive to reductions in recharge. Model results are also very sensitive to changes in the vertical hydraulic conductivity of the aquitards; these are factors which control the rate of exchange of water between shallow and deeper aquifers.

In the Core Model area, nearly 90% of the recharge eventually discharges to the stream network north and south of the moraine. Model simulations indicate that stream baseflow discharge patterns are highly variable, and are controlled by a complex combination of topography and subsurface layer geometry and permeability. Less than 5% of the recharge discharges directly from the aquifers into the Lake Ontario and Lake Simcoe. Permitted groundwater pumping equals approximately 6% of the total recharge. Steady state simulations, even with all municipal wells operating at maximum permitted rates, suggests that long-term pumping rates are sustainable (i.e. the wells will not go dry).

Flow patterns in the moraine are more complex than previously thought. Earlier work suggested that flow is predominantly north-south, perpendicular to the axis of the moraine. Modelling and capture zone analysis show that a considerable portion of flow in the ORM is radial from two mounds in the eastern and western portions of York Region. Flow naturally converges on the areas where the moraine narrows, such as in Uxbridge and the Yonge Street basin, which is perhaps a more descriptive term than the Yonge Street Aquifer. The analysis suggests that the Yonge Street Aquifer (YSA) is actually a combination of three hydraulic conditions, including a topographic basin, a tunnel channel and bedrock valley. Model simulations indicate that breaches in the aquitards and deep bedrock valley systems play an important role in the groundwater flow system.

Particle tracking analyses were conducted to define capture zones for the York Region municipal wells. Results showed that the 25-year time of travel zones for municipal wells in the

YSA tended to overlap and create geographically limited capture zones. Pumping from the deeper aquifers minimizes the drawdowns in the shallow aquifer and thereby minimizes the impact on baseflow in the streams.

The database, hydrostratigraphic layers and groundwater flow model are significant fundamental technical products for the YPDT Coalition. These products can be used as the technical foundation for future water resources investigations, monitoring programmes, and resource planning and protection activities. However, all three products will need ongoing refinement and support if they are to remain relevant to understanding and managing the impact on water resources, of future growth and development in the GTA and in the larger ORM area.

Groundwater Modelling of the Oak Ridges Moraine Area

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TABLES

1 Introduction

The Oak Ridges Moraine (ORM) stretches 160 km across southern Ontario from the Niagara Escarpment in the west to Trenton in the east (**Figure 1**). The moraine serves as the height of land separating southward flowing drainage (towards Lake Ontario) from northward flowing drainage into Lake Simcoe as shown in the topographic map in **Figure 2**.

The region has an extensive history of groundwater use. Provincial records show that over 147,000 public and private water wells have been drilled within the ORM watersheds. Groundwater protection and management is an important issue for the entire region.

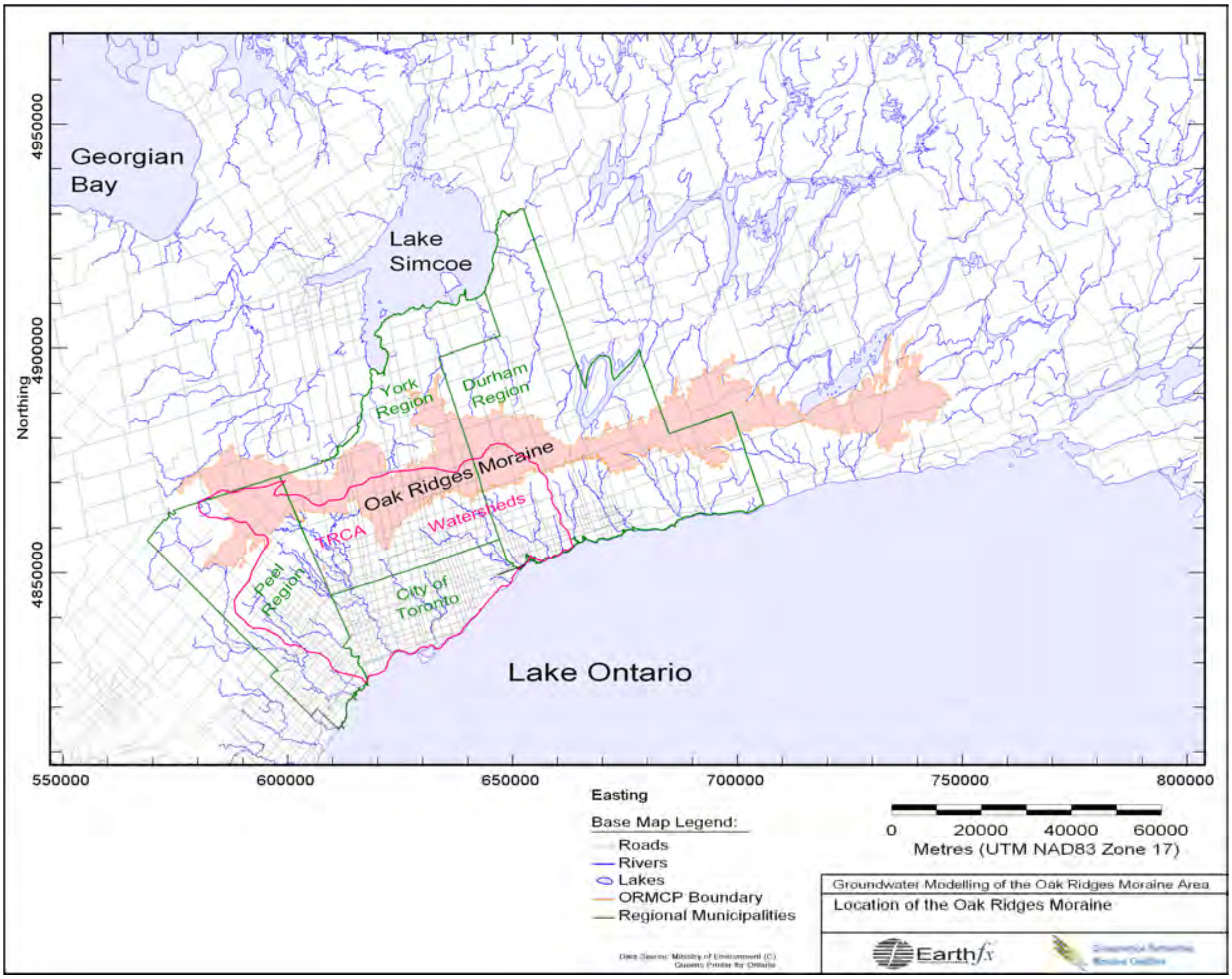

Figure 1: Location of the Oak Ridges Moraine, Southern Ontario, Canada.

The ORM has long been the focus of significant attention by the Provincial Government, as well as the public, owing to land development pressure from the rapidly growing communities in the Greater Toronto Area (GTA). The moraine is recognized as a regionally significant groundwater recharge area because the aquifers recharged by the ORM provide drinking water for hundreds of thousands of residents and also provide baseflow to the headwaters of hundreds of streams.

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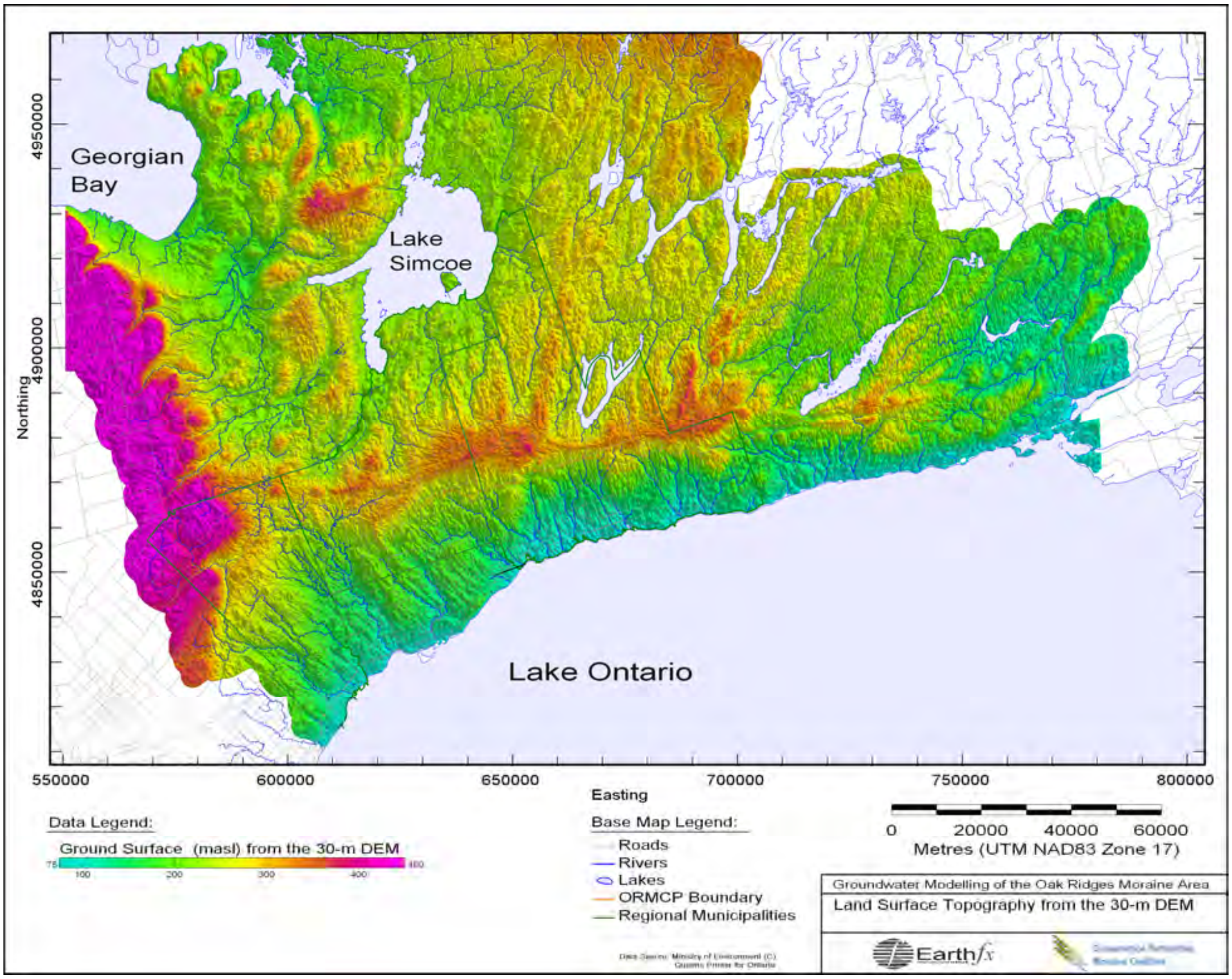

Figure 2: Digital elevation model showing the Oak Ridges Moraine as a ridge separating Lake Ontario from Lake Simcoe.

In the early 1990's, a study of the hydrogeological significance of the ORM was prepared to investigate the role of the moraine in the hydrogeology of the Toronto area (Intera Kenting, 1990). Shortly thereafter, the Provincial government released guidelines for managing land use on the moraine (Ontario Ministry of the Environment (MOE), Ministry of Natural Resources (MNR), and Ministry of Municipal Affairs and Housing (MMAH, 1991). Since that time, several studies investigated technical and land use issues related to the moraine (e.g. Oak Ridges Moraine Technical Working Committee, 1994). This work resulted in the Oak Ridges Moraine Conservation Act and the accompanying ORM Conservation Plan in late 2001. These regulations significantly curtail land development on the ORM. While new development pressures have been limited by these new regulations, the impact of existing land use and extensive groundwater extraction still needs to be investigated. To better characterize the hydrogeological function of the ORM, the current study was conducted to construct a numerical groundwater model for the ORM area.

In addition to the above work, the Geological Survey of Canada undertook a multi-year investigation resulting in an understanding of the sedimentological processes that formed the moraine. Also, of particular importance, is the Yonge Street Aquifer, a poorly defined area stretching roughly along Yonge Street in York Region, which has been heavily relied upon to supply groundwater to the communities of Richmond Hill, Oak Ridges, Aurora and Newmarket. There is particular need to understand the extents of this aquifer complex and its capacity to provide long term sustained yield to these communities.

1.1 Project Overview

To advance the understanding and management of the groundwater system across a large part of southern Ontario, a partnership was developed between four municipal governments (Regional Municipalities of York, Peel, and Durham, and the City of Toronto (YPDT)) and the associated Conservation Authorities (Credit Valley, Toronto and Region, Lake Simcoe and Region, Central Lake Ontario, Ganaraska and Kawartha). At the same time, the nine Conservation Authorities having jurisdiction on the Oak Ridges Moraine (the above six CA's plus Otonabee, Lower Trent and Nottawasaga) were also interested in cooperatively evaluating groundwater resources and formed a coalition, the Conservation Authority Moraine Coalition (CAMC).

This study, initiated by YPDT and CAMC and known as the YPDT-CAMC Groundwater Management Strategy Study, has the Oak Ridges Moraine as a common physiographical element of interest to all partner agencies. In 2000 to 2001, the study completed a Phase 1 investigation consisting largely of an inventory of groundwater initiatives carried out in the southern Ontario area (AMEC et al., 2001). More recently, the partnership spearheaded a series of technical studies, including the current regional groundwater modelling investigations as well as strategic data acquisition initiatives (See Appendix A). Another significant component of the YPDT strategy is to establish some consistency by preparing model guidelines and policies for managing and protecting groundwater resources across the ORM area.

1.1.1 Concurrent and Related Projects

This report satisfies the Terms of Reference documents and presents the analysis and results of three interrelated groundwater studies within the YPDT area, including:

1. Aquifer Characterization Study - Regional Groundwater Model
2. Aquifer Characterization Study – Yonge Street Aquifer; and
3. Aquifer Characterization Study - TRCA Watersheds

The studies are linked because the TRCA watersheds and the Yonge Street Aquifer fall entirely within the ORM Regional Model Study Area. **Figure 3** shows the extents of the two study areas. The first modelling study, referred to as the *Regional Model*, covers the entire Oak Ridges Moraine area, while the second, referred to as the *Core Model,* covers the TRCA watersheds, York Region, and parts of Peel and Durham Regions with greater resolution.

A number of other related projects were undertaken while these modeling studies were underway, some of these led by the CAMC YPDT study and others by York Region. The related studies are listed in Appendix A. Information, conceptual insight, and analysis was shared among all projects. The database construction project provided a foundation for all the analyses. A single database and GIS mapping system ensured that there was seamless and consistent data used throughout. The regional modeling project provided a high-level conceptual framework for the smaller-scale studies but also benefited from the detailed analysis performed in the sub-regional studies. For example, the sub-regional studies provided greater insight into the local-scale variability of the aquifer and aquitard systems which, in turn, guided regional model calibration efforts.

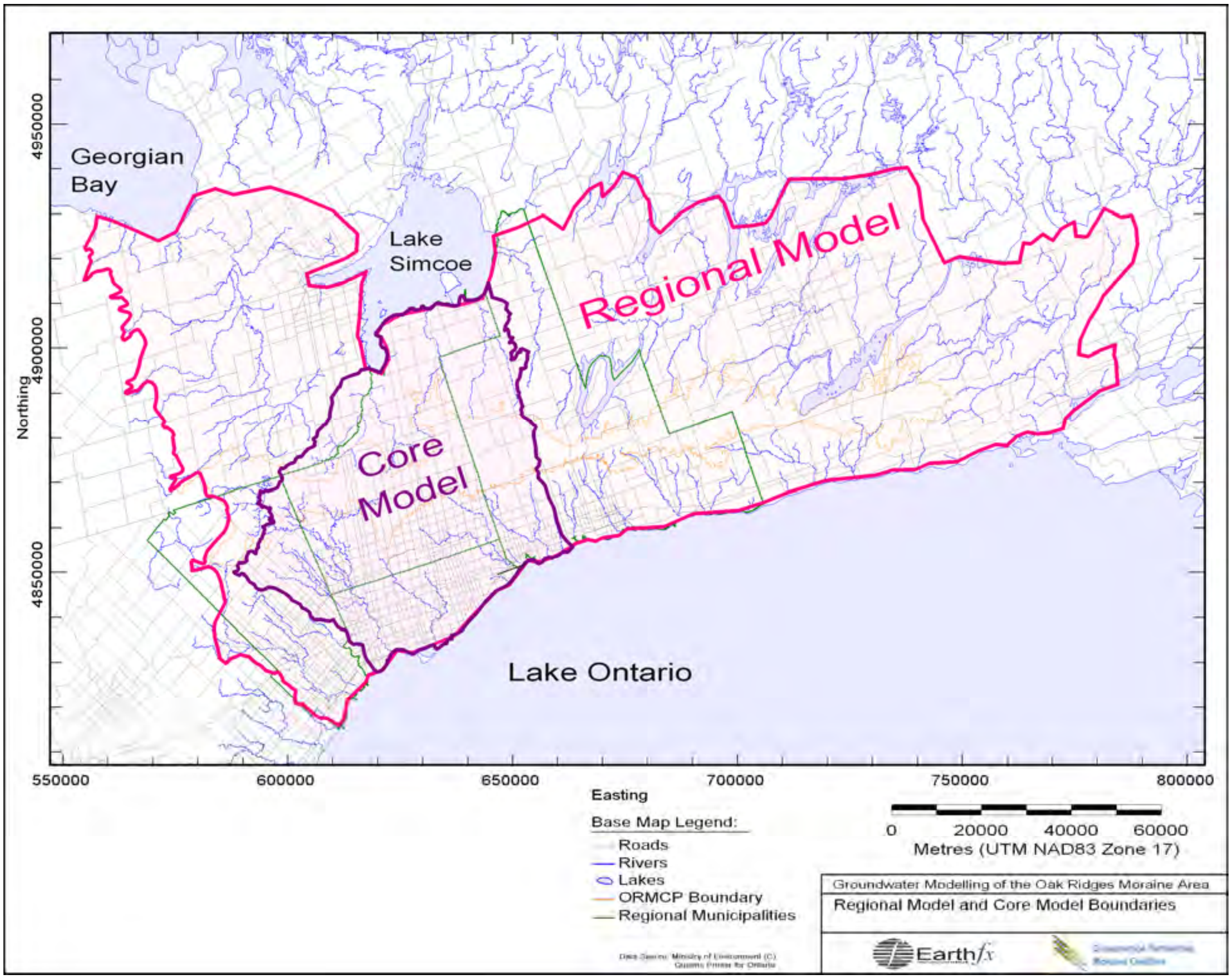

Figure 3: Regional Model and Core Model boundaries

1.1.2 Study Area Extents

The extents of the Regional Model study area were defined early in the process to encompass all watersheds originating on the ORM and to extend to natural flow divides, major river boundaries, or large lakes. The extent of the ORM model area is shown in **Figure 3**. The core model study area was based on the result of the preliminary regional modelling.

1.2 Project Objectives

This report presents an integrated summary of the analyses and modelling results for both the ORM Regional and Core Model studies. The specific objectives of each of the studies are as follows:

1.2.1 ORM Regional Model Objectives

The goal of the Regional Model project was to improve the understanding of the groundwater system of the ORM thus facilitating the better management and protection of this unique resource. The main task within this investigation was to develop and calibrate a regional-scale numerical groundwater flow model of the ORM that can:

- simulate regional groundwater flow within the complex, multi-aquifer system;
- provide a framework for the more detailed, sub-regional models;
- serve as a tool for the quantitative evaluation of the potential impacts of development on groundwater quantity and quality;
- analyze groundwater/surface water (GW/SW) interaction; and
- help identify gaps in the hydrologic and geologic data available for the study area.

1.2.2 TRCA Watershed Model Objectives

The objective of the TRCA Watershed Model study was to develop a quantitative understanding of the groundwater flow system in the TRCA area so that the TRCA can better understand, manage, and protect the groundwater resource. Specific objectives of the study were to:

- contribute input to the regional groundwater flow model encompassing the entire ORM;
- contribute hydrogeologic input, including a geologic model and delineation of boundary conditions, for the Yonge Street Aquifer Characterization study;
- provide hydrogeological input needed for watershed and water balance studies as specified in the ORM Conservation Plan;
- provide the detailed hydrogeologic understanding necessary for TRCA Watershed Management Strategies that deal with issues related to quantity and quality of streamflow and water balance;
- provide the necessary tools required for the analysis of proposed land use changes on a site and watershed scale, and
- assist with providing the aquifer characterization necessary for wellhead protection area (WHPA) studies being carried out on behalf of the Regional Municipalities within the TRCA area.

1.2.3 York Region – Yonge Street Aquifer Characterization Objectives

The objective of the Yonge Street Aquifer Characterization study was to develop a quantitative understanding of the groundwater flow system in the area surrounding the Yonge Street Aquifer. This area was expanded during the course of the study to cover the entire Regional Municipality of York. The quantitative understanding gained will help York Region better manage and protect the groundwater resource that supplies the regions' municipal wellfields and provides baseflow to streams. Specific objectives of the study were to:

- analyze hydrogeologic data to develop a conceptual model for York Region including the Yonge Street Aquifer area;
- develop and calibrate a numerical model for York Region including the Yonge Street Aquifer with the ability to assess potential groundwater capacity and to analyze the impact of municipal pumping on groundwater levels and baseflow to streams;
- provide a model that can be used for wellhead protection area (WHPA) studies being carried out for the Regional Municipality, and to assess and design groundwater

monitoring networks across the region;
- provide hydrogeological input needed for watershed and water budget studies as specified in the ORM Conservation Plan; and
- contribute input to the regional groundwater flow model encompassing the entire ORM.

1.3 Study Approach

As noted in Section 1.2, integrated regional and sub-regional scale analysis was a key aspect of the modelling approach used in these coordinated studies. Other key elements of the approach (methodologies) warrant specific mention because they underlie the analysis in subtle yet important ways. These methodologies are further detailed in the following sections.

1.3.1 Integrated Database Management and Modelling

Efficient, integrated database management techniques were used throughout the modelling studies. By completely integrating the model with the underlying relational database, the model could be adjusted and refined as the database grew during the study period. The main benefit of this approach was that it recognized that new information will continue to be added to the database. As new data are collected, the information can easily be compared to, and interpreted relative to the conceptual model framework. If needed, the framework can be refined. This approach will facilitate model validation and allow the database and model to be used together as an effective, integrated decision support system for future water resources planning.

Central to this approach is that the model was built upon and connected to a general-purpose environmental database structure (referred to as the “Earthfx data model”), as opposed to a database built specifically for modelling purposes. This will facilitate the expansion of the model to include additional simulation processes (such as advanced surface water/groundwater modelling or recharge models) and to be adapted for a broader range of applications than those addressed here. For example, the current database has detailed information on climate (e.g. daily temperature and rainfall data) which are utilized in modelling to calculate runoff, evapotranspiration, and groundwater recharge.

1.3.2 Integrated Hydrostratigraphic Interpretation

The Geological Survey of Canada provided an excellent stratigraphic framework for creating a preliminary regional-scale flow model. In developing the Core Model, based largely on a need to better understand deeper aquifer systems, a significant effort was made to refine this interpretation through a re-examination of the water well records.

The methodology used to map the hydrostratigraphy involved inspection and interpretation of well records on thousands of cross sections drawn through the study area. The method was based on the principal that all aspects of the data management, display, and processing could be automated *except* the interpretation. All available hydrogeologic information, including screen locations, water levels, water found indicators, and previous stratigraphic interpretations, were presented visually on section for interpretation. The concurrent posting of multiple types of borehole information was instrumental in identifying a number of significant characteristic patterns in the water well records.

1.3.3 Representation of Stream/Aquifer Interaction

The ability to accurately simulate the complex interaction between groundwater and surface water is critical to building a model that can facilitate planning and protection of the groundwater-fed streams that emanate from the ORM. Because smaller tributaries are often more sensitive to small changes in the groundwater system, considerable effort was made to refine the groundwater model so that each small stream reach could interact independently with the groundwater system. To achieve this small model cells and better representation of the stream bottom characteristics were used.

1.4 Structure of Document

Section 2 of this report provides background information on the geologic history and stratigraphy, physiography, and topography of the study area. Section 3 discusses the current understanding of the hydrostratigraphy of the area and presents maps and sections that describe the conceptual hydrostratigraphic model developed as a framework for the groundwater models. Section 4 describes the general approach taken to developing the regional-scale and subregional scale numerical groundwater models. Section 5 present results of analyses of groundwater levels and surface water flow data that were used in developing calibration targets for the numerical models.

Section 6 present specific details related to the development of the Regional Model and discusses model boundaries, input data, and results of model calibration. In a similar manner, Section 7 present specific details related to the development of the Core Model and discusses model boundaries, input data, and results of model calibration, sensitivity analyses, and sample model applications. Section 8 provides a summary of the report along with recommendations for future work.

Appendices to the report provide additional detail on the data used in the study, methods used in data analysis, and a summary of the geologic model developed by the Geological Survey of Canada which provided a strong foundation for much of the work done in this study.

2 Background

2.1 Literature Review

There are many previous studies and reports in the ORM area and the challenges of reviewing and assimilating these documents were identified early in the project. To facilitate literature review a process of report scanning was undertaken. Report scanning was performed for two main reasons: 1, to compile, capture and archive historic work, and 2, to make the report library easily available to all scientists involved in the project.

Over 1500 technical reports were scanned and converted into Adobe Acrobat PDF format. In addition, tiled digital photographs were taken of over 2400 large format maps and cross sections that accompanied many of the reports. A metadata database containing information on each report has been prepared and the database (in a searchable form) and entire report library are available to the partner agencies on-line at the ORM Project web site.

The reports span a broad time frame, spatial scale and scope. The majority of the reports are classified as “site” scale, with another 25% classified as slightly broader “local” scale. The remaining larger scale studies have been performed predominantly by the GSC, OGS and MOE. The scope of the documents ranges from short letter reports to major investigations such as the Interim Waste Authority (IWA) landfill site evaluations. The report library represents many man hours worth of projects and data collection.

Many hours were spent reviewing and assimilating the information stored in the report library. Key information was incorporated into the project database. Literature review was not assigned to one person or limited to one phase of the study. The accessible digital library was used by all scientists through all phases of the interpretation, modelling and analysis. The review included both qualitative and quantitative aspects. For example, some key high quality boreholes were found within the historic reports, and in many cases these became “anchor” points. Continued mining of the report library will yield additional value.

2.2 Previous Work

There have been many studies conducted over the past 50 years to characterize the geological framework and groundwater flow system of the ORM. Early work was frequently restricted to local-scale investigations with limited data and mapping. More extensive provincial-scale studies (White, 1975; Sibul et al., 1977; and Singer, 1981, Hunter et al., 1996) provided significant insight into the geology and hydrogeology of the ORM. Physiography and land use in the area was described in Chapman and Putnam (1984). In the mid 1990’s, the MOE compiled water well records into a regional-scale report for southern Ontario (Singer et al., 1997). Recent advances in the understanding of glacial processes, plus the availability of new data, have allowed the study team to build on and update these earlier studies.

More recently, studies by the GSC and the OGS have significantly advanced the understanding of the key geological processes that contributed to the formation of the ORM (e.g. Barnett et al., 1998; Sharpe et al., 1999; and Logan et al., 2001). The GSC also produced maps of surficial geology, bedrock surface topography, and isopach and surface topography maps for the stratigraphic units at a scale of 1:200,000 (maps are reproduced in Appendix B). The stratigraphic and isopach maps were based largely on the interpolation of geologic “picks” determined through database queries and rules whereby key “golden spike” boreholes were used to “train” the poorer quality water well records (Logan et al., 2001).

An extensive review of all previous work is beyond the scope of this document because of the extensive number of reports found in the study area. Where relevant, previous work, particularly that of the GSC and OGS, is referenced and discussed in detail.

2.3 Summary of Data Compilation and Management

A large volume of information was compiled into a database format that supported the development of a conceptual understanding of the study area, a refined hydrostratigraphic model of the Core area, and regional and sub-regional groundwater flow models. A comprehensive discussion of the database construction project is provided in the companion report “YPDT Hydraulic Data Management System”, (Earthfx, Inc., 2003). More detail on the data compilation can also be found in Appendix C (Section 3).

The primary components of the database are 135,000 MOE water well records. Associated with these are over 1,800,000 water level measurements and 600,000 geological descriptions. The database also includes 13,000 geotechnical and monitoring wells, 200 municipal supply wells with pumping data, 250 surface water monitoring stations with daily flow data, and 520 climate stations with the common daily climate measurements. These data are stored in an open and flexible relational format and should prove useful to a wide variety of future applications.

The tight integration of the database, geologic interpretation and flow model is particularly important to the current and long term success of the project. The database is directly connected to the model, facilitating the evaluation and visual review of both components. The extensive geologic interpretation and flow modelling have helped to check and correct errors in the database.

2.4 Geologic Understanding

The purpose of this section is to present the geology of the study area. Much of this information is based on previous research and this section only provides a brief synopsis of the extensive prior work. It is important to note that there is still considerable academic discussion and ongoing research into many aspects of the glacial processes that led to the deposition of the stratigraphic framework. This report covers some of the more recently developed concepts but does not attempt to compare, contrast or confirm any particular conceptual model. In general the report tends to adopt the GSC terminology, in particular, the term “tunnel channels” were accepted and used to describe large-scale erosional features.

The development of a conceptual geologic model is an important first step in the groundwater model development process. The considerable previous work on the stratigraphic framework provided an excellent foundation for the conceptual hydrogeologic model.

A summary of previous geologic and stratigraphic work is presented in Section 2.4, while hydrogeology (discussion of the aquifer and aquitard layers) is covered more fully in Section 3. Section 2.4 begins with an overview of the major geologic events which shaped the area (a geologic “timeline”), followed by a discussion of surficial geology, physiography and topography. This is followed in Section 2.5 by a more detailed description of the overburden stratigraphy, based primarily on recent work by the GSC.

2.4.1 Stratigraphic Framework

The geology of the area can be characterized as consisting of sedimentary bedrock units overlain by unconsolidated sedimentary materials that have been deposited and modified by glacial, fluvial and lacustrine processes. To understand the geologic setting, the stratigraphic framework must be established. The stratigraphic framework is a conceptual description of the individual geologic units and the sedimentological processes (deposition and erosional) that deposited and affected them.

Understanding the geologic timeline provides important insight into the geology of the study area. The following (simplified) sequence of events occurred (**Table 1**):

Table 1: Simplified geologic timeline for the study area

Name	Time	Dominant Processes	Description
1. Paleozoic Bedrock	550 to 350 million year BP (before present)	Deposition	Paleozoic bedrock layers deposited on Canadian Shield
2. The “Big Gap” (Eyles, 2002)	350 million to 135,000 years BP	Erosion	Extensive erosion of the bedrock surface (bedrock unconformity)
3. Pleistocene Sediment	135,000 to 10,000 years BP	Glacial Processes (deposition)	Complex deposition and reworking of sediment materials during glacial advances and recessions

Even though there are no sediments existing today that are interpreted to have been deposited during the “Big Gap”, it plays a pivotal role in the study area. The extensive erosion of the bedrock surface over hundreds of millions of years resulted in the formation of numerous deep bedrock valley systems. The influence of these valley systems on the subsequent glaciation and deposition of the upper sediment layers is complex. Some evidence from water well records indicates that the upper units may drape into the valley systems. Where infilled with permeable sediments, the bedrock valleys form significant interconnected aquifer systems and historically have been drilling targets for new municipal water supply wells.

Previous work on the regional stratigraphic framework has ranged from conceptualization to full-scale digital mapping of stratigraphic layers. The stratigraphic framework for the study area is outlined below and consists of (from lower most or oldest unit):

1. Canadian Shield (older than 550 million years)

2. Paleozoic Bedrock (550 to 350 million years BP)
    - Simcoe Group Limestone
    - Georgian Bay Shale/Blue Mountain Shale
    - Queenston Shale
    - Cataract and Clinton Group Sandstones and Shales
    - Amabel/Lockport Dolostone

3. Regional Unconformity “The Big Gap” (350 million to 135,000 years BP)

4. Pleistocene Sediments (135,000 to 10,000 years BP)
    - York Till (or equivalent)
    - Don Formation (or equivalent)
    - Scarborough Formation (or equivalent)
    - Sunnybrook Drift (or equivalent)
    - Thorncliffe Formation (or equivalent)
    - Newmarket Till (also referred to as the Northern Till)

    - Regional unconformity (channel infill deposits) (after about 20,000 years BP)

    - Oak Ridges Moraine (about 13,300 years BP)
    - Halton/Kettleby Till (or equivalents, including Wentworth Till)

    - Glaciolacustrine Deposits (sand, silt and clay) (about 12,500 years BP)

5. Recent fluvial deposits (sands, silts, and clay along streams)

2.4.2 Paleozoic Bedrock

The limestone and shale bedrock units of Paleozoic age that underlie the study area were mapped by Johnson (Johnson et al., 1992). A coloured map based on the 1:1,000,000 scale OGS mapping is presented in **Figure 4**. The Paleozoic bedrock units were deposited on the Canadian Shield over a period of 200 million years, beginning approximately 550 million years BP. A complex sequence of mountain-building events, driven by plate tectonics, occurred over this time. Sediments from the erosion of these mountains infilled the Michigan Basin (a large circular-shaped basin centred on the State of Michigan) and were subsequently lithified. These limestone and shale units make up the upper sedimentary bedrock units that underlie the study area (**Figure 1**).

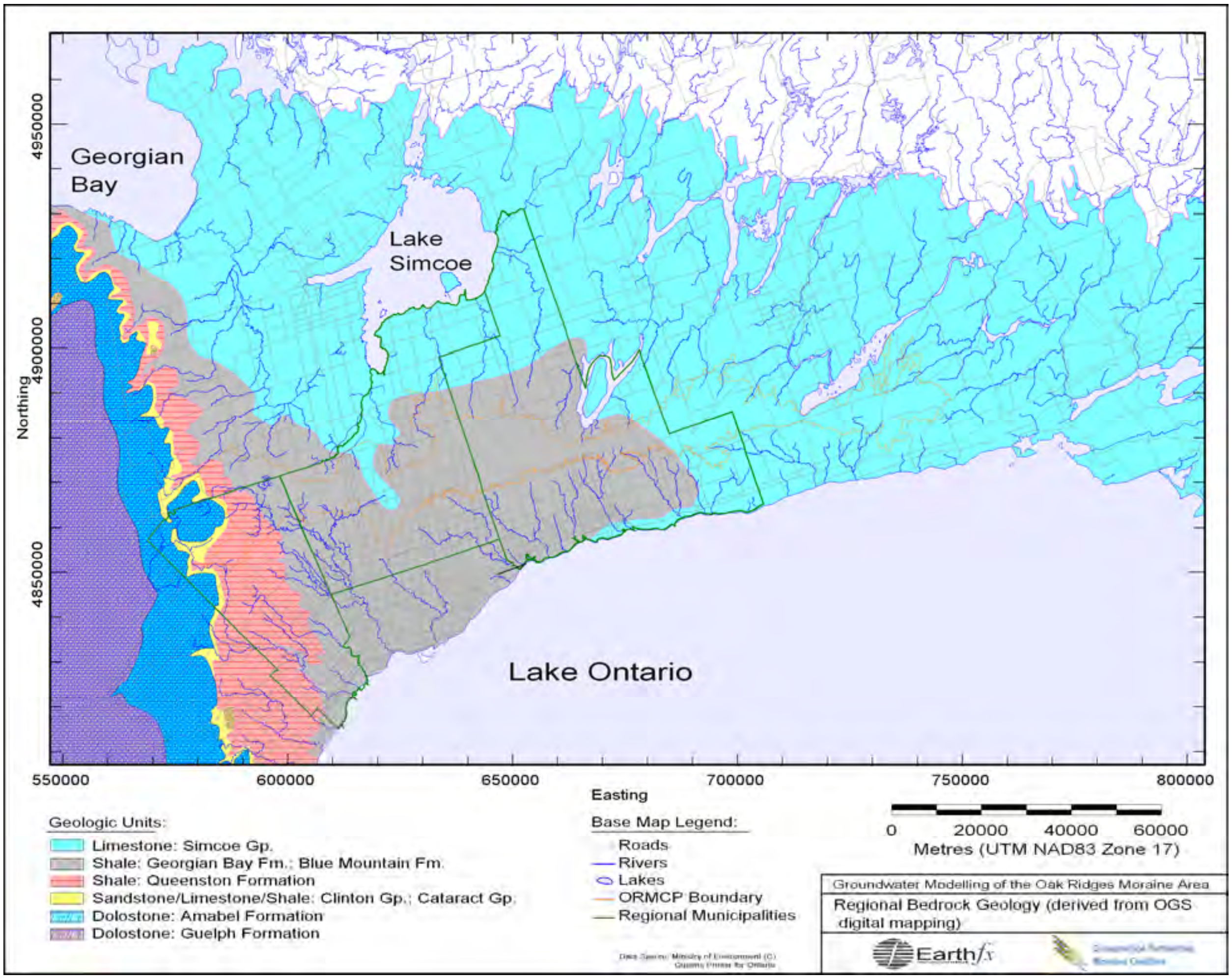

Figure 4: Regional bedrock geology (derived from OGS digital mapping)

The bedrock units found immediately beneath the glacial sediments within the study area consist primarily of limestone of the Middle Ordovician Simcoe Group (Verulam Formation) in the northeast and east, and shale of the Upper Ordovician Blue Mountain and Georgian Bay Formations in the south and northwest (Johnson et al., 1992). To the west, a series of younger units, including the Guelph and Amabel Formations, the Clinton-Cataract Group, and the Queenston Shale, are exposed in the vicinity of and above the Niagara Escarpment. The bedrock units are between 505 and 440 million years old and were deposited in an ancient sea known as the Iapetus Ocean which formed following the break up of the supercontinent Rodinia approximately 600 million years BP.

The progression from older limestones (Simcoe Group) to younger shales (Blue Mountain/Georgian Bay) provides evidence for a progression from shallow, reef forming areas to deeper water conditions. This change in depositional environment about 440 million years BP was created by the collision of the North American tectonic plate with Europe. This collision, known as the Taconic Orogeny **(Figure 5**), buckled the crust beneath the study area, creating basins and arches with thick sedimentary packages accumulating within interior seas in the Michigan and Appalachian basins on either side of the Findlay-Algonquin Arch. The Ordovician limestone and shale lie unconformably upon Precambrian shield rocks 1.45 to 1.1 billion years old that are at least 70 km thick. The sedimentary rocks dip to the west at approximately 6 m per km (Johnson et al., 1992), as shown in **Figure 6** (Eyles, 2002).

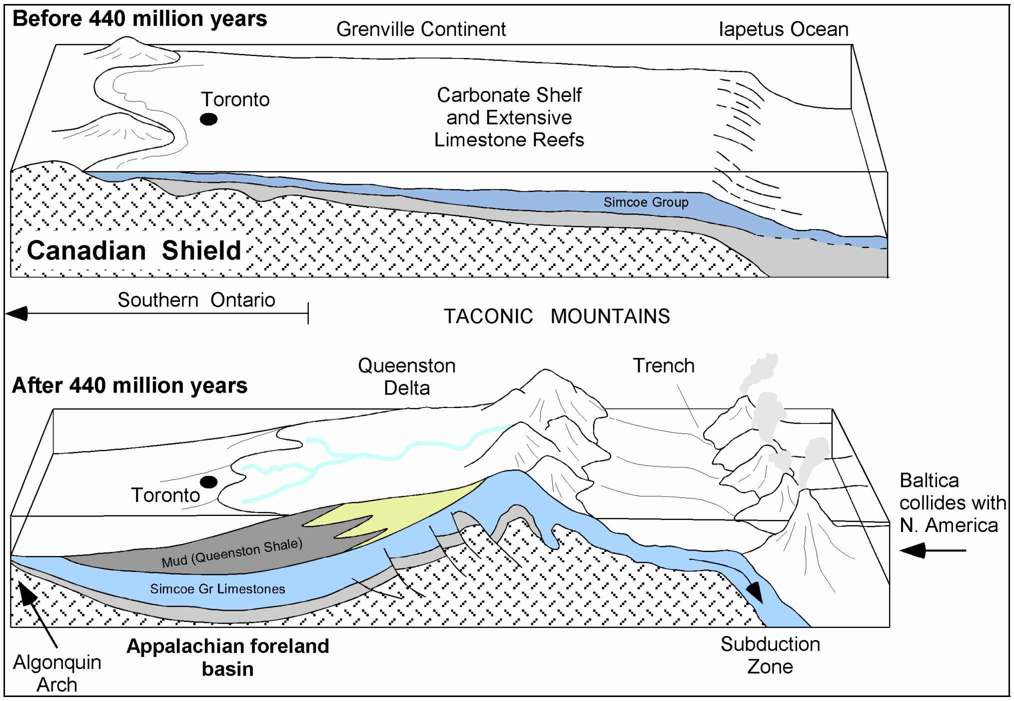

Figure 5: Marine deposition conditions before and after the Taconic Orogeny (Figure from Eyles, 2002).

The structure of deeper Precambrian and Paleozoic formations has a broad control on groundwater resources and flow patterns in the area. A major northeast trending structure in Shield rocks (Easton, 1992), labelled CMBBZ or Central Metasedimentary Belt Boundary Zone in **Figure 6**, may control the position of lakes at the Precambrian/Paleozoic contact and possibly the orientation of the bedrock valleys that occur in the northern ORM area (Scheidegger, 1980). A complementary set of northwest and northeast trending fracture patterns (Sanford et al., 1985) and the presence of erodable shale units (Spencer, 1881), may also control the position of the Paleozoic bedrock valleys. These lakes and structures may have also been enhanced by glaciofluvial erosion (Gilbert and Shaw, 1994). Hence, the underlying structure and bedrock morphology influence the regional hydrogeology of the ORM. Finally, small-scale features, such as weathering and near surface fractures and jointing in the bedrock, may also influence groundwater flow patterns.

The limestone bedrock units are much more productive and therefore better aquifer targets when compared to the shale units. However, the carbonate rocks comprising the Simcoe Group can often be poorly fractured with low permeability resulting in poor aquifers and many areas with poor water quality. In general, the shales are also poor aquifers, although where weathered and fractured, they can provide sufficient groundwater for domestic purposes.

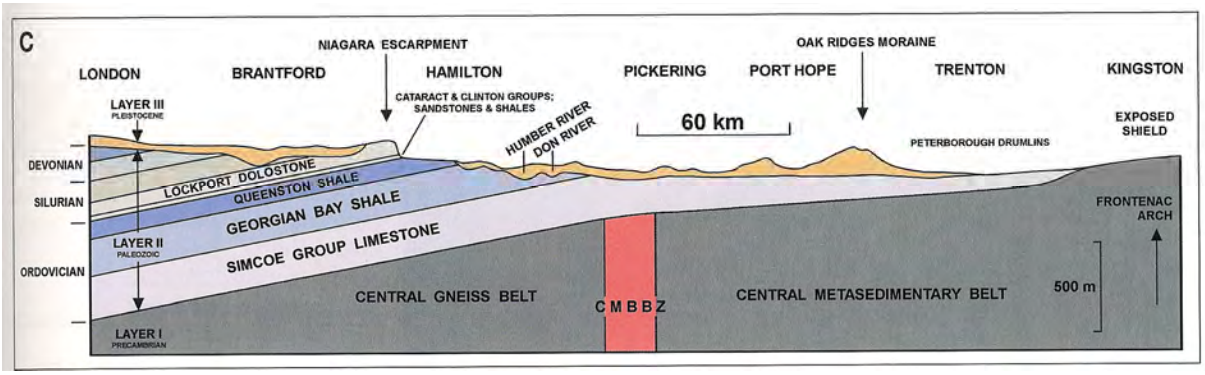

Figure 6: West-East cross section showing bedrock layers and CMBBZ (Eyles, 2002)

2.4.2.1 The "Big Gap": Mesozoic and Cenozoic Erosion of the Bedrock

In many situations understanding what is missing is more challenging than understanding what remains. This is particularly true for understanding the bedrock surface in the ORM study area. Eyles (2002) speculates that as much as seven kilometres (km) of bedrock material was eroded from the basin over a period of 150 million years. Recognizing and understanding this extensive history of erosion of the bedrock surface is important to understanding the deeper groundwater flow system.

The most visible evidence of erosion is the Niagara Escarpment, which forms the western most limit of the Oak Ridges Moraine. The Niagara Escarpment is not the result of a fault, as some other escarpments, but instead is a "cuesta" which was formed by differential erosion of the bedrock layers that dip to the southwest. Through a process called "sapping", the underlying soft rocks (shale) erode away relatively quickly and the more resistant caprock (limestone and dolostone) are undermined and break off, creating a cliff-like slope. Formation of the Niagara Escarpment began somewhere to the north and east of its present location. Historic bedrock river systems also likely had an influence on the formation of the Niagara Escarpment.

In the west half of the study area, the Paleozoic bedrock surface beneath the ORM has been deeply eroded as part of an ancient mid-continent river system (Eyles, 2002 and Eyles et al., 1993). This river system, named the Laurentian River, is believed to have been the main drainage course for the Great Lakes basin (see inset map in **Figure 7**). Bedrock mapping suggests that the Laurentian River appears to have flowed within a broad valley in a direction from Georgian Bay southeast towards (and beneath) the City of Toronto (Spencer, 1881).

The general locations of the Laurentian bedrock valley system and numerous smaller valleys have been mapped on a regional basis by Eyles et al. (1993) and are shown on **Figure 7**. Evidence of these bedrock valley systems has also been identified on various map sheets within or near the study area by the OGS (Holden et al., 1993a; 1993b; 1993c; 1993d; Karrow, 1970; 1992; Rogers et al., 1961; Sharpe and Clue, 1978; and White, 1975). A composite of these maps is shown in **Figure 8**. (A reinterpretation of this and related bedrock data is discussed in more detail in Section 3.3.2 and shown in **Figure 23**).

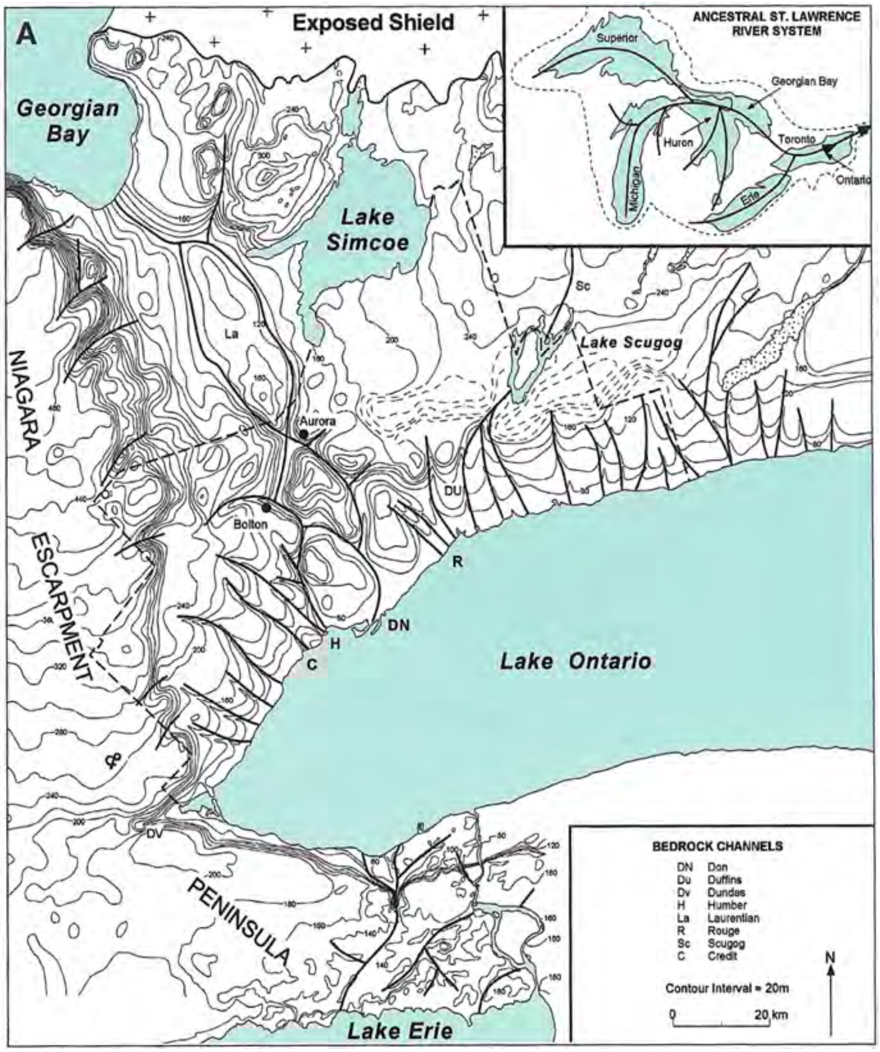

Figure 7: General position of the bedrock valley systems and related ancestral drainage patterns of the basin (Eyles et al., 1993)

The GSC created a digital bedrock surface map of the study area as part of their digital stratigraphic model (Brennand et al., 1997). A page-sized recreation of the surface based on data provided by the GSC is shown in **Figure B119** in Appendix B. Figures showing the other GSC stratigraphic model surfaces are also presented in Appendix B. The refinement of the bedrock surface within the Core Model area is discussed in Section 3.

The geometry of the bedrock surface is not well known beneath the ORM because few wells intersect bedrock which can typically be greater than 100 m in depth. Investigations using location-corrected water-wells, hydrogeological borehole data, and seismic reflection profiles indicate a trunk and tributary valley system (Brennand et al., 1997). In the west, valleys eroded into the Niagara Escarpment form tributary valleys to the main Laurentian Channel (Hunter et al., 1996).

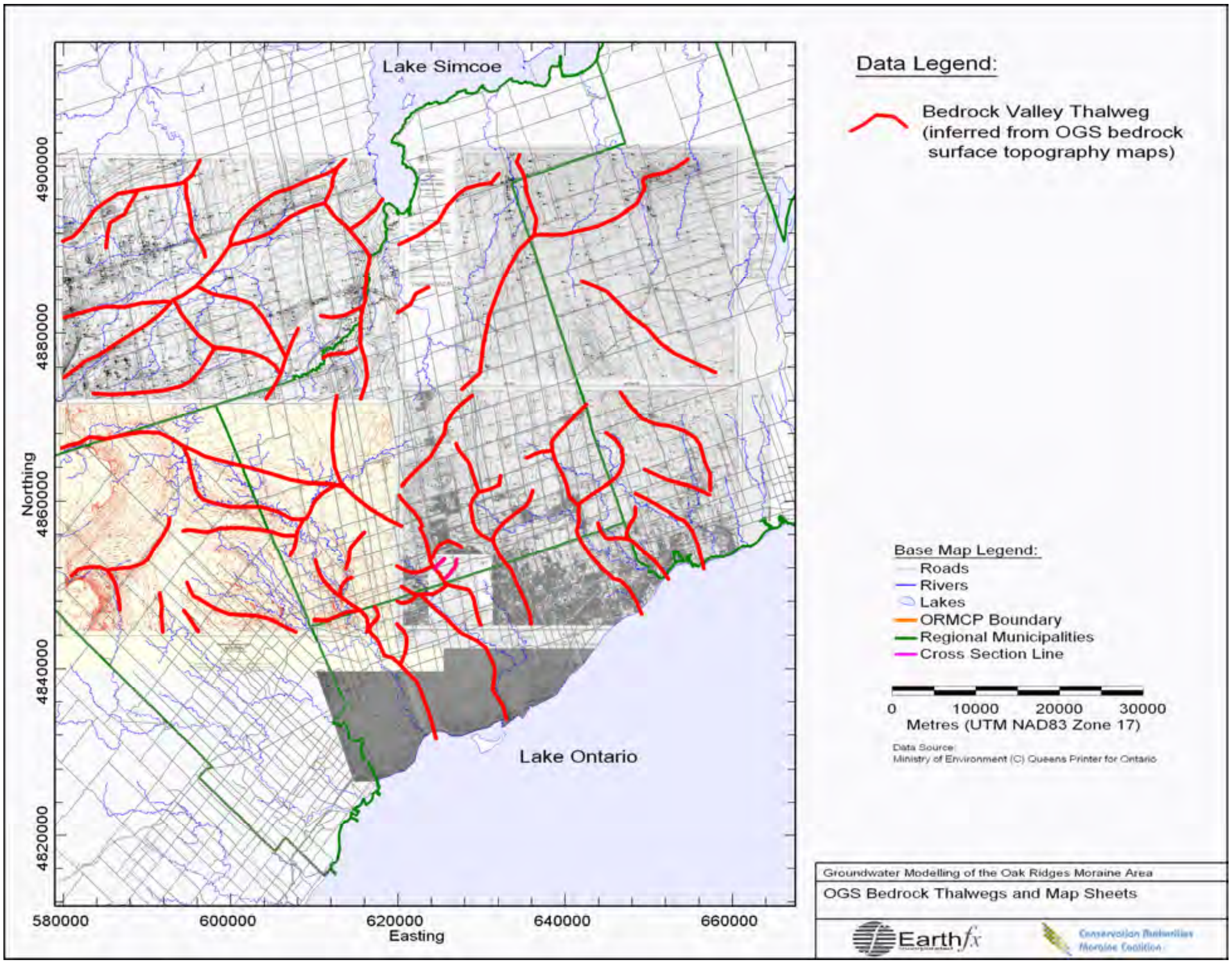

Figure 8: OGS bedrock surface topography map sheets showing bedrock valley thalwegs

The interconnectivity of the bedrock valley systems is important, for if they are connected, they may act as conduits for groundwater flow. A river of continental scale, such as the Laurentian Channel, would have had sufficient flow in its main channel and tributaries to form a significant interconnected valley network.

A bedrock plateau referred to as the Simcoe rise dominates the east and north of the study area. A portion of this plateau is visible in the northernmost section of **Figure B119** in Appendix B. The Simcoe rise, while not as pronounced as the Niagara Escarpment in the west, defines the northeastern limits of the broad depressional area in which the Laurentian River generally flowed, although tributaries to the Laurentian River may well have originated on this highland.

A small "finger" like feature of limestone in central York Region is visible on the OGS bedrock maps (**Figure 4**). No direct borehole evidence for this feature was found in the water well records, however, the position of the finger is roughly consistent with the position of a bedrock valley tributary identified in Newmarket. The river flowing within this valley may have eroded through the Georgian Bay shale, exposing the underlying Simcoe Group limestones in the bottom of the valley.

Ancient rivers and subglacial ice scouring were not the only erosive forces that affected the bedrock surface. There is some evidence to suggest that subglacial outburst events might also have had enough energy to erode both sediment and bedrock layers (Sharpe et al., 2002a). The subglacial outburst channels formed by such events, referred to as “tunnel channels”, are discussed further on in this report.

2.4.3 Recent Glaciation

The remnants of two main periods of glaciation are present in the study area. Relatively few sediments of the Ilinoian Glaciation and Sangamon Interglacial periods remain, thus the stratigraphic column is dominated by sediments of the more recent Wisconsinan period. The sediments of the Ilinoian glaciation period (approximately 135,000 years before present (BP)) are limited to the York Till deposits most commonly found in the deeper bedrock valley systems, particularly in the south.

The last major ice advance, the Late Wisconsinan, (25,000 to 12,000 years BP) was from the northeast (**Figure 9**) and along the axis of the Great Lake basins. During this interval, the Laurentide Ice Sheet deposited a thick widespread till sheet or amalgamated sheets generally referred to in the Toronto area as the Newmarket Till (also referred to as the Northern Till). This till overlies thick lower deposits and both sequences continue under the ORM. This regional till sheet is variable in thickness (Sharpe et al., 2002b) and has been eroded in many locations by meltwater to form a regional unconformity consisting mainly of drumlinized till and a network of channels (Barnett, 1990). The ORM sediments rest on this eroded terrain and formed approximately 12,000-13,000 BP (Gwyn and Cowan, 1978).

Figure 9: Maximum extent of the Laurentide ice sheet approximately 18-20,000 years BP.

The ORM occurs as thick stratified sediments, partly capped by thin Halton Till along its southern flank. The ORM sediments were deposited in association with a glacial lake (Gilbert, 1997 and Barnett et al., 1998) set in a re-entrant or cavity between thick ice lobes of the Laurentide Ice Sheet to the north and a low-relief ice lobe occupying the Lake Ontario basin to the south (**Figure 10**). ORM deposits are part of a larger system of ice-controlled meltwater deposition during final deglaciation that includes stratified moraines west of the ORM (Gwyn and Cowan, 1978).

The south flank of the ORM is capped by a till unit referred to as the Halton Till. The youngest glacial deposits consist of glaciolacustrine sediments that form a thin veneer over the Halton and Kettleby Till units. The location of these surficial deposits is shown on the surficial geology map provided as **Figure 12**, and are discussed in more detail in the following section.

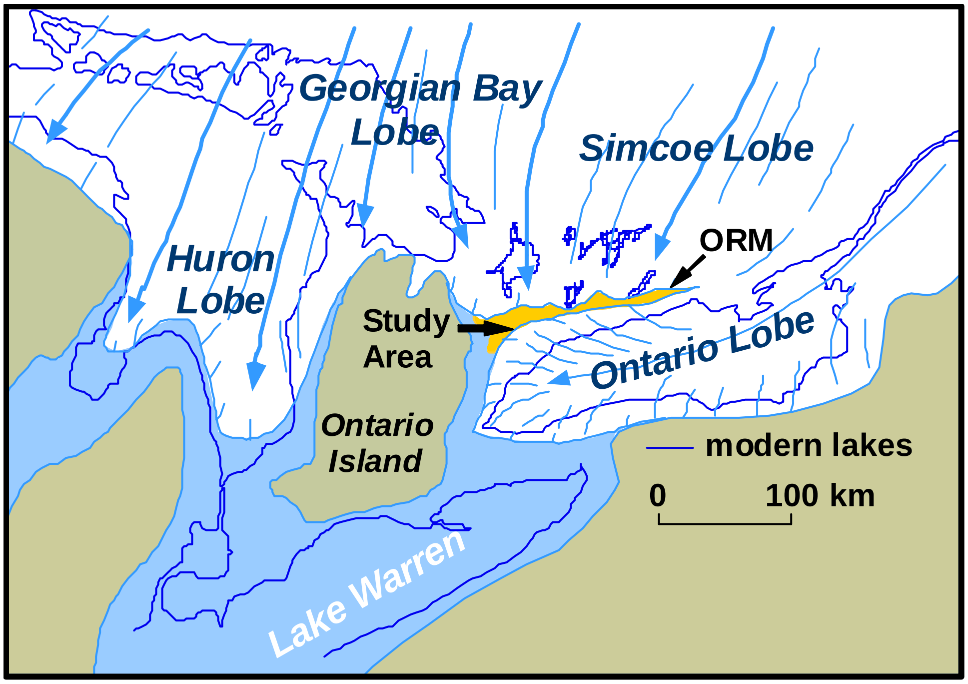

Figure 10: Deposition of the Oak Ridges Moraine between two ice lobes approximately 12-13,000 years ago (from Chapman and Putnam, 1984).

2.4.3.1 Quaternary Sediments

Quaternary glacial sediments within the study area consist of glacial and interglacial deposits formed within the last 135,000 years (Eyles, 2002 and Karrow, 1989). Recent summaries describe the glacial history of southern Ontario (Barnett et al., 1991), the ORM (e.g. Barnett et al., 1998) and till plains south of the ORM (Martini and Brookfield, 1995 and Boyce et al., 1995).

Quaternary glacial and non-glacial sediments are exposed along the southern boundary of the study area along the Lake Ontario bluffs and in the Don Valley Brickyard (e.g. Eyles and Clark, 1988; Karrow, 1967; and Brookfield et al., 1982) and underlie the ORM (Duckworth, 1979, Sado et al., 1984; and Eyles et al., 1985). This complex package consists of till, glaciolacustrine and glaciofluvial sands, silts, clays and diamictons and includes Illinoian-age till and warm-climate interglacial sediments overlain by Early to Middle Wisconsinan age (25-90,000 years BP) glacial lake sediments (Karrow, 1967) (**Figure 11**). **Table 2** provides a schematic summarizing the Quaternary sediments generally found in the central part of the study area.

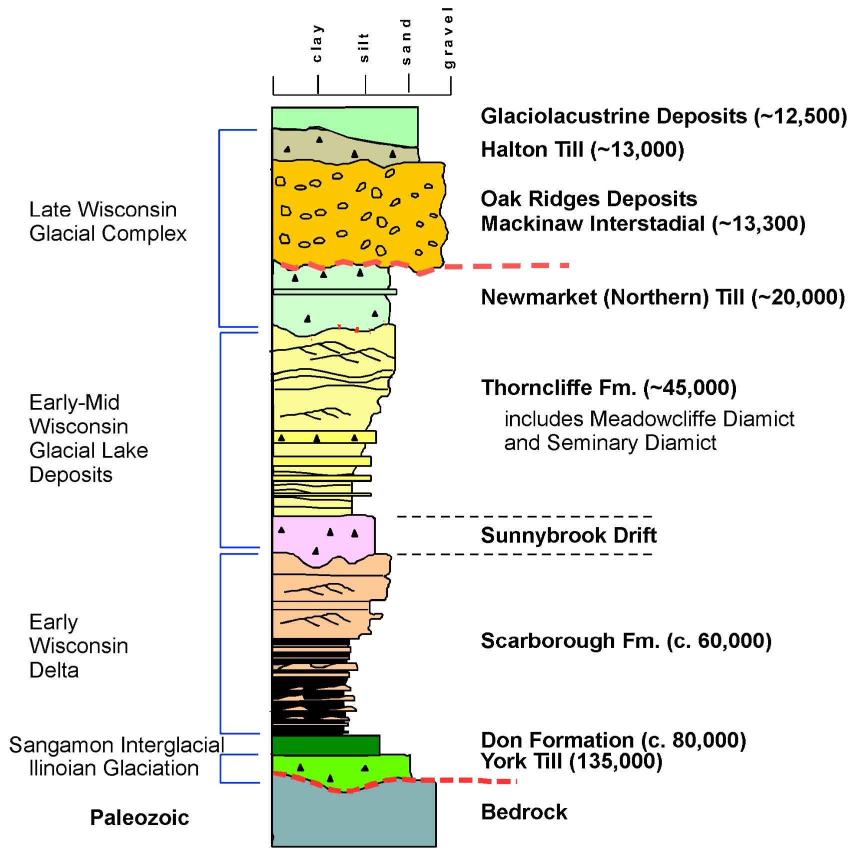

Figure 11: Quaternary deposits found within the study area (from Eyles, 2002).

A number of different geologic studies have been conducted across the ORM area. Early work on the ORM has been summarized by Duckworth (1979), Gwyn and Cowan (1978), and Chapman (1985). These studies have relied on analysis of water well records, earlier geologic mapping (e.g. Deane, 1950), and later work by the OGS (Watt, 1957 and Karrow, 1967). This geologic mapping was important for regional hydrogeological assessments conducted by Haefeli (1970), the Ontario Ministry of Environment (Turner, 1977; 1978; Sibul et al., 1977; Ostry, 1979; and Vallery et al., 1982) and others (e.g. Howard and Beck, 1986 and Howard et al., 1997). Much of this earlier geologic work has been updated by the GSC (Russell et al., 2002b) and by the work conducted as part of this study.

These studies have used different terminology for the various Quaternary deposits found within the study area. **Table 2** summarizes the nomenclature from various studies and provides an initial attempt at correlation of the terminology used. Obviously there is a lack of widespread use of formal stratigraphic names in the study area. It should be noted that not all deposits shown on **Table 2** are present everywhere throughout the study area. For example, north of the ORM, the Sunnybrook Drift (or equivalent) is largely absent and the Newmarket Till overlies limestone bedrock with local occurrences of Thorncliffe Formation (or equivalent) fluvial and lacustrine deposits. In the western part of the study area south of the ORM, the deposits generally include the Thorncliffe Formation (or equivalent) and younger units. In many locations in the west the Halton Till directly overlies bedrock and all older deposits are absent.

Table 2: Geological correlation for the Oak Ridges Moraine study area

Geologic Correlation for the Oak Ridges Moraine/South-Central Ontario study area.

Classification		WEST ORM					TORONTO-CENTRAL ORM			EAST ORM					ORM
		west Georgian Bay Lobe	northeast Simcoe Lobe	southeast Ontario Lobe	north Simcoe Lobe	south Ontario Lobe									
Dreimanis&Karrow,1972 Johnson et al.,1991	~Age	Orangeville Area Cowan, 1976			Bolton Area White, 1975		Karrow 1967	Westgate 1979	Boyce et al 1995	Gwyn 1976a; b	Brookfield et al. 1982		Funk 1977	Singer 1974, 1981	GSC
Holocene	10 ka														
Late Wisconsinan					Lake Schomberg	Lake Peel	Lake Iroquois	Lake Iroquois	Lake Iroquois		Lake Iroquois	Unit 6	Lake Iroquois	Proglacial Lake	
Port Huron Stade	13 ka		Kettleby Till Newmarket Till	Wentworth Till	Northern Upper Till	Wildfield Till Halton Till	Upper Leaside Till	Halton Till	Halton Till	Halton Till	Bouchette Till	Unit 5	Upper Drift	Upper Glacial Unit	Halton Till
Mackinaw Interstade	13.4 ka				sa,si,cl,gr	sa,si,cl,gr		Interstadial?	Mackinaw Interstadial		Mackinaw Interstadial				Oak Ridges Moraine
Port Bruce Stade	14.8 ka	Tavistock Till	Orangeville Interlobate Moraine	Port Stanley Till											
Erie Interstade	15.5 ka	glaciolacustrine													
Nissouri Stade	20 ka	Catfish Creek Till			Northern Lower Till	Wentworth Till	Lower Leaside Till	Westhill till	Northern till	?	Bowmanville till	Unit 4	Upper Drift	Middle Glacial Unit	Newmarket Till
Middle Wisconsinan	30 ka	unknown			absent	absent	Seminary Till Meadowcliffe Till	Thorncliffe Formation		Clarke Deposits	Bond Head Till	Unit 3 Unit 2C Unit 2B Unit 2A	Middle Drift	Clarke Deposits	Lower Sediments
	60 ka					Sunnybrook Till	Sunnybrook Drift				Port Hope Till	Unit 1	Lower Drift	Lower Glacial	
Early Wisconsinan	115 ka	unknown				Scarborough Fm.	Scarborough Fm.								
Sangamonian	135 ka	unknown					Don Fm.								
Illinoian	190 ka	unknown				York Till	York Till								
Upper Silurian	~418 Ma														
Middle Silurian															
Amabel Fm.			dolomite		dolostone										
Fossil Hill Fm.			dolomite		dolostone										
Lower Silurian															
Cabot Head Fm.			shale/sandstone/shale		shale/limestone										
Manitoulin Fm.			dolomite		dolomitic limestone										
Whirlpool Fm.			sandstone		sandstone										
Upper Ordovician	~438 Ma														
Queenston Fm.			shale		red shale										
Georgian Bay Fm.					shale/siltstone/limestone										
Blue Mountain Fm. (Whitby Fm.)					shale		shale	shale	shale	shale			shale	shale	shale
Middle Ordovician	~478 Ma														
Simcoe Group (Lindsay Fm.)										limestone			limestone	limestone	limestone

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Notes:

1 Production of this chart required some interpretation of the information provided in each of the sources referenced. Future use and interpretation may lead to some refinement.

2 Quaternary units containing aquifers shown in yellow.

2.4.4 Surficial Geology

The surficial geology of the study area, as mapped by the Geological Survey of Canada, is shown in **Figure 12**. The areas outside the GSC mapping area have been filled in with data released, in draft form, by the OGS (This information was further refined and released in final form by the OGS in 2003). The map shows the location of the major till units (predominantly Halton Till and Newmarket Till), coarser sediments associated with the Oak Ridges Moraine, and beach deposits associated with glacial Lake Iroquois and Lake Algonquin.

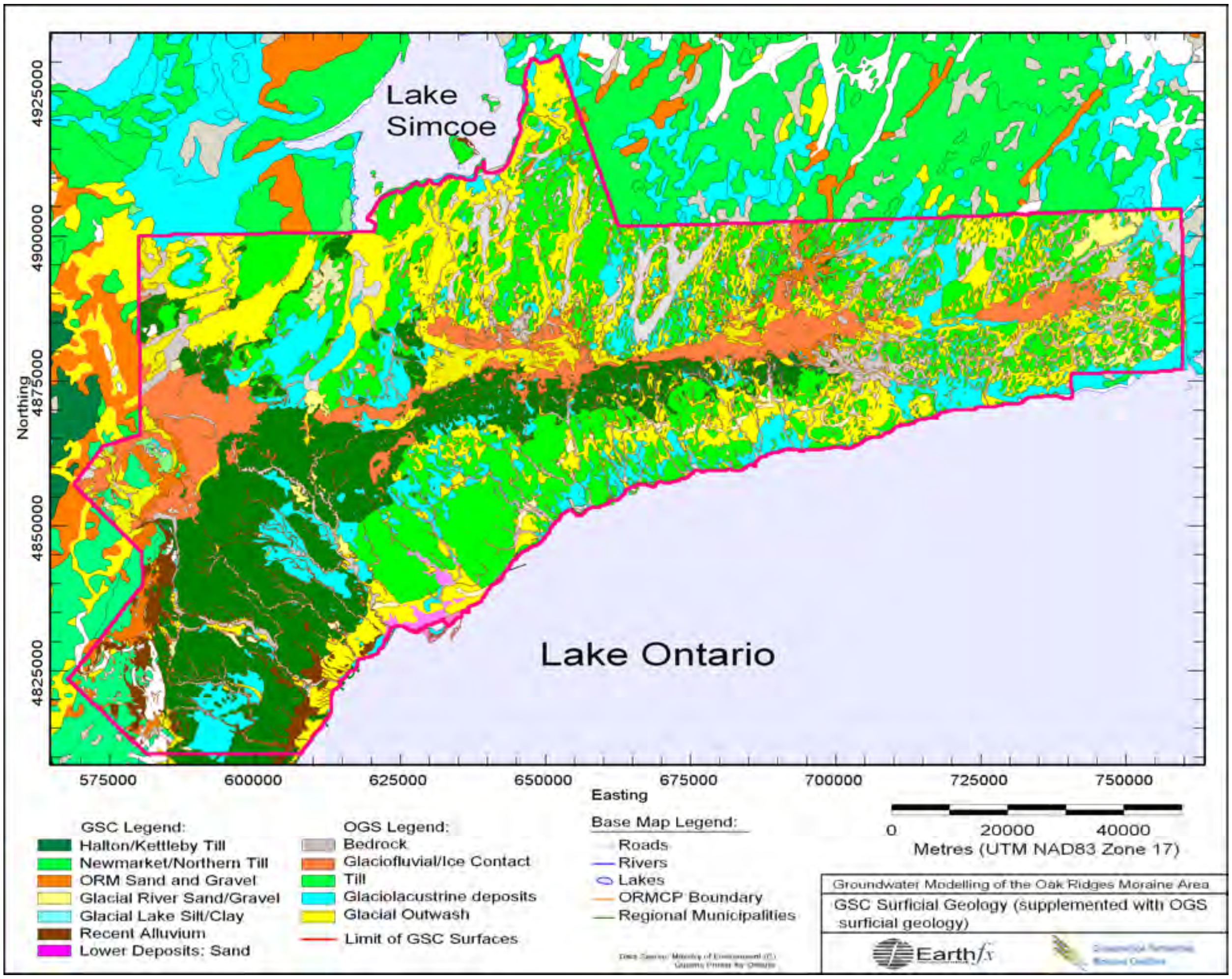

Figure 12: Surficial geology (simplified from Sharpe et al.,1997 and from OGS, 2003)

An enlargement showing a 3-D perspective view of Toronto and York Region looking from the southeast) is provided in **Figure 13**.

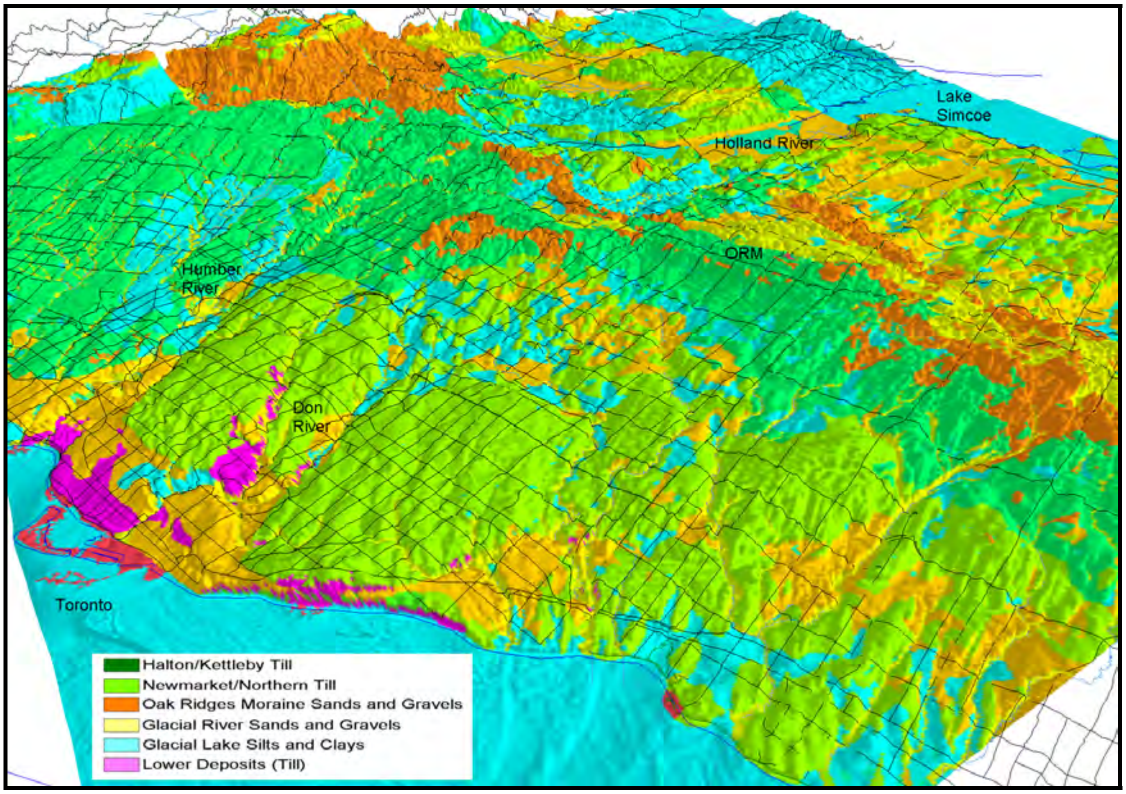

Figure 13: Surficial geology showing onlapping of Halton Till onto south flank of the ORM (3-D view looking to the northwest).

2.4.5 Physiography

The physiography reflects the complex geologic history of the study area and is described in Chapman and Putnam (1984). A section of their map, showing the major physiographic features, is presented in **Figure 14**. The Oak Ridges Moraine, the brown shaded area in the centre of **Figure 14**, stands out as one of the most distinctive physiographic units of Southern Ontario (Chapman and Putnam, 1984). The surface is hilly, with a knob and basin (hummocky) relief. The main ridge of sand and gravel deposits is generally believed to be an interlobate moraine that formed during the recession of the Wisconsinan glaciation about 13,000 years ago. It passes east-west through the centre of York Region, roughly midway between Lake Simcoe and Lake Ontario (**Figure 2**). The ridge formed by the ORM ranges in altitude from 405 masl in the east to 305 masl in the west and extends eastward from the Niagara Escarpment to the Trent River, a distance of over 160 km.

The majority of the moraine's hills are composed of sandy or gravelly materials, however, some of the highest points are formed of till which caps the sand. The elongate structure can be divided into four major "wedges" where the north-south extent of the moraine widens. These wedges are located, from west to east, in the vicinity of Albion Hills, Uxbridge, Pontypool, and east of Rice Lake (Barnett, 1998).

Due to its predominantly sandy surface soils and hummocky topography, the moraine serves as the primary recharge area to underlying aquifers. The ORM forms a surface water and groundwater divide between water flowing south to Lake Ontario and water flowing north to Lake Simcoe and the Kawartha Lakes. While few streams are located on the moraine itself, springs along the lower slopes of the moraine provide groundwater discharge to streams that drain the till plains to the north and south. These springs have their source areas on the Oak Ridges Moraine.

The area south of the Oak Ridges Moraine has been divided into three physiographic regions: the South slope; the Peel Plain, and the Iroquois lake plain (Chapman and Putnam, 1984). In the GTA area, the South Slope is a smooth, faintly drumlinized clay till plain containing the deeply incised stream valleys of the Credit, Humber, Don, and Rouge Rivers. Elevations range from about 280 masl where the South Slope intersects the ORM to about 80 masl near the Lake Ontario shoreline. Further east, larger rivers that dissect the South Slope include the Ganaraska River, Shelter Valley Creek, and the Trent River along the eastern boundary of the model area.

In the west, the Peel Plain lies within the centre of the South slope area and is a faintly undulating to flat till plain with a lake clay veneer. The Peel Plain is also deeply incised by the stream valleys. Finally, the Iroquois lake plain represents the near-shore area of glacial Lake Iroquois. Beach sand and lacustrine silts and clays have been deposited on the 5-km wide lake plain. Embayments along the former shore (e.g. in the Duffins Creek and Trent River areas) have resulted in Lake Iroquois sediments being deposited a greater distance north of the present Lake Ontario shoreline. The Halton and older tills have been cut down and eroded by wave action in the west part of the study area.

North of the ORM, the physiographic regions include the Schomberg Clay Plain, Simcoe Lowlands, and the Peterborough Drumlin Field. The Schomberg Clay Plain is marked by thick deposits of varved lake clays. The Simcoe Lowlands were flooded by glacial Lake Algonquin and contain flat-bottomed valleys floored by sand, silt, and clay. The Peterborough Drumlin Field is notable for both its drumlins and eskers.

The western edge of the study area encompasses the Niagara Escarpment, a cuesta ridge stretching from the Niagara Falls area in the south to Georgian Bay in the north. The Escarpment forms a prominent ridge some 30 m height along much of its length. In areas where the ORM abuts against it, the Escarpment is buried and no cliff edge is visible. Above the Escarpment, three physiographic regions are noteworthy: the Guelph Drumlin Field; the Hillsburgh Sandhills and the Horseshoe Moraines (which includes the Paris, Galt and Moffat Moraines).

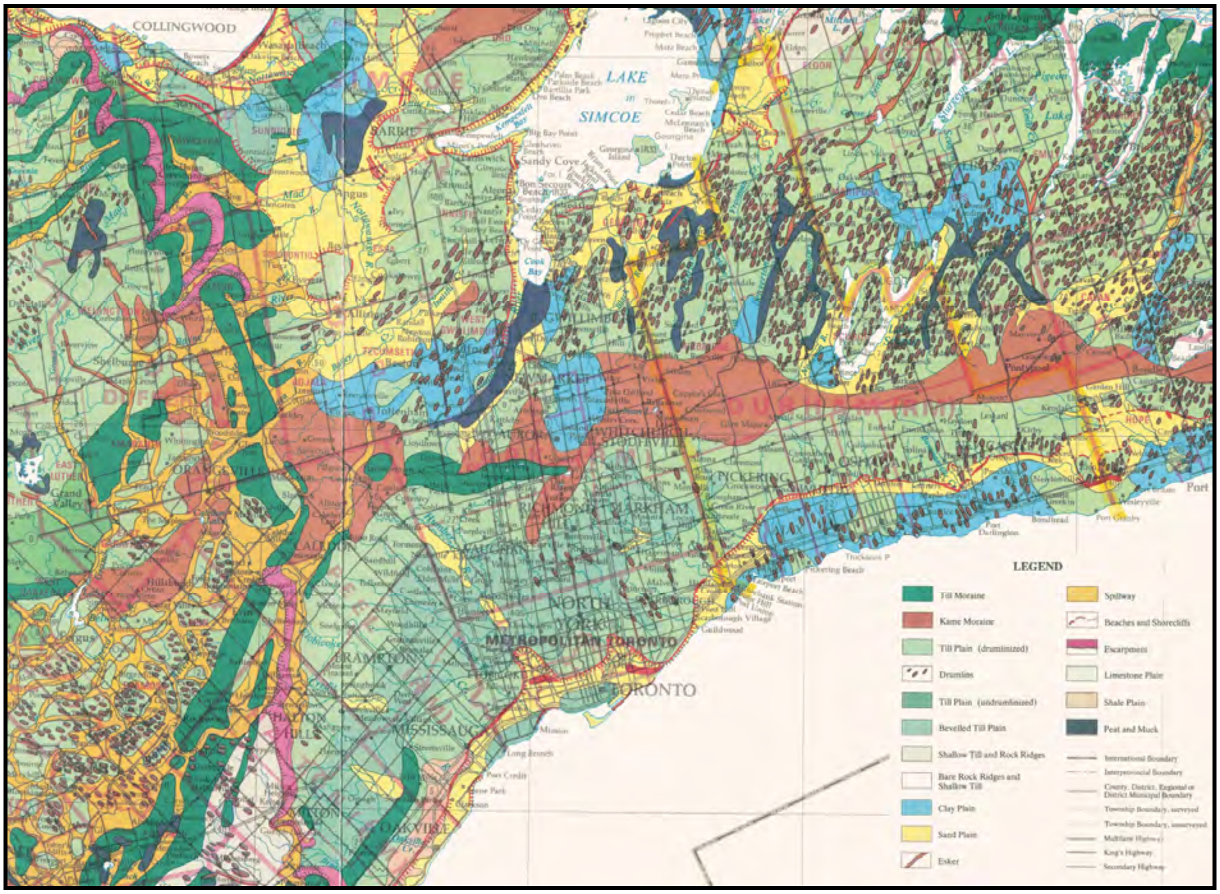

Figure 14: Physiographic regions from Chapman and Putnam (1984).

2.4.6 Topography

The Oak Ridges Moraine forms the height of land running east-west through in the centre of the study area (**Figure 2**). Land slopes down to the north and south on either side of the moraine. Land surface topography in the central part of the study area varies from a minimum elevation of 75 masl (metres above sea level) at Lake Ontario to a maximum of about 405 masl on the crest of the ORM south of the town of Uxbridge in Durham Region (**Figure 15**). Land surface topography at Lake Simcoe is at an elevation of about 219 masl. Above the Niagara Escarpment, in the northwest parts of the Credit River watershed, the ground surface rises to just over 500 masl.

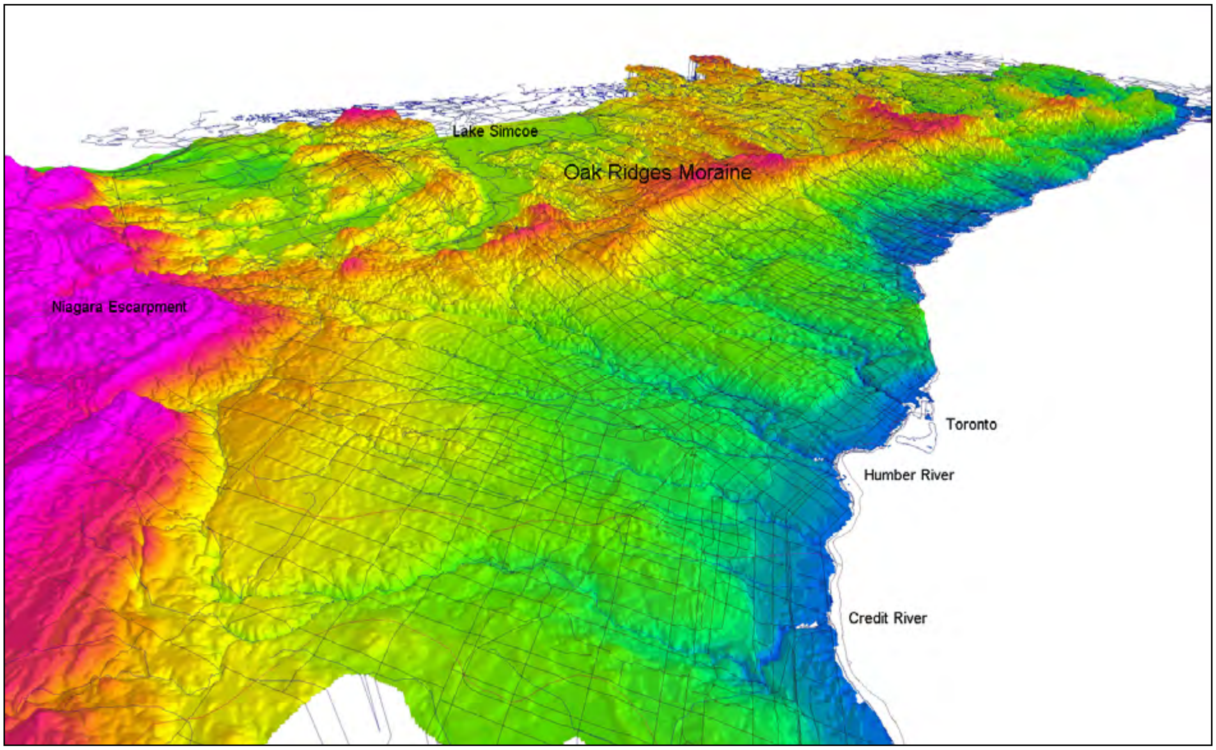

Figure 15: 3-D view of the ground surface, looking northwest from Hamilton, Ontario. The ORM is visible as a long ridge (in red).

The MNR provided two digital elevation models (DEM) for the study area, including a 10-m and 30-m DEM. The hydrologically-corrected 10-m DEM was used as the basis for all modelling except within the City of Toronto, where 10-m coverage was not available. Instead, the 30-m DEM was used within the general bounds of the City of Toronto. Hydrologic correction of the DEM, which was carried out by MNR, adjusted the elevations in the vicinity of streams to ensure that all the streams in the network continuously flowed downhill. This aided in the accurate representation of the stream network within the model.

2.5 Stratigraphy of Sedimentary Deposits

This section presents a detailed discussion of the complex sedimentary deposits in the study area. The focus of this discussion is on the central portion of the study area, particularly where the Laurentian River bedrock valley system passes through York Region and the City of Toronto. This is the area where the thickest and most complete package of sediments is found and also the area where the greatest amount of data is available. The stratigraphic units extend further to the east and west but many of the units are truncated to the north by the rise in the bedrock surface.

2.5.1 Sediment Thickness

The thickness of unconsolidated sediment within the study area ranges from approximately zero, where bedrock outcrops at ground surface, to 270 m where the Oak Ridges Moraine overlies the Laurentian Channel, as derived from bedrock surface topography (Brennand et al., 1997) and land surface topography. A map showing estimated sediment thickness (based on the GSC digital geological model) is provided in **Figure 25** and in Appendix B (**Figure B120**). The unconsolidated sediments are thinnest in the northeast near Lake Simcoe, north of Rice Lake, and in the southwest within Peel Region. The thickest sequences of Quaternary deposits are situated over two general areas: one is in the vicinity of the Oak Ridges Moraine while the other is within the vicinity of the Laurentian Valley system. It is within the thick valley sediments that older deposits such as the Sunnybrook Drift and Scarborough Formation are more likely to be found. Other areas of thicker sediments occur locally within the bedrock valley tributary systems. In the thinner sediment areas, the older sediments are largely absent.

2.5.2 GSC Digital Stratigraphic Layers

The stratigraphic framework for the study area has been studied in detail over the last 12 years by researchers at the Geological Survey of Canada (Sharpe et al., 1999). The GSC has developed their conceptual stratigraphic model (shown schematically in **Figure 16**) and interpreted the available borehole data to construct what are referred to as the Version 1 digital stratigraphic surfaces. These surfaces define the tops of five geologic units, which are (from youngest to oldest):

1. Halton Till (Russell et al., 2002a);
2. Oak Ridges Moraine Deposits (Russell et al., 2002b);
3. Newmarket Till (Sharpe et al., 2002b);
4. Lower Sediments (including York, Scarborough, Sunnybrook and Thorncliffe units) (Sharpe et al., 2002c); and
5. Bedrock (Brennand et al., 1997).

Regional unconformities occur upon the bedrock and Newmarket Till surfaces. The GSC has also provided preliminary information on the locations of tunnel channels and breaches in the till aquitard that trend roughly north-south to northeast-southwest through the study area (Russell et al., 2003). These digital surfaces formed the basis for the ORM Regional Model and are discussed further below.

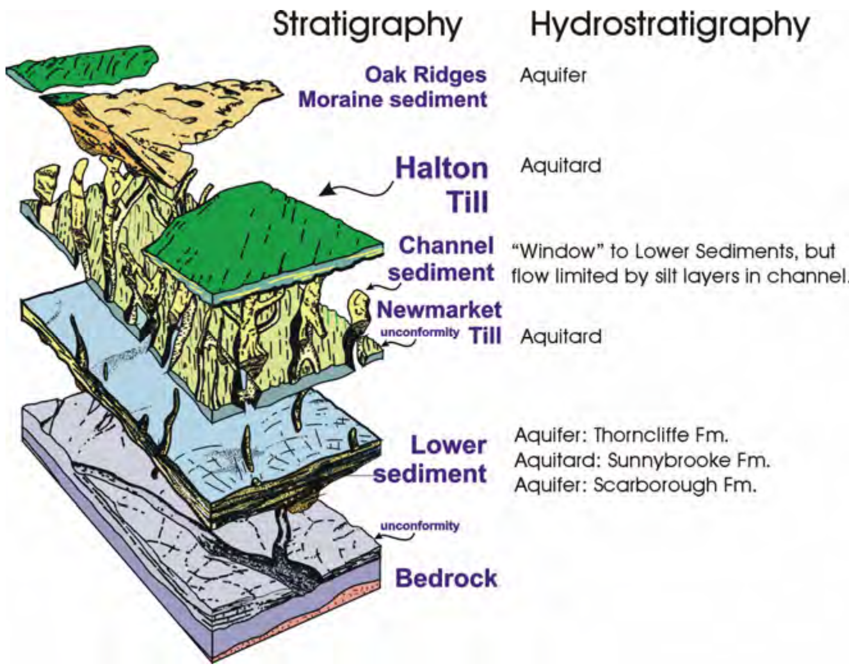

Figure 16: GSC stratigraphic model of the ORM area (from Sharpe et al., 1999)

2.5.3 Pre-Wisconsinan Deposits

2.5.3.1 York Till

The York Till is the oldest known glacial sediment in southern Ontario and was deposited during the Illinoian glaciation approximately 135,000 years BP (Eyles, 2002 and Barnett, 1992). The York Till occurs only sporadically within the study area and is believed to be preserved mainly in lows directly on the bedrock surface. The till is described as dark grey with a sandy silt matrix and includes clasts of the underlying shale. The York Till has been described in outcrops near Woodbridge (Karrow et al., 2001) and in the Don Valley Brickyard (Eyles and Clark, 1988). The till is also interpreted to occur immediately above bedrock in a borehole drilled by Gartner Lee Limited in Uxbridge (GLL, 2003). Given the discontinuous nature of this deposit and the paucity of deep borehole data within the study area, the York Till has not been mapped for this investigation.

2.5.3.2 Don Formation

The Don Formation was deposited between approximately 125,000 to 80,000 years BP during a warm interglacial period known as the Sangamon Interglacial (Eyles, 2002). Like the York Till, the Don Formation is only rarely preserved within the study area. It has been observed in outcrops near Woodbridge (Karrow et al., 2001) and in the Don Valley Brickyard (Eyles and Clark, 1988). The unit is described as having alternating beds of fossiliferous sand and mud deposited in near-shore areas of an ancestral Lake Ontario. The sands represent wave-agitated near-shore conditions with the muds representing calmer near-shore conditions (Eyles, 2002). Given the discontinuous nature of this deposit and the paucity of deep borehole data, this unit has also not been mapped during this study. It is also assumed that the sand and mud of this deposit would be impossible to distinguish from the overlying Scarborough Formation based on the data presently available.

2.5.4 Wisconsinan Deposits

2.5.4.1 Scarborough Formation

The Scarborough Formation marks the onset of the Wisconsinan glaciation which started approximately 100,000 years BP. The Scarborough Formation deposits are interpreted as a fluvio-deltaic system fed by large braided melt-water rivers draining from an ice sheet depositing prograding organic-rich (peat) sands over silts and clays (Karrow, 1967 and Eyles, 1997). The lower prodelta silts and clays are up to 60 m thick at the Scarborough Bluffs along Lake Ontario and are believed to be in transitional contact with the muds of the underlying Don Formation (Eyles, 1987). The upper sands are channelized in some locations, possibly as a result of fluvial erosion due to fluctuating lake levels. The delta is considered to extend over 200 km^2 and was deposited by a large river flowing from Georgian Bay along the Laurentian Channel to ancestral Lake Ontario. Lake levels must have been approximately 45 m higher than present with the top of the Scarborough Formation occurring at approximately 120 masl in the Toronto area, perhaps indicative of some type of ice damming to the east.

Scarborough Formation deposits are believed to extend from the Lake Ontario shore northward towards Lake Simcoe (Fligg and Rodrigues, 1983; Eyles et al., 1985; Pugin et al., 1996; and Sharp et al., 1996). Organic matter and methane gas in the Alliston aquifer (Aravena and Wassenaar, 1983 and Turner, 1977) are interpreted to indicate organic-rich Scarborough Sand deposits in the Laurentian channel. However, others believe that the Alliston Aquifer Complex is contemporaneous or part of the Thorncliffe Formation deposits (Eyles, 1997). The Scarborough Formation (or equivalent) is only found in appreciable thickness within the Laurentian Valley. The Scarborough Formation is absent in the northeast and west where it is truncated by the higher bedrock elevation of the Simcoe Rise and Niagara Escarpment. It is also absent in the western part of the study area, west of Woodbridge and Kleinburg and northwest of Nobleton, where younger sediments directly overlie bedrock. Further details regarding unit thicknesses and orientation are included in Section 3.

2.5.4.2 Sunnybrook Drift

The Sunnybrook Drift was deposited in close proximity to the edge of the ice sheet which reached the study area about 45,000 years ago. The Sunnybrook Drift is interpreted to be a clast-poor mud (silt and clay) deposited on the floor of a glacially dammed lake approximately 100 m deeper than the modern Lake Ontario (Eyles, 2002). Boulders and pebbles are rare and are interpreted to be dropstones from melting icebergs. An alternate explanation is that this unit consists of multiple diamicton (till-like) beds resulting from the inter-fingering of ice marginal flow tills and subglacial deformation and lodgement till (Barnett, 1992). Another interpretation is that this unit is a deformation till resulting from glacial overriding of lake clays (Hicock and Dreimanis, 1989) and has been identified near Woodbridge as a pebble-free mud (White, 1975). The Sunnybrook Drift is generally less than 10 to 20 m thick but thickens over lows such as within bedrock valley systems. It has also been partially removed by erosional processes, particularly along the western part of the study area where the bedrock rises in Peel and Halton Region. Further details are provided in Section 3.

2.5.4.3 Thorncliffe Formation

The Thorncliffe Formation includes glaciofluvial deposits of sand and silty sand, yet further to the south is comprised of predominantly glaciolacustrine deposits of silt, sand and pebbly silt and clay. In general, this unit was deposited by glacial meltwaters entering a deep, ice-dammed ancestral Lake Ontario. The Thorncliffe Formation is characterized by significant facies changes over short distances, generally on the kilometre scale (Interim Waste Authority Limited, 1994a-e; M.M. Dillon Limited, 1990). The basal part of this unit is often marked by silt-clay rhythmites. This unit was deposited approximately 30,000 to 50,000 years BP (Barnett, 1992). The pebbly silt and clayey silt units within the Thorncliffe are known as the Seminary and Meadowcliffe Diamict units where they occur along the Scarborough Bluffs and are believed to have limited extent north of the Bluffs (Barnett, 1992; Eyles and Eyles, 1983; and Karrow, 1967).

Recent geotechnical investigations for trunk sewer projects in York Region, particularly along 16th Avenue, have encountered considerable variation in grain size and thickness of sands within the Thorncliffe Formation. This is interpreted to represent the deposition of coarser material by fluvial or subaqueous processes in a north to south linear or fan-like fashion from a more northerly source (Sharpe et al., 2002c), perhaps similar to that proposed for parts of the underlying Scarborough Formation (Kelley and Martini, 1986). The fine-grained sand and silty sand deposits represent deposition in a more distal or lateral position from the sediment source.

Thorncliffe Formation deposits are present through most of the study area, however locally they may be absent due to non-deposition or to erosion by glacial ice or subglacial tunnel channel activity. Where they occur, the tunnel channel infill deposits are often in lateral hydraulic connection with the adjacent Thorncliffe Formation deposits into which they have been cut. The Thorncliffe Formation is generally absent in the northeast near Lake Simcoe where thin, younger tills often occur directly over limestone bedrock. The top of the Thorncliffe Formation is generally less than 260 masl beneath the Oak Ridges Moraine and drops to approximately 150 masl along the York Region/Metropolitan Toronto boundary. The general drop in elevation of the unconsolidated sediment stratigraphy from north to south and westward towards the Laurentian bedrock channel is typical for the study area and basically reflects a generalized draping of the unconsolidated sediments upon the bedrock surface. A map showing the estimated top of the Thorncliffe Formation (based on the GSC digital geological model) is provided in Appendix B (**Figure B121**).

2.5.4.4 Lower Sediment Thickness

The GSC digital stratigraphic model grouped the York, Scarborough, Sunnybrook and Thorncliffe units together as the Lower Sediments. A map showing estimated Lower Sediment thickness (based on the GSC digital geological model) is provided in **Figure B122**.

As part of the current study, the GSC Lower Sediment unit was vertically subdivided into three units, corresponding to the Scarborough Aquifer (or equivalent), the Sunnybrook Aquitard (or equivalent), and the Thorncliffe Aquifer (or equivalent). Details regarding the interpretation and methodology for subdividing the Lower Sediment unit are provided in Section 3.

2.5.4.5 Newmarket Till

The Newmarket Till is a diamict deposited by the Laurentide Ice Sheet when it advanced to its maximum extent, approximately 18-20,000 years BP. The Newmarket Till is sometimes referred to as the Northern Till, Lower Leaside, or Lower Halton Till (see Table 2).

The Newmarket Till is typically a massive, frequently over-consolidated, stony (3-10 %) and dense silty sand diamicton (e.g. Gwyn, 1976; Barnett et al., 1991; and Sharpe et al., 2002b). Locally, the unit can contain 2-5 cm thick interbeds of sand and silt, boulder pavements, and fractures and joints. It can also contain small injections, dykes, breccia and rafts from lower sandy beds. Discontinuous sand beds, up to 1-2 m thick, may also be present. In rare instances, it can contain thin rhythmites or isolated clay laminae. The impact of this complex structure on the hydrogeological properties of the Newmarket Till is discussed in Section 3.

The till matrix is predominantly calcite-cemented sandy silt to silty sand with a clast content mainly comprised of limestone with a minor component of Canadian Shield materials. The Newmarket Till has been traced as a stratigraphic marker across the entire study area and separates the upper aquifer systems associated with the Oak Ridges Moraine sediments from the lower aquifer systems that occur within deposits of the Thorncliffe Formation and the Scarborough Formation. The Newmarket Till contains breaches where it has been eroded by subglacial meltwater activity.

The Newmarket Till is subglacial in origin with incremental till accumulation, periodically interrupted by meltwater scours and localized deposition of sand and silt (Boyce et al., 1995; Sharpe et al., 2002b). The till is characterized by high seismic velocities in downhole sonic logs obtained over wide areas. The contrast in velocities between the till (2000-3000 m/s) and overlying sediments (1500-2000 m/s) makes it a prominent reflector on seismic profiles (Pullan et a., 1994; Boyce et al 1995; and Pugin et al., 1999). The extent and stratigraphic relationship of the Newmarket Till to other till sheets has been discussed in Sharpe et al (1994b), and Boyce et al (1995).

The sedimentary character of this till indicates some loading from overlying ice during deposition, but not enough to rearrange widespread fine sedimentary structure within the underlying Thorncliffe Formation. Locally, the diamicton is interbedded and appears to have formed as debris flows. In other places, discontinuous boulder pavements may be found with striated upper surfaces. In total, this diamicton complex includes thick massive sequences to bedded and interbedded layers of diamicton that formed by a variety of subglacial processes (Sharpe et al., 2002b).

The Newmarket Till surface undulates north of the ORM (Gwyn and DiLabio, 1973) and has been interpreted to carry both drumlins and channels as part of a regional unconformity. This erosional surface is considered to have been formed by subglacial sheet-flows, producing drumlins (Shaw and Sharpe, 1987) followed by waning-stage, entrenched flow, producing channels (Brennand and Shaw, 1994). GSC researchers have interpreted that the upper surface of the Newmarket Till forms a regional unconformity (Sharpe et al., 2002b).

The Newmarket till is locally up to 100 m thick but typically is approximately 20-30 m thick. The till has been partially or fully eroded where glacial meltwater flow has cut down into underlying sediments. The top of the Newmarket Till is generally less than 300 masl beneath the Oak Ridges Moraine and drops to approximately 170 masl along the York Region/ Metropolitan Toronto boundary. A map showing the estimated top of the Newmarket Till (based on the GSC digital geological model) is provided in **Figure B123** and a map showing the estimated thickness of the Newmarket Till is provided in **Figure B124**.

2.5.4.6 Regional Unconformity (“Tunnel Channels”)

The GSC Stratigraphic Framework identified a regional unconformity at the top of the Newmarket Till (Sharpe et al., 1999). Erosional features at this unconformity include an interpreted network of south to southwest-oriented channels that have cut into or through the Newmarket Till. The GSC has attributed this channel network to subglacial meltwater flood events (Barnett, 1990; Shaw and Gilbert, 1990; and Russell et al., 2002) as illustrated in **Figure**

17. The infill deposits within these “tunnel channels” are attributed to waning flow after the flood event (Shaw and Gorrell, 1991) as shown in **Figure 18**.
The most significant point with respect to tunnel channels is that there have been erosional events that, in some areas, cut into the surface of the Newmarket Till and possibly the underlying sediments. The erosional channels were subsequently in-filled. Whether these erosional events were subglacial or subaerial and the actual processes that caused the erosion are not issues that will be resolved in this report.

As part of the current study, these channels have been located, extended, and refined from information provided in Russell et al (2003) and from the interpretation of ground surface topography north of the Oak Ridges Moraine. The surface expression of the channels disappears beneath the ORM. Mapping (Barnett, 1993), drilling (Barnett, 1993), and seismic reflection profiling (Pugin et al., 1996) show that channels continue beneath the ORM. The channels at surface are 1 to 4 km wide and tens of metres deep. The channels buried beneath the ORM tend to be narrower (1 to 2 km wide) but still tens of metres deep (Pugin et al., 1999).

The channels generally contain sandy sediments that fine upwards. However, some channels contain thick (10-15 m), cross-bedded gravels at the base (Shaw and Gorrell, 1991; Pugin et al., 1999 and Russell et al., 2002). Coarse sediment infills within the channels show NE-SW trends (parallel to surface channels). In this study, an evaluation of the upper channel sediments suggested that silt layers are common in the upper portions of the channel infill deposits. These channels may be hydrogeologically significant since they can serve as high yield aquifers (Sharpe et al., 1996). Also, depending on the late stage channel infill, the channels will affect the amount of leakage between upper aquifers associated with the Oak Ridges Moraine and deeper aquifers situated within the Thorncliffe Formation and the Scarborough Formation.

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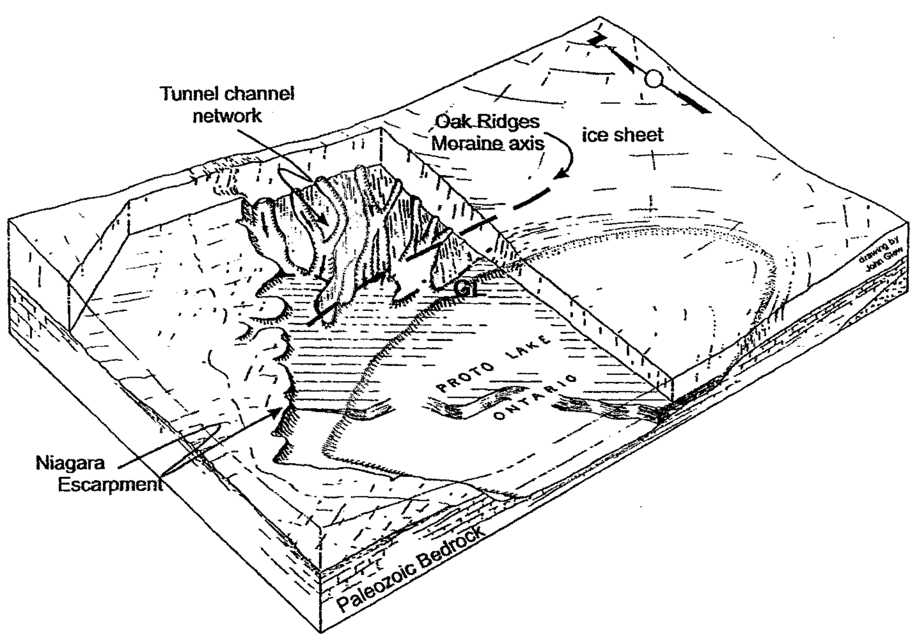

Figure 17: Subglacial flow leading to erosion of tunnel channels (from Russell et al., 2002).

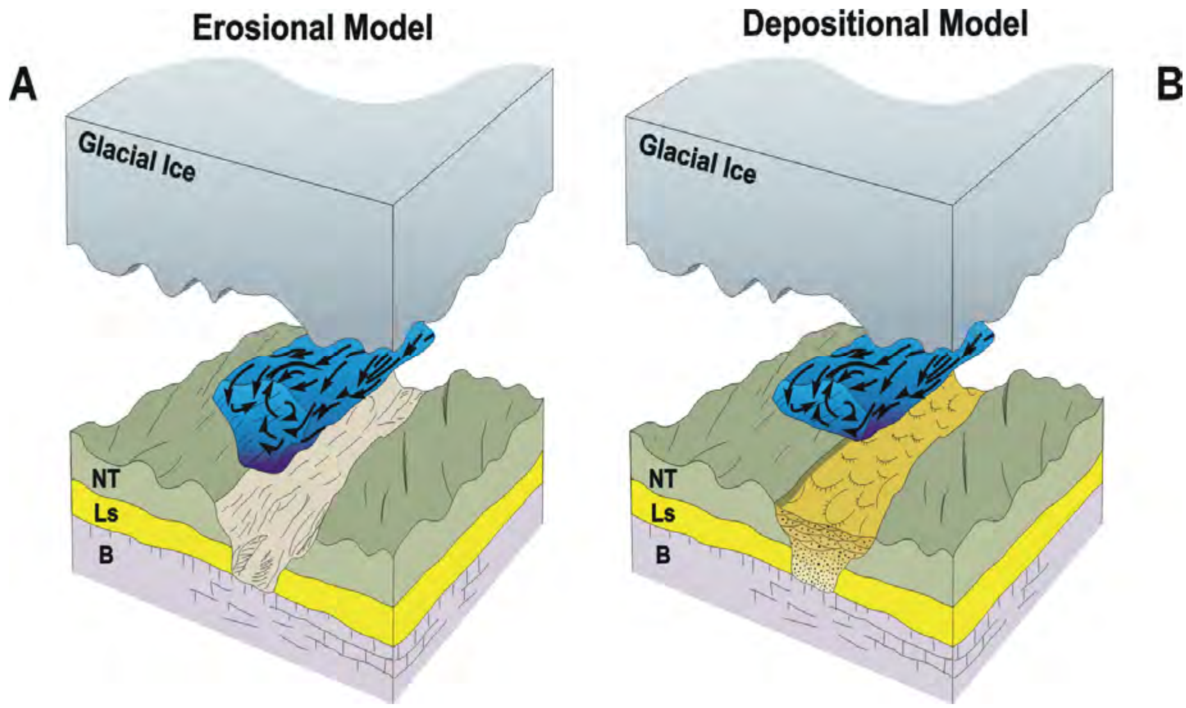

Figure 18: Erosional and depositional process in tunnel channels. (Figure provided by the GSC)

Various channel systems are interpreted to trend generally southwest through the study area (**Figure 19**). Further details on the tunnel channel systems are included in Russell *et a*l. (2003). One major channel system in the Core Model area trends from the Holland Landing area southward toward Nobleton and Kleinburg. In the Holland Marsh area, this channel appears to follow a tributary of the Laurentian Valley that emanates from Cooks Bay on Lake Simcoe. Another example is the interpreted channel system that trends through the Mount Albert and Ballantrae areas and appears to terminate somewhere beneath the moraine. This termination is attributed to a dissipation of energy, likely due to a combination of the southward sloping stratigraphy and the flood flows reaching a deeply ponded area such as proto-Lake Ontario (**Figure 17**). The channel configurations within the Core Model area are discussed and shown in more detail in Section 3. The general location of channel features across the Regional Model area is shown in **Figure 19**.

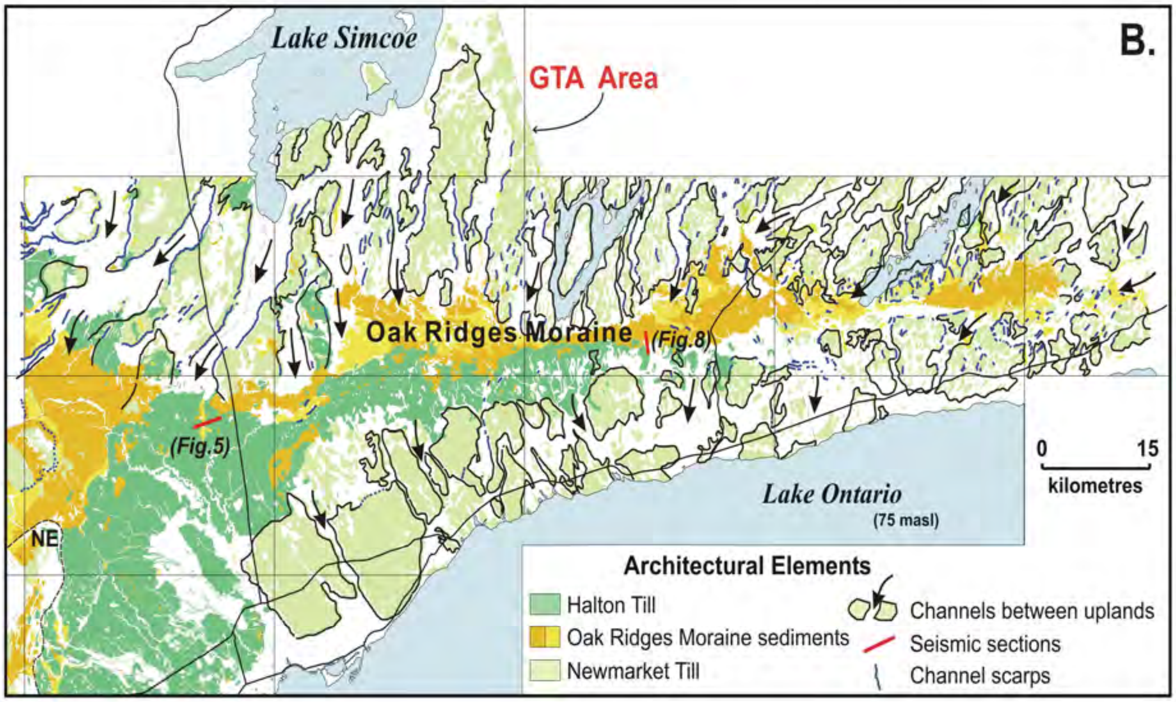

Figure 19: Inferred position of tunnel channels. (Figure provided by the GSC)

2.5.4.7 Oak Ridges Moraine (ORM) Deposits

The ORM is an extensive stratified sediment complex 160 km long and 5 to 20 km wide, arranged as four sediment wedges, each widening westward. The wedges sit distal to large channels extending from Albion Hills, Uxbridge, Pontypool and Rice Lake (Sharpe et al., 1994; and Barnett et al., 1998). ORM deposits occur primarily within fan-shaped bodies that are around 10 to 100 m thick, 100 to 5,000 m long and 10 to 1000 m wide. These sediments are arranged from coarse to fine downflow (westward) and upsection. Core logs show that moraine sediments may consist of two to three fining-upward sequences (Gilbert, 1997 and Russell et al., 1997).

Rhythmically interbedded fine sands and silts are the dominant ORM sediments, but coarse, diffusely-bedded sands and heterogeneous gravels are prominent locally, at the apex of fans and at depth in channels (**Figure 21**). Clay laminae are also present locally. ORM sediments have predominant NE-SW to E-W paleoflow indicators. The deposits are interpreted as glaciofluvial, transitional to glaciolacustrine subaqueous fan, and delta sediments, deposited in a glacial lake ponded between two glacial ice lobes (the Simcoe and Ontario lobes) and the Niagara Escarpment to the west (**Figure 20**). While **Figure 20** shows fans being deposited from the north and the south between the ice wedges, more recent studies of the sedimentology have shown the predominant paleoflow direction in the ORM sediments to be east-west and therefore ORM deposition from the north and south was likely minimal.

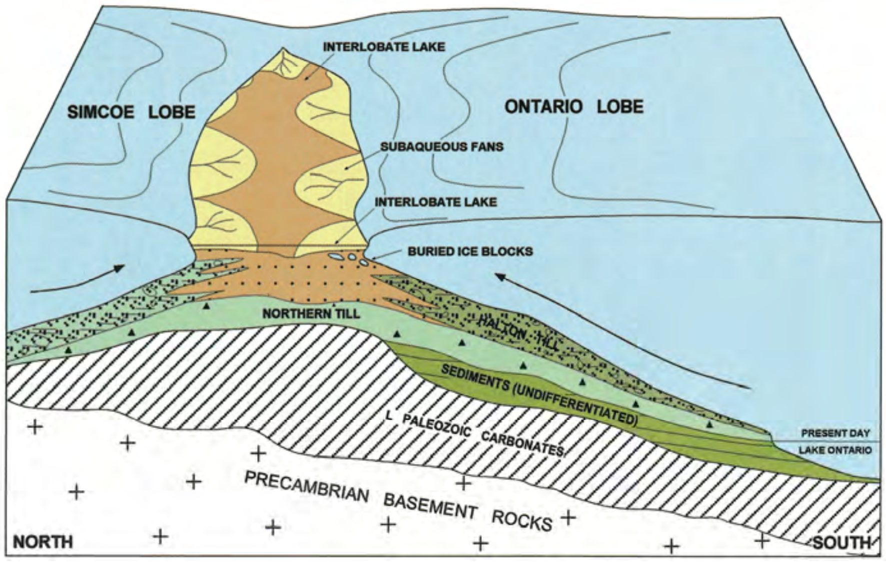

Figure 20: Deposition of the Oak Ridges Moraine between two lobes of the Laurentide ice sheet, about 13,000 years BP (Eyles, 2002)

The deposition of the Oak Ridges Moraine sediments is envisioned to be a combination of four major depositional stages, beginning with high energy subglacial channels depositing coarse gravels in east-west trending eskers. These eskers would have terminated at high energy subglacial fans (a second phase of deposition). Subsequently glacial fan and delta formations emerged with the deposition of fine sands as the ice receded (**Figure 21**). The last depositional phase was a lower energy environment with ice marginal deposits including glaciolacustrine stratified sediments and debris flow deposits. This complex sedimentary sequence consists primarily of granular deposits (Barnett et al., 1998).

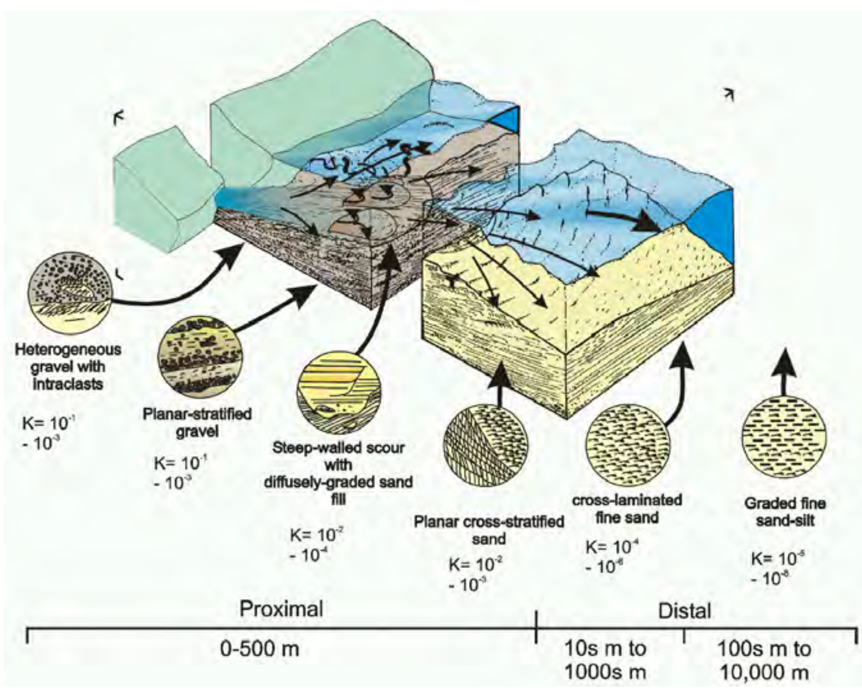

Figure 21: Depositional facies associated with subaqueous fan sedimentation along the Oak Ridges Moraine (from Russell et al., 2002b).

A map showing the estimated thickness of the Oak Ridges Moraine Sediments (based on the GSC digital geological model) is provided in **Figure B125**. Generally, the Oak Ridges Moraine deposits are less than 90 m thick in the core of the moraine but are thinner along the north and south flanks of the moraine where they are covered by surface tills.

There remains considerable uncertainty about the origin and nature of sand and gravel deposits identified on the flanks of the moraine. The borehole and water well record database show the presence of significant sand bodies lying either within a single till unit or sandwiched between two different till units, particularly in the low lying areas south of the moraine. These deposits may be associated with the sedimentological processes that created the moraine and therefore lie on top of the Newmarket Till or, alternatively, they may be isolated sand bodies within the Newmarket Till. If they do correspond to Oak Ridges deposition, then there is a greater probability that they are hydraulically connected to the ORM. Alternatively, if they are an element of the Newmarket Till, they would more likely be hydraulically isolated from the ORM.

North of the moraine, similar sand and gravel deposits (surrounded by diamicts) were identified within the till uplands. Only a few of these uplands are capped by Kettleby Till (Sharpe et al., 1997) and most have Newmarket Till at surface. These uplands have been dissected by tunnel channels, suggesting that the sands were deposited prior to erosion by the tunnel channels, and therefore most likely occur within or beneath the Newmarket Till.

2.5.4.8 Halton/Kettleby Till

The last glacial ice advance over the southern part of the study area occurred from the Lake Ontario Basin about 13,000 years BP and resulted in the deposition of the Halton Till by the Lake Ontario ice. During the same time, late stage ice in the Lake Simcoe area deposited the Kettleby Till, a silty clay to clay till. A map showing the estimated thickness of these two units (based on the GSC digital geological model) is provided in **Figure B126**.

The Halton Till is texturally variable but is generally a sandy silt to clayey silt till interbedded with silt, clay, sand and gravel (Russell et al., 2002). In some areas it is very clay-rich where the Ontario Ice Lobe has overridden glaciolacustrine deposits of the Lake Ontario basin. The Halton Till is typically 3 to 6 m thick but locally it can exceed 15 to 30 m in thickness for example, at Mount Wolfe and in the King Township areas in the western part of the study area (Russell et al., 2002 and White 1975). On the southern flanks of the ORM it has overridden the granular Oak Ridges Moraine deposits extending as far north as Oak Ridges in Richmond Hill and to Vandorf Sideroad near Stouffville. Some researchers have mapped the Halton Till within the City of Toronto, however, the GSC have mapped the surficial till in this area as the Newmarket Till.

2.5.4.9 Surficial Glaciolacustrine Deposits

The uppermost regionally significant surficial geologic unit consists of a sequence of glaciolacustrine deposits that form a veneer over the underlying Halton, Kettleby, and/or Newmarket Tills. These deposits can include near shore sands and gravel beach deposits of the Lake Algonquin and Lake Iroquois shorelines located in the north and south of the Core Model area. It can also include fine sands, silts and clays of glaciolacustrine pondings in the Aurora, Newmarket and East Gwillimbury area in the north-central part of the study area. These sediments generally form a thin veneer over the underlying deposits, although locally they can be several metres thick. These units represent local ponding of water or higher water levels in Lake Ontario and Lake Simcoe following retreat of the glaciers approximately 12,500 years BP. For example, Glacial Lake Iroquois (ancestral Lake Ontario) water levels were at least 40 to 60 m higher than present, due to ice blockage and damming of water along the St. Lawrence River (Anderson and Lewis, 1985 and Eyles, 1997). Maximum lake levels for Glacial Lake Algonquin (ancestral Lake Huron) in the Lake Simcoe area are believed to have been 245 to 260 masl (Finnamore, 1985 and Sharpe et al., 1997), which is up to 40 m higher than present Lake Simcoe lake levels. Shoreline elevations are still slowly changing as a result of postglacial isostatic rebound (Eyles, 1997).

3 Hydrostratigraphy

The GSC/OGS stratigraphic framework presented in the previous section provided an excellent foundation on which to build the hydrogeologic model. The GSC stratigraphic surfaces were adapted for use in a groundwater model and formed the basis of the ORM Regional Model project. The Core Model, on the other hand, was constructed from a set of refined hydrostratigraphic surfaces, the development of which is described in this section. The analyses described here were applied only to the Core Model area but will be applied to the remainder of the ORM study area in the near future.

3.1 Stratigraphic Surfaces and Hydrostratigraphic Surfaces

The purpose of this section is to review the conceptual stratigraphic framework from a hydrogeologic (aquifer and aquitard) perspective and to present the refined Core Model hydrostratigraphic surfaces.

In this report, the term "hydrostratigraphy" is used to reflect an emphasis on permeability. While the difference is sometimes subtle, stratigraphic layers are defined based on their geologic history and depositional processes whereas hydrostratigraphic layers are defined with an emphasis on their hydrogeologic properties: i.e., whether they are composed of predominantly aquifer or aquitard materials. Also, the term "aquifer complex" is used to signify a unit with mostly moderate to high permeability sediments that may or may not be laterally continuous but are likely derived from similar depositional processes. For example, the term Thorncliffe Aquifer Complex is used to describe material that is believed to be mostly within the Thorncliffe Formation (or equivalent) that is mainly sand and silty sand but also includes smaller-scale bodies of silt or silty clay. The term "or equivalent" has been used to extend the stratigraphic nomenclature established in studies along the Lake Ontario shoreline (e.g. Karrow, 1967) northwards to the Lake Simcoe area. For instance, the term Sunnybrook Aquitard (or equivalent) is used to describe aquitard material separating deposits of the Thorncliffe Aquifer Complex from the Scarborough Aquifer Complex. Because there is limited information available on the deeper units, it is not known for certain whether the various aquifer units that occur within the Lower Sediments of the study area are exactly the same as those described along the Lake Ontario shore. However, the extension of the nomenclature used at the Scarborough Bluff "type section" provided a common reference framework into which aquifers and aquitards were placed and referenced.

Many of the geologic processes that produce aquitards (regional till sheets, glacial lakes) are more laterally extensive and uniform than the complex processes that result in coarse grained aquifer deposits (e.g. fluvial channels). This observation underlies the development of the hydrostratigraphic model layers as it was easier to identify and map the aquitard layers. The remaining (intervening) sediments thus form the aquifers. The hydrostratigraphic units delineated as aquifers, however, are not always of high permeability since the depositional history of the aquifer units is quite complex and fine grained sediments (silts) can be found juxtaposed with coarser-grained sediments. Additional effort was directed at differentiating the coarse and fine grained sediments within the aquifer layers primarily based on the hydraulic conductivity of the materials present.

There are a number of features of the stratigraphic framework that were considered to strongly influence the flow of groundwater through the unconsolidated sediment system. These include:

1. The orientation and connectivity of the bedrock valleys.
2. The thickness and continuity of the Newmarket Till that separates the shallow aquifer system from the deeper part of the flow system and the thickness and continuity of the Sunnybrook Drift that separates the intermediate and deeper aquifers within the Lower Deposits. (Mechanisms that control the flow of groundwater through these aquitards (such as presence of fractures or sand inclusions) are described elsewhere (e.g. Gerber et al., (2001); Gerber (1999); and Gerber and Howard (1996; 2000)).
3. The location of tunnel channels which have eroded through the Newmarket Till and possibly through deeper units. The nature of the infill sediments controls the amount of leakage between the shallower flow system and the deeper flow system. The infill for one tunnel channel system, located near King City and Nobleton, was described by Russel et al. (2002). The infill material for most of the other erosional channels remains more uncertain.
4. The thickness, continuity, and nature of the deposits of the Oak Ridges Moraine that form a regionally-significant recharge area and the thickness, continuity, and nature of the sediments that form the deeper aquifers within the Lower Deposits package. Details regarding the geologic deposits mapped within the Core Model area are expanded upon in the next section and are described in sequence from oldest to youngest.

The following hydrostratigraphic units were considered key to the Core Model area:

1. Glaciolacustrine deposits (sand, silt and clay): aquifer or aquitard
2. Halton/Kettleby Aquitard
3. Oak Ridges Aquifer Complex (ORAC)
   Regional Unconformity – tunnel channel infill deposits
4. Newmarket Aquitard
5. Thorncliffe Aquifer Complex (TAC)
6. Sunnybrook Aquitard (or equivalent)
7. Scarborough Aquifer Complex (SAC), and
8. Bedrock (aquifer or aquitard)

The Don Formation and underlying York Till have not been mapped within the Core Model area because of the paucity of deep detailed information that would be necessary to delineate these deposits. Possible occurrences of Don Formation sands have been included in with Scarborough Sands while possible occurrences of York Till have been included in with silt and clay of the Scarborough Aquifer Complex or underlying bedrock.

3.2 Core Model Layer Refinement

The GSC surfaces needed to be refined to provide the local detail needed to construct the Core Model. These refinements included:

- the stratigraphic surfaces were constructed at a regional scale; some local-scale details, obtained in site-specific studies (e.g. in the vicinity of York Region wellfields), had to be added;

- the stratigraphic boundaries were picked based on lithologic indicators; other secondary, but hydrogeologically important, indicators such as well screen position and water levels were used to better define hydrostratigraphic boundaries;
- the Lower Sediments needed to be divided into multiple aquifer and aquitard layers to correctly simulate the effects of pumping from deeper (high capacity) municipal wells;
- the tunnel channel infill sediemnts were subdivided to account for the fining upwards sequences and presence of semi-confining silt layers;
- the continuity of aquifer systems needed to be represented in the hydrostratigraphic layer construction process; and
- bedrock valley systems needed to be incorporated into the hydrostratigraphic surfaces in a manner that could provide continuity of the sediments in-filling the valleys.

Specifics related to three of the most important issues are described below. Additional detail is provided in the methodology Appendix D.

3.2.1 Subdivision of the Lower Sediment Unit

Classification of the Lower Sediments into one stratigraphic unit resulted in a maximum thickness of over 150 m for this unit. Although suitable for a more regional perspective, simulating this unit as a single layer within the groundwater model neglects the presence of the semi-confining Sunnybrook aquitard unit and the presence of tunnel channels that penetrate through this unit in places. In considering the Core Model and its overall objectives, many of the municipal pumping wells in York Region were noted to tap into one or both of the aquifers within the Lower Sediments. Therefore greater control on the vertical distribution of permeability within the Lower Sediments was required for wellhead protection area delineation. Although the data were sparse, preliminary cross-section analysis indicated sufficient lithologic variation to make an attempt at subdividing the Lower Sediments into the Thorncliffe Aquifer Complex, Sunnybrook Aquitard, and Scarborough Aquifer Complex.

3.2.2 Refinement Based on Groundwater Indicators

A second issue became apparent as the stratigraphic surfaces were reviewed and integrated with other hydrogeologic data on cross sections. Owing to the complexity and lithologic gradations within the formations it became apparent that stratigraphic layers and aquifer/aquitard boundaries were not always coincident. For example, in reviewing the stratigraphic surfaces surrounding municipal supply wells in York Region, it was found that well screens were sometimes located within the GSC Newmarket Till stratigraphic layer.

These observations led to the incorporation of additional hydrogeologic indicators into the layer refinement process. While well screen location proved to be a reliable co-indicator of aquifer position, other factors such as static water levels, “water found” indicators, driller’s notes, and locations of contact springs also proved useful. For these reasons, the Core model surfaces are referred to as “hydrostratigraphic” units, since their boundaries are biased towards aquifer/aquitard contacts. This refinement resulted in the majority of well screens lining up within aquifer units.

3.2.3 Continuity of Valley and Channel Systems

The third issue that emerged was related to the representation of channel and valley systems within the model. Simple automated interpolation of sparse point data (well picks) rarely produces layer surfaces that realistically represent the structure and continuity of complex hydrogeologic features such as channel and valley systems. The interconnection of aquifers within these features is considered critical to understanding and being able to simulate the movement of groundwater.

For example, simple automated interpolation tends to produce surfaces that exhibit anomalously low “bulls-eyes” that reflect individual wells located within a bedrock valley system. These isolated lows are true to the data, but in themselves they do not reflect the geological model of an elongate erosional channel system. Aquifer materials within these lows are thus represented as being isolated and down-valley flow systems cannot be simulated correctly.

The GSC stratigraphic surfaces were generated from a combination of point gridding and rule-based corrections (Logan et al., 2001). While this approach proved far superior to simple gridding, the scale and intended use of those surfaces did not require the strict continuity, especially of linear aquifers, deemed necessary for the numerical flow model.

3.2.4 Layer Refinement Approach

To fully represent the complexity of the hydrostratigraphy of the study area, methods were developed to integrate the borehole lithology picks, hydrogeologic indicators, as well as expert intuition and conceptual understanding of the sedimentological processes into the model layer refinement process. The process also utilized the conceptual depositional models developed by the GSC and a conceptual fluvial model for the Laurentian River valley system.

Database integration, flexible data visualization, efficient layer picking tools, and the capture of expert intuition using three-dimensional (3-D) constraint polylines were essential to the hydrogeologic model construction process. The multi-step approach developed for this study is described in Appendix D of this report. Application of the methodology resulted in a hydrostratigraphic model that not only honours the borehole and well data but also the conceptual understanding of the processes that formed the moraine and underlying layers.

3.3 Hydrostratigraphic Interpretation Results

3.3.1 Overview

The resulting hydrostratigraphic surfaces represent a significant advance in the understanding of the aquifer and aquitard layers within the Core Model study area. **Figure 22** shows a three-dimensional (3-D) fence diagram through the Core Model area with the bedrock surface as a base. A number of bedrock valleys and tunnel channels are visible on the fences.

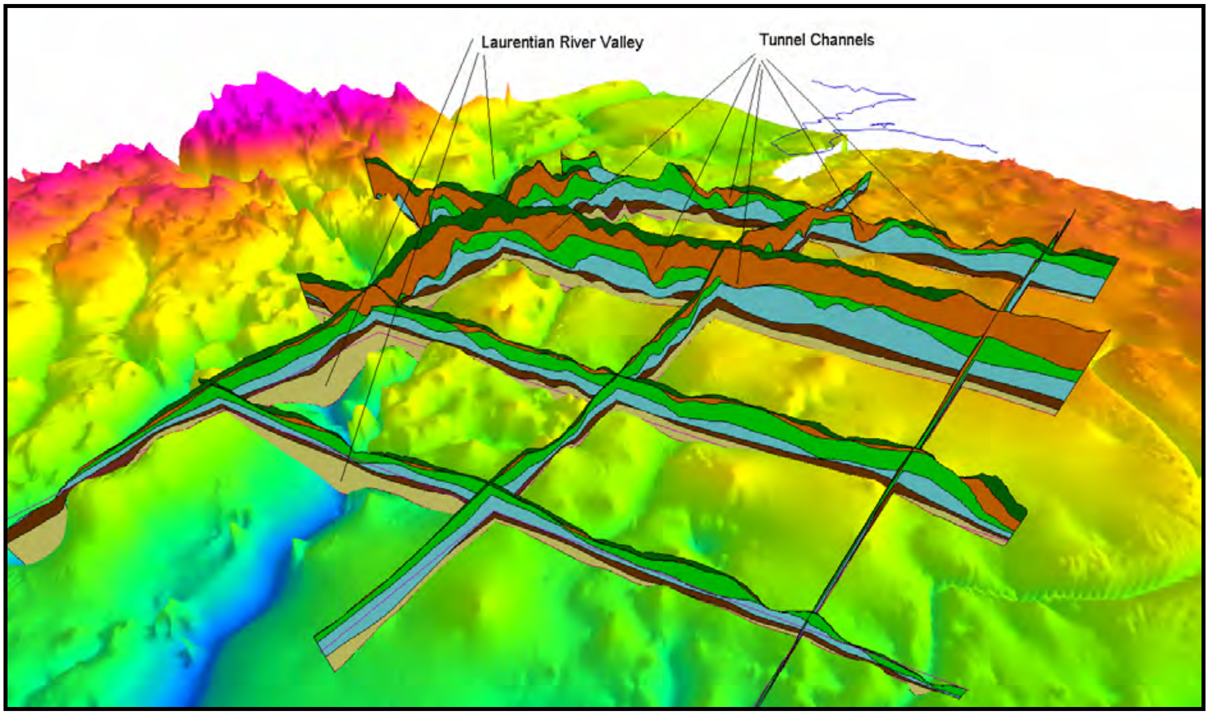

Figure 22: Bedrock surface and fence diagram of sediment layers. (View from Toronto looking northwest. Width of 3-D viewport is approximately 150 km.)

Over 67,000 geologic layer picks were made in the study area, along with over 12,000 polyline vertex points (see Appendix D). This represents a ratio of 85% borehole picks to 15% interpretation constraint points. The majority of the polyline constraints were required to enable the interpolation processes to correctly represent the conceptual understanding of the bedrock valley systems and tunnel channels.

The surfaces exhibit some broad patterns, such as the general southward dip of the top of the Thorncliffe surface south of the moraine. Another trend is an apparent rise in the Newmarket Till under the moraine. The refined surfaces are broadly similar to the GSC stratigraphic surfaces; however a few significant differences do exist. For example, the Newmarket Aquitard is deeper than the GSC layer in some areas (possible explanations are presented in the following sections). Although difficult to quantify, the hydrostratigraphic surfaces also exhibit less local-scale variation than the GSC surfaces, likely due to the extensive use of on-section correlation in the refinement process (see Appendix D). Other features, such as the tunnel channels and bedrock valleys, are more clearly defined in the surfaces because of differences in the interpretation methodologies.

Patterns observed during the process of hydrostratigraphic layer refinement helped verify the conceptual depositional models that describe the distribution of sediments within the moraine (e.g. Barnett et al., 1998 and Russell et al., 2002). For example, three patterns of silt deposition were identified, including a fining upward sequence in the tunnel channels, fining westwards patterns in ORM fan deposits, and lacustrine silts deposited at a later time in the exposed tunnel channel valleys.

A significant addition within the hydrostratigraphic model was the subdivision of the Lower Sediment unit. Subdivision of the Lower Sediments unit into the Thorncliffe Aquifer Complex, Sunnybrook Aquitard, and Scarborough Aquifer Complex was difficult beneath the ORM because of limited data; however, sufficient data were generally available north and south of the moraine. Together with the refinement of the bedrock surface, the Scarborough Aquifer Complex now exhibits considerable thickness in the deep Laurentian River valley systems. The hydrostratigraphic model also added a more permeable semi-confining silt layer within the Newmarket Aquitard in the tunnel channels zones. Enhanced groundwater movement through these units was evaluated with the flow model as described further on in this report.

3.3.1.1 Surface Variability

The surfaces exhibit a degree of local-scale noise or variability. This variability is due to three general factors, including:

1. Geologic Variability
   - gradational formation boundaries
   - drumlinization of the Newmarket Till
   - Possible presence of granular (i.e. sandy textured) sub-units within the Newmarket Till
   - Regional variations in till signatures
   - Erosion and/or non-deposition of certain units

2. Data Errors
   - survey errors (positional and elevation)
   - errors/bias in drillers descriptions and lithologic boundaries
   - biases in the spatial distribution and depth of wells
   - data gaps both spatially and with depth

3. Interpretation Errors
   - picking process errors (errors/bias introduced by the geologists)
   - gridding errors (errors/bias introduced by the interpolation algorithms)

The uneven spatial distribution of the boreholes impacted both the correlation and gridding process. As most wells are located along roads, cross section correlation was generally more consistent when performed along road lines. While both east-west and north-south sections were viewed, most work was performed on east-west sections because they were generally perpendicular to the orientation of the tunnel channels. Identifying the tunnel channels on north-south sections was particularly difficult because of the complex erosional processes that took place at the sides of the channels.

3.3.2 Bedrock Surface

An updated bedrock surface was produced for the Core Model area which built upon the previous bedrock topography mapping by the GSC and OGS. The new surface is based on a conceptual model of a fluvial Laurentian River drainage system with associated tributaries. This surface has been imposed through all of the known bedrock lows as well as beneath deep sediment wells that did not intercept the bedrock surface (**Figure 23**).

Also shown on **Figure 23** are points where wells or boreholes actually encountered bedrock. Most bedrock wells or boreholes occur near the shores of Lake Ontario, Lake Simcoe and the near the Niagara Escarpment. There are less data in areas of thick sediment accumulation such as beneath the ORM. Few boreholes were available within the City of Toronto except along major engineering alignments such as the subway lines.

Figure 24a shows the locations of the polylines used to constrain the bedrock surface and join areas of low elevation. Standard error of estimate for the geostatistical interpolations of the bedrock surface is shown in **Figure 24**b. The interpreted polyline points were included in the error analysis although, technically, these points were inferred and not actually measured. Locations without data have a higher probable error in the estimated value (**Figure 24**b). For instance, a standard error of 10 m means the surface elevation has a 68% (one standard deviation) chance of being within ±10 m of the estimated value. Comparison of the new bedrock surface (**Figure 23**) with the GSC Version 1 surface (Appendix B) shows that the major difference between the two is the interpreted presence of a continuous valley system which influences deep groundwater flow patterns.

Select high quality deep boreholes which had a strong influence on the interpretation of the bedrock valley system included:

1. GSC Nobleton (Sharpe et al., 2003): This well was drilled through the crest of the moraine and into the main branch of the buried Laurentian Channel and includes almost 60 m of Scarborough materials (and possibly older units). It encountered approximately 36 m of sand and gravelly sand within the Scarborough Aquifer Complex. Bedrock was located at approximately 75 masl.

2. MNR Brampton TH1 (Haefeli, 1972): The well is located in the Humber branch of the Laurentian Channel near the split north of the City of Toronto. The geophysical logs for this borehole indicate almost 32 m of high resistivity Scarborough Aquifer Complex materials including 15 m described as “gravel, coarse boulders, very rough”.

3. YPDT Heart Lake Road (drilled by YPDT in 2002): This borehole is located near the Niagara Escarpment in the deep Caledon tributary of the Laurentian valley. It encountered sands and silts with the bottom 20 to 30 m consisting of coarser-grained materials.

4. YPDT High Park (drilled by YPDT in 2003): This borehole did not encounter thick Scarborough sediments, however, the well initially flowed naturally at over 2300 L/m and declined to about 900 L/m over the longer term, and had a static head over 18 m above ground surface suggesting that considerable groundwater resources occur within the valley system.

5. GLL Newmarket 87-5 (Gartner Lee, 1987): This borehole, located on Bayview Avenue south of Vivian Road in Newmarket, is drilled into the deep Newmarket Tributary of the Laurentian Channel. The borehole has a total depth of over 240 m (800 feet). Bedrock was never encountered, suggesting that the bedrock elevation is below 12 masl. The borehole was critical to the delineation of the Mount Albert tributary. Drill results and seismic and geophysical logs indicate that the infill sediments were mostly silt, with some sand and gravel layers. Overall, the well was not suitable for municipal water supply. The thickness of sediments result in considerable transmissivity even though the infill materials are not coarse-grained.

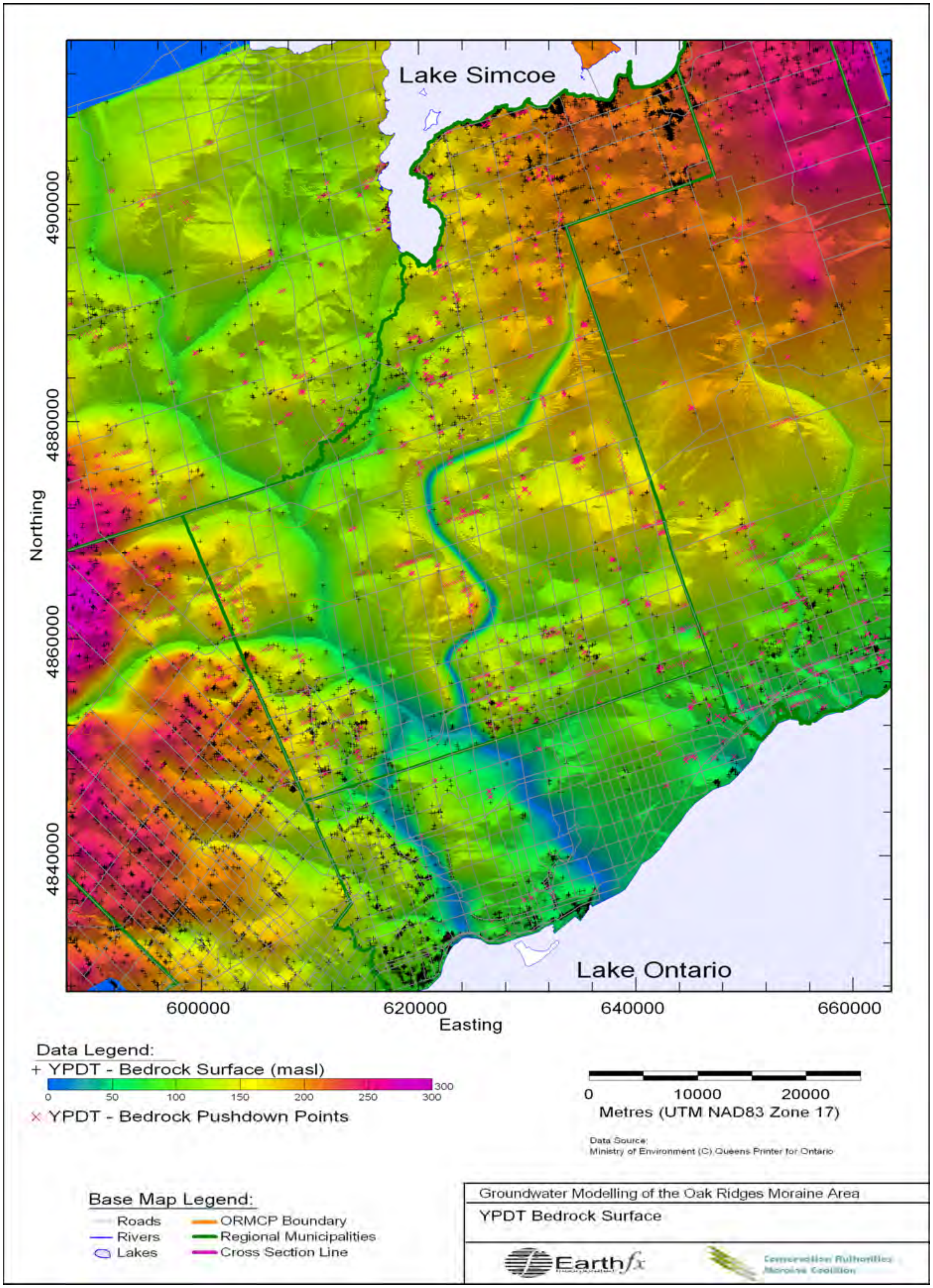

Figure 23: Bedrock surface topography.

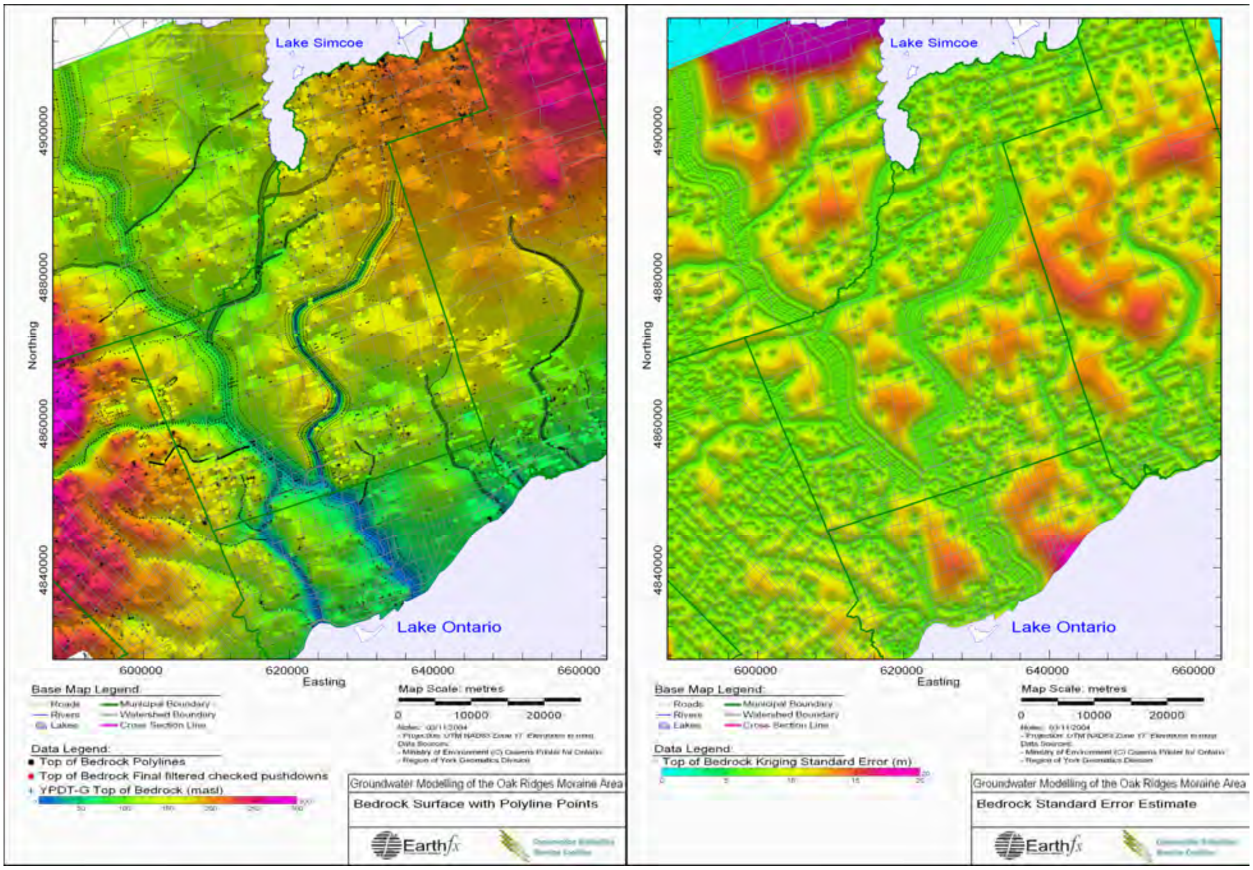

Figure 24: (a) Bedrock polylines and (b) standard estimate of error.

The major channel of the Laurentian River valley trends northwards along the western part of York Region near Maple and Nobleton. Major tributaries drain to the main Laurentian channel from the west through Bolton and Kleinburg. Major tributaries also drain from the east along the Holland Marsh area from Lake Simcoe through east of Bradford and from Mt. Albert through Aurora, King City and Richmond Hill before meeting up with the main Laurentian channel. Two main outlets are interpreted along the Lake Ontario shoreline: one near Humber Bay and the other east of the Toronto Islands which follows the original Don River channel. These two outlets may represent different periods in the evolution of the river valley system.

The thickness of sediments above the bedrock surface is shown on **Figure 25**. Sediment thickness is greatest beneath the ORM and within the bedrock channel system.

To illustrate the difference between the bedrock generated with and without the Laurentian Channel interpretation a second version of the bedrock surface was created. The second version was created without the polyline constraint points and also without the pushdown well points. This “raw” surface is shown in **Figure 26**. The overburden thickness calculated from this surface is shown in **Figure 27**.

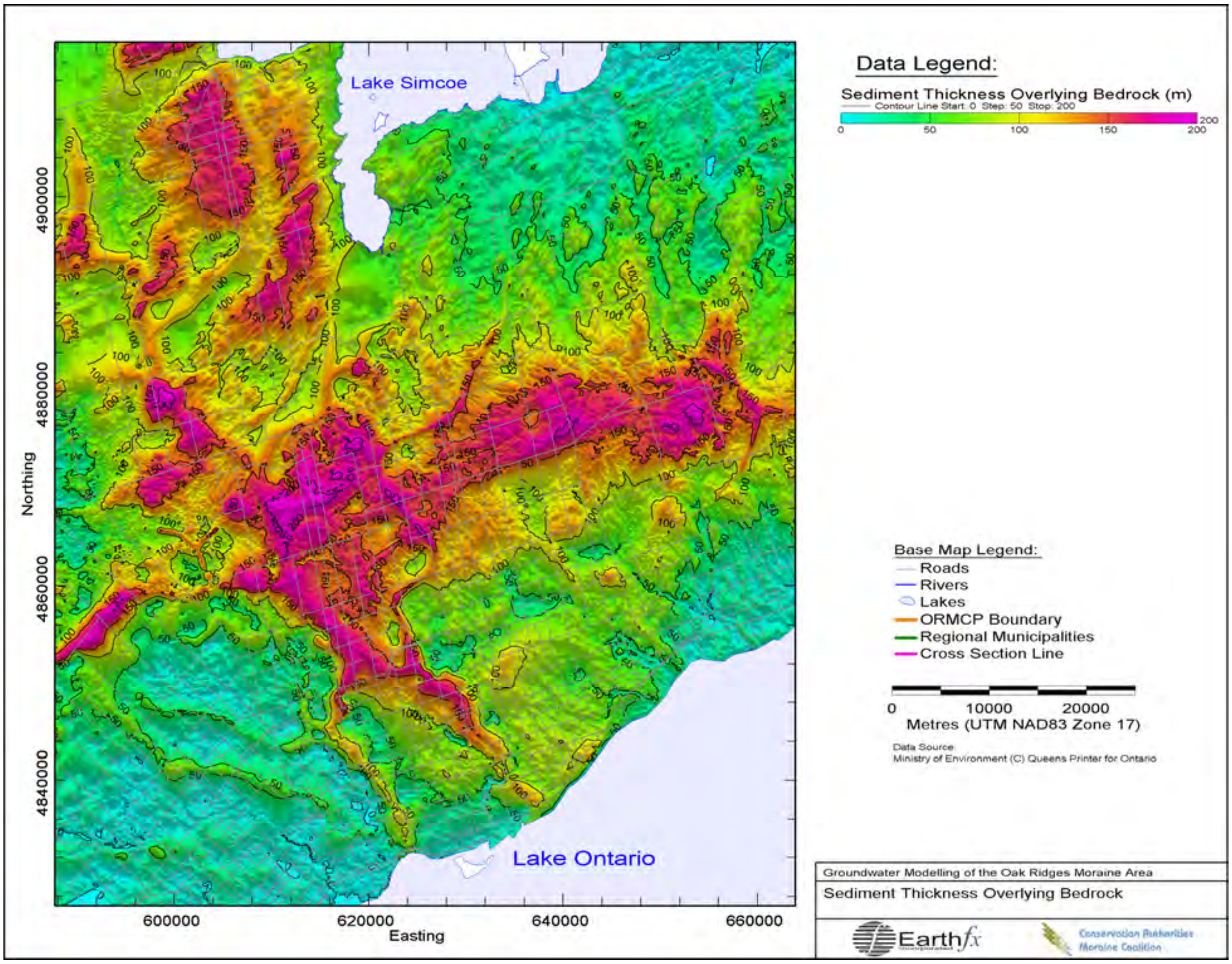

Figure 25: Sediment thickness overlying bedrock.

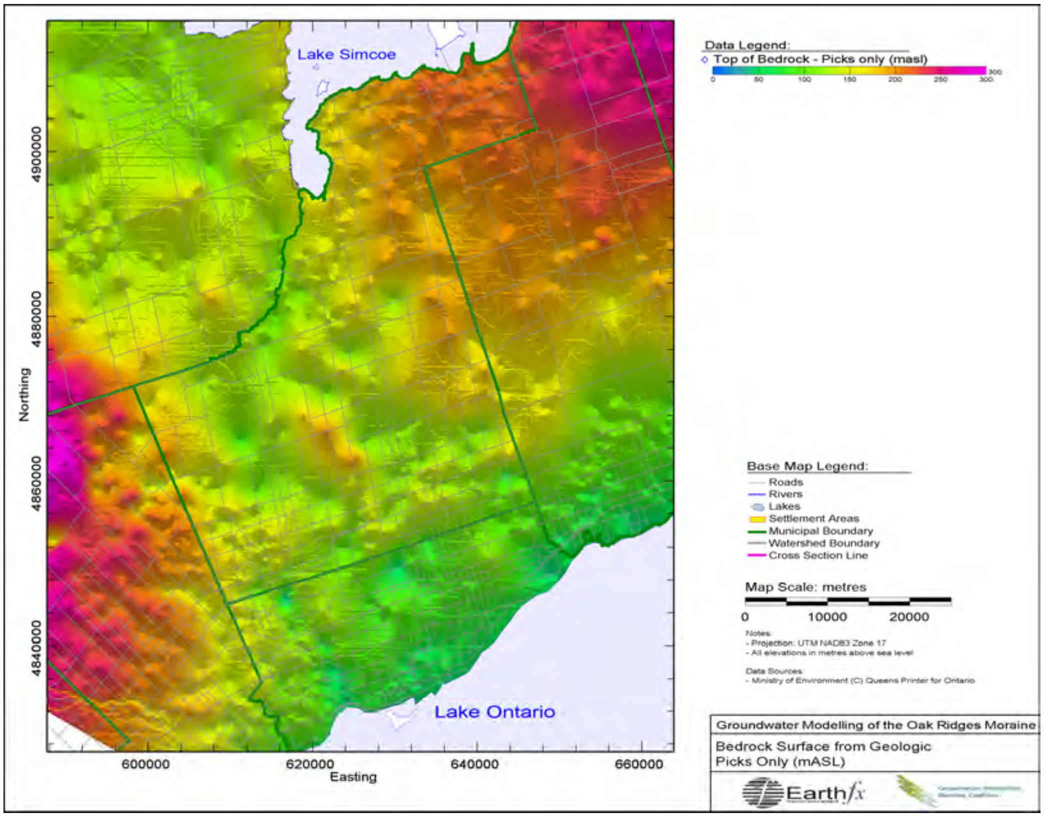

Figure 26: Bedrock surface from well picks only (no polylines or pushdown analysis)

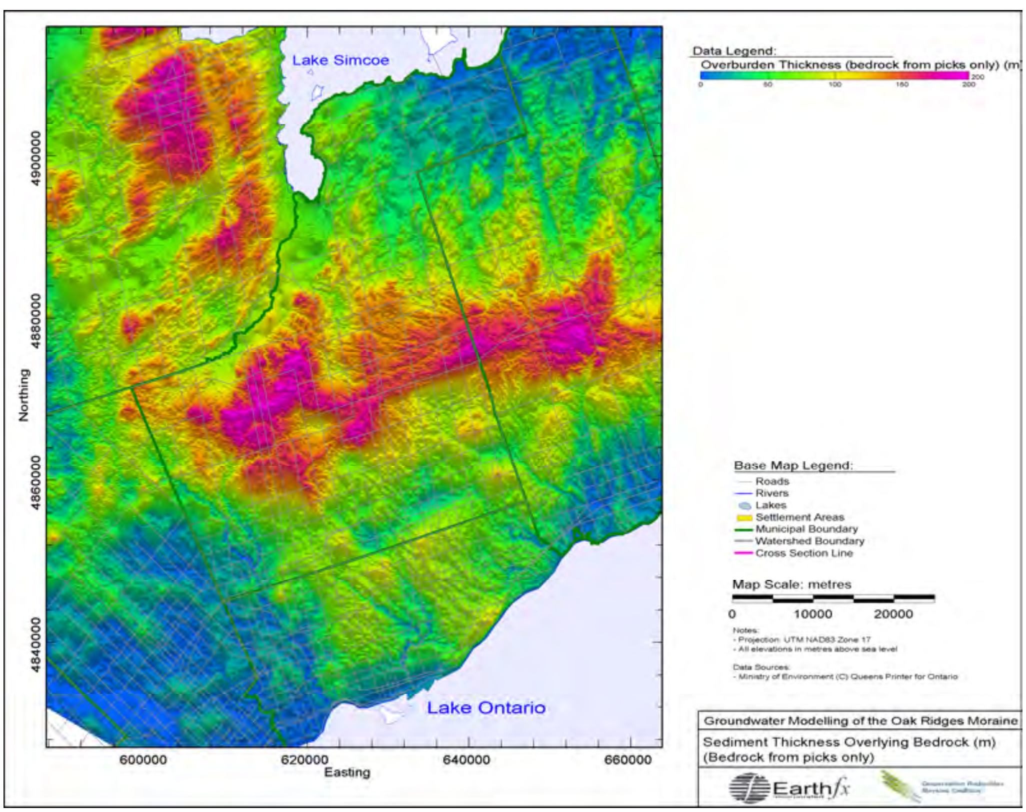

Figure 27: Overburden Thickness (Bedrock surface from picks only)

3.3.3 Scarborough Aquifer Complex

The interpolated upper surface of the Scarborough Aquifer Complex is shown in **Figure 28**. The thickness of the Scarborough Aquifer Complex sediments is shown in **Figure 29**. White zones on the map within the Core Model area indicate locations where the data indicate that the Scarborough Aquifer Complex is not present.

To the northeast, the Scarborough Aquifer Complex is pinched by the bedrock but, for digital layer continuity reasons, it has been extended into this area to represent lower aquifer materials that may or may not actually be Scarborough Formation proper.

The Scarborough Aquifer Complex is interpreted to drape into the bedrock valley systems and this is reflected in the isopach map (**Figure 29**). The presence of a thick layer of in-fill materials, even if not highly permeable, is significant because this results in higher transmissivity values for the Scarborough Aquifer Complex within the valley systems. The higher transmissivity enables the Scarborough Aquifer to transmit considerable volumes of groundwater.

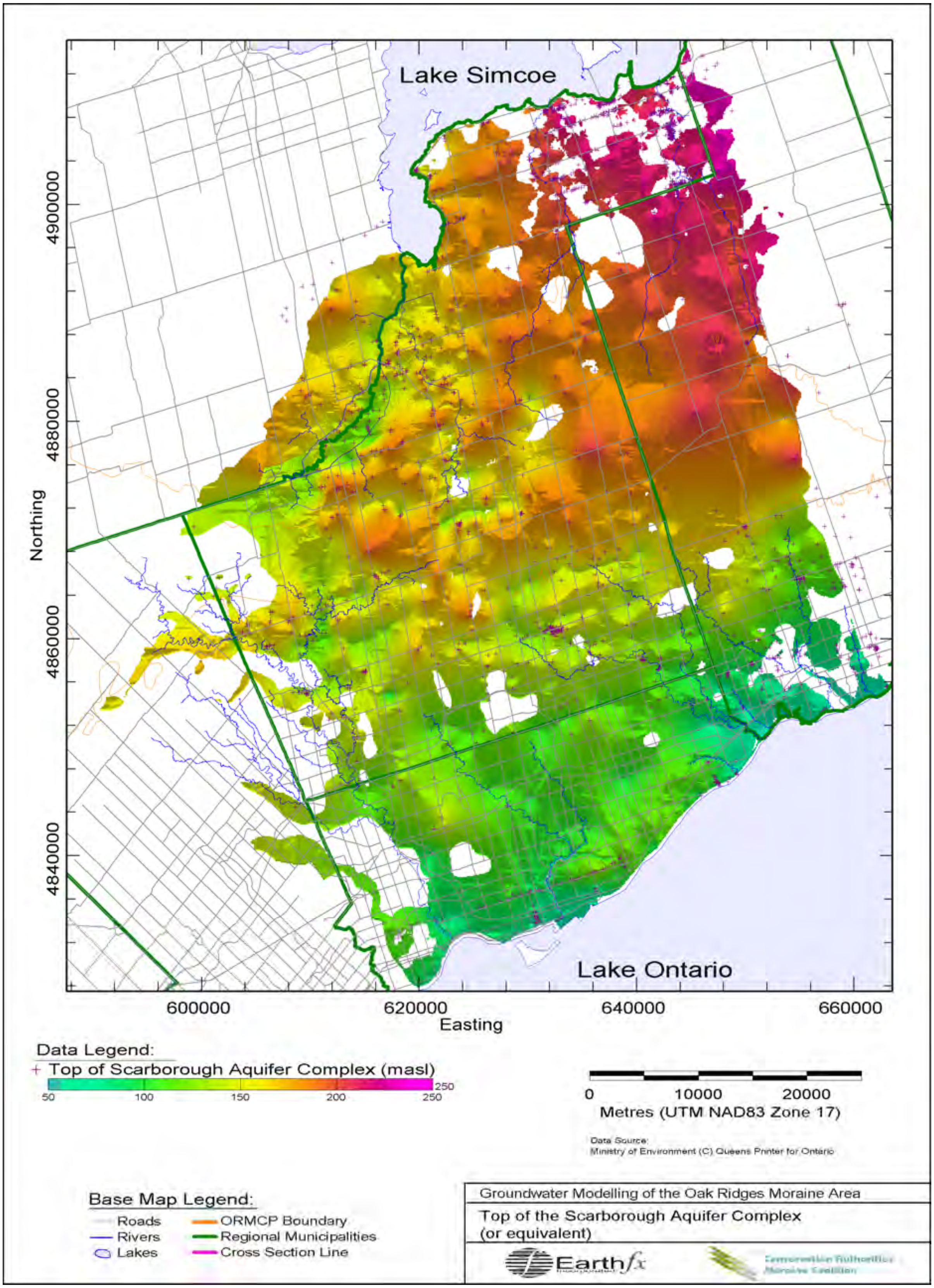

Figure 28: Elevation of the top of the Scarborough Aquifer Complex (or equivalent).

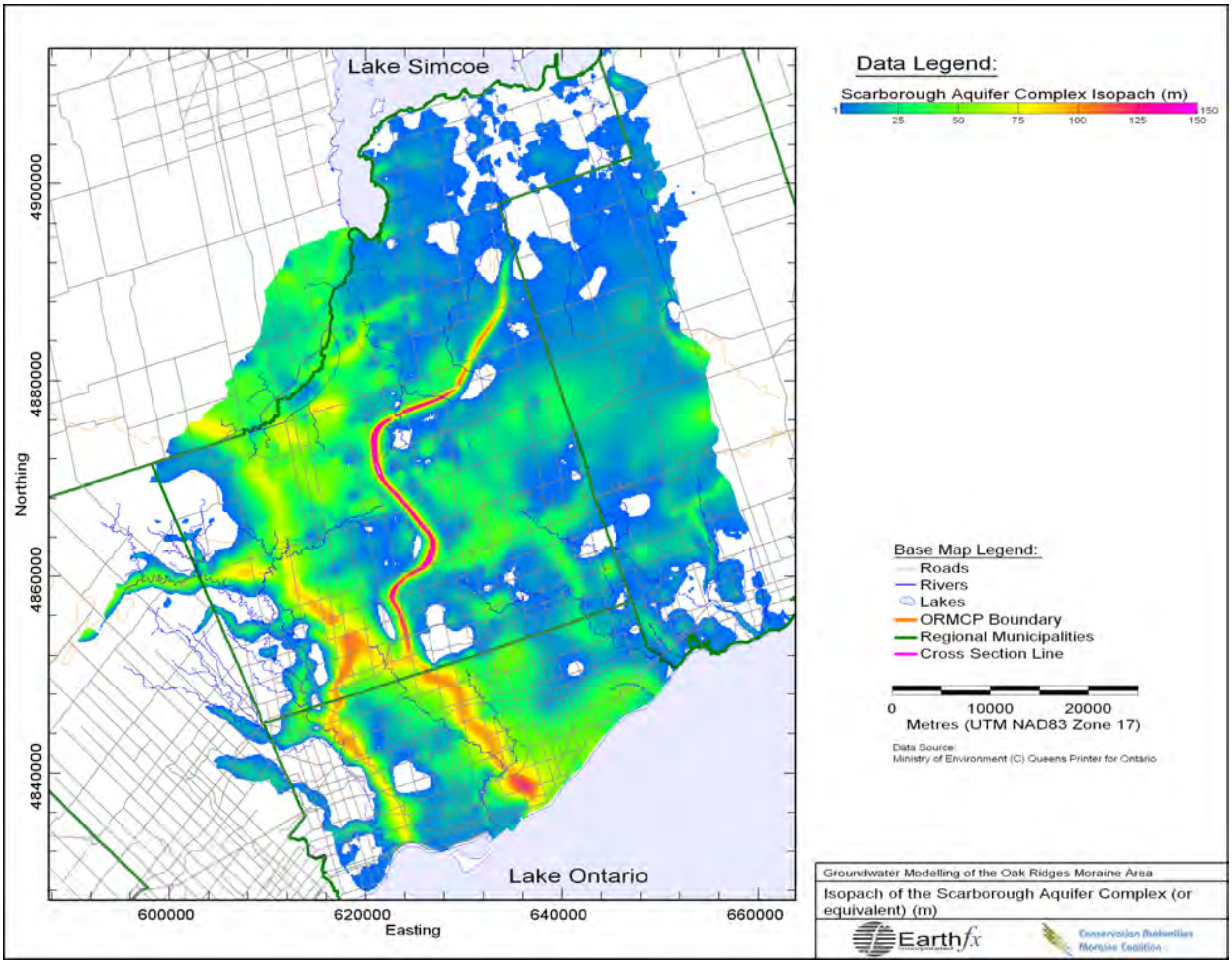

Figure 29: Isopach map of the Scarborough Aquifer Complex (or equivalent).

3.3.4 Sunnybrook Aquitard

The Sunnybrook Aquitard (or equivalent) separates the Thorncliffe Aquifer Complex from the underlying Scarborough Aquifer Complex. The interpolated upper surface of the Sunnybrook Aquitard (or equivalent) is shown in **Figure 30**. The thickness of the Sunnybrook Aquitard (or equivalent) sediments is shown in **Figure 31**.This aquitard is not present over the western part of the study area and is also not present in the northeast along the southern shore of Lake Simcoe (**Figure 30**). It should be noted that some pick symbols appear in areas where the unit is absent. These picks were used to define the "pinch-out" zone. This unit is generally thickest where it drapes into depressions on the surface of the underlying Scarborough Aquifer Complex such as at the Scarborough Bluffs (**Figure 31**).

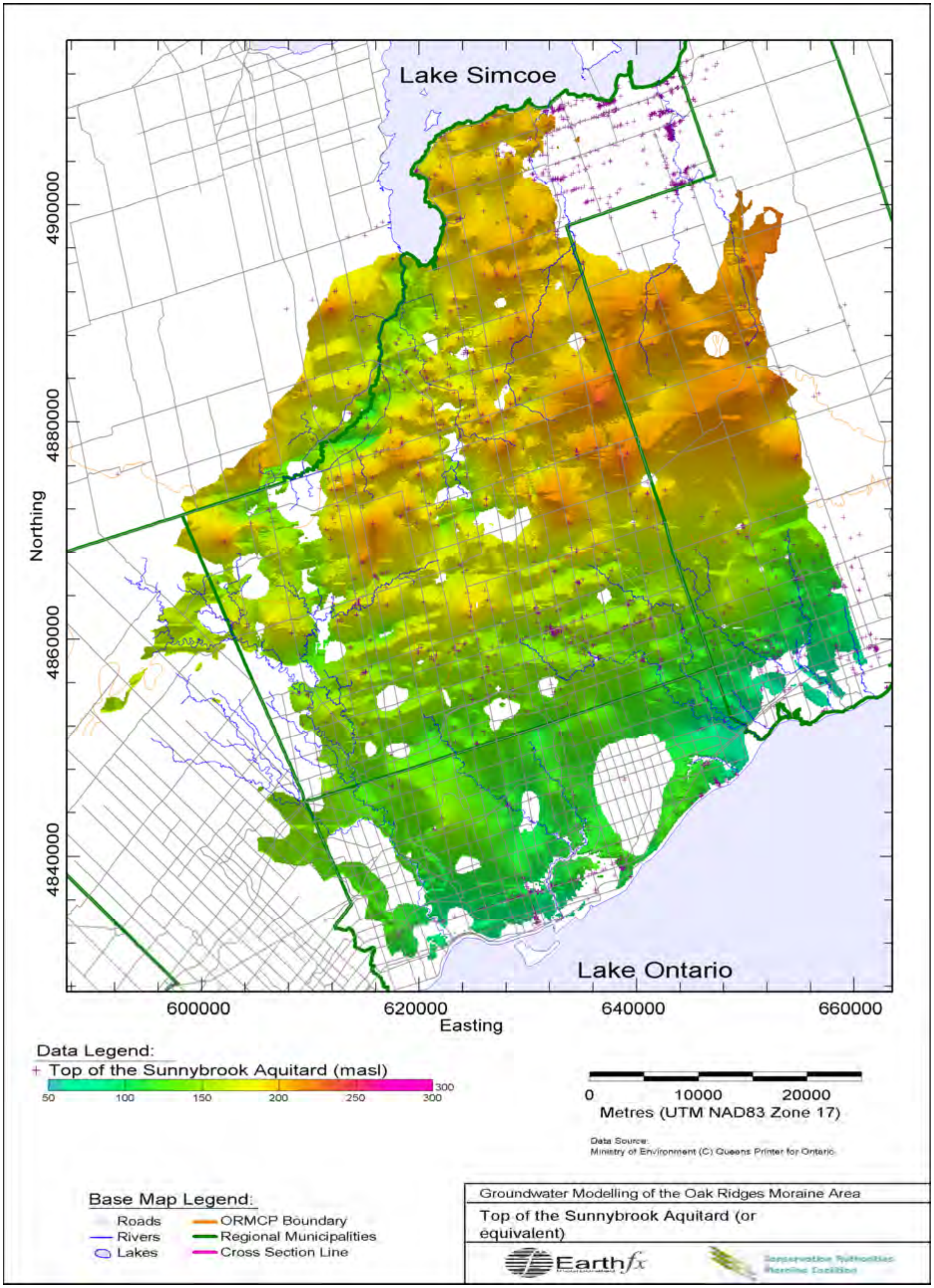

Figure 30: Elevation of the top of the Sunnybrook Aquitard (or equivalent).

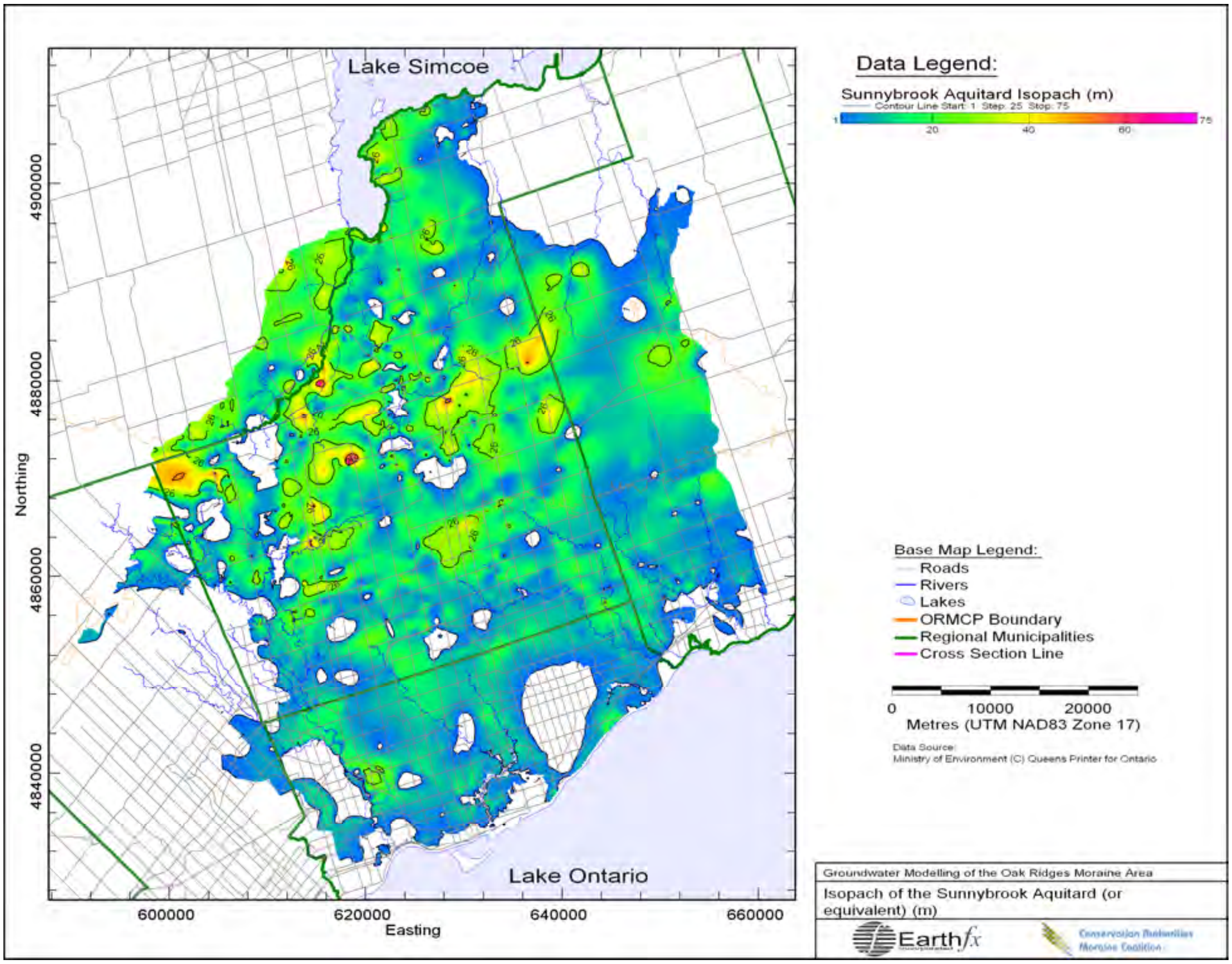

Figure 31: Isopach of the Sunnybrook Aquitard (or equivalent).

3.3.5 Thorncliffe Aquifer Complex

The interpolated top of the Thorncliffe Aquifer Complex is shown in **Figure 32**. The highest point on this surface occurs along and to the north of the Oak Ridges Moraine, mimicking ground surface elevation. This unit is also thickest beneath the Oak Ridges Moraine with maximum thickness approaching 50 m, as shown in the isopach map in **Figure 33**. **Figure 34** shows the depth from ground surface to the top of the Thorncliffe Aquifer Complex. The aquifer is up to 150 m below ground surface beneath the Oak Ridges Moraine. The unit has been interpreted to have been eroded by deep tunnel channels in the vicinity of the Yonge Street area in Newmarket and in the West Holland River valley.

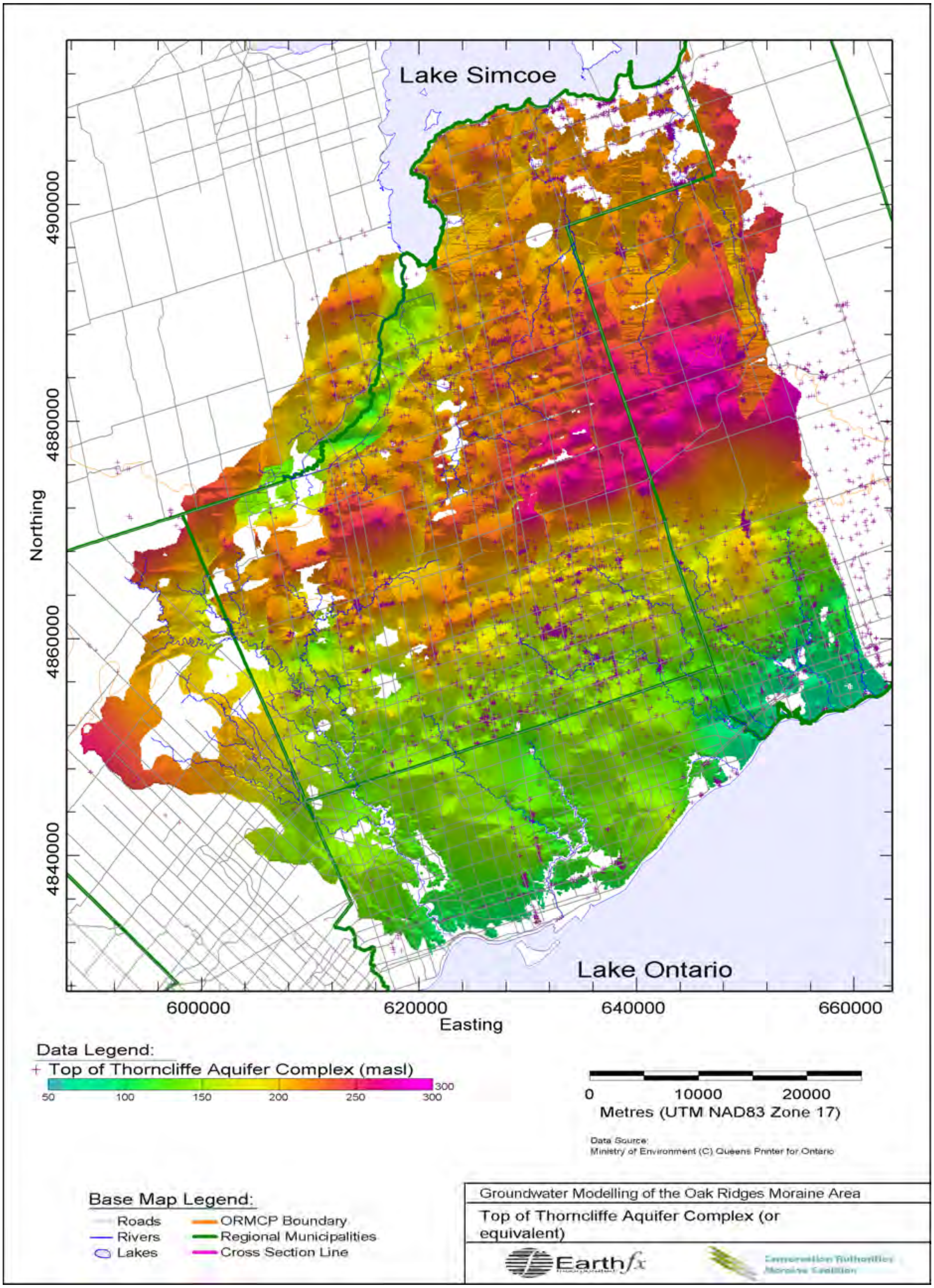

Figure 32: Elevation of the top of the Thorncliffe Aquifer Complex (or equivalent).

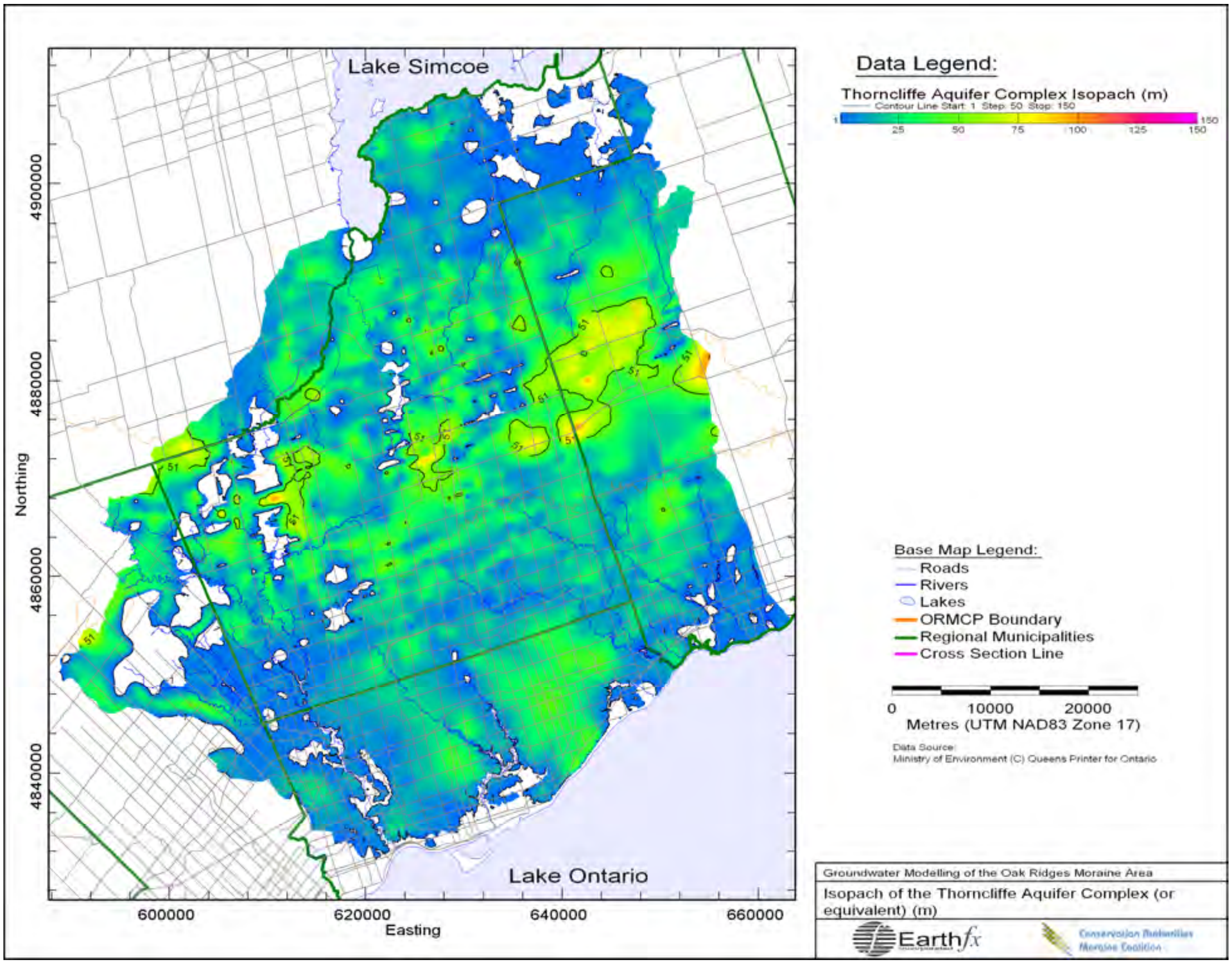

Figure 33: Isopach of the Thorncliffe Aquifer Complex (or equivalent).

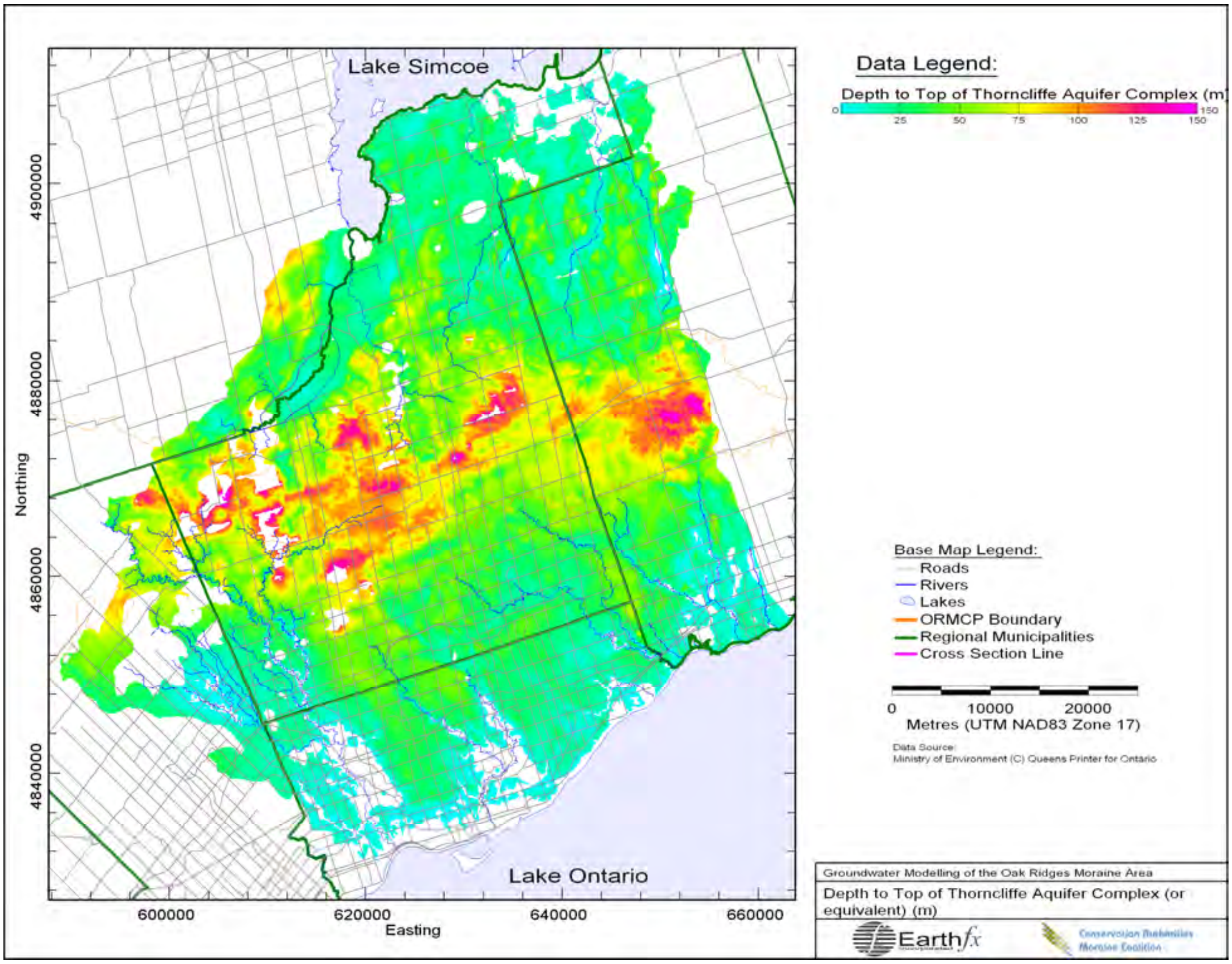

Figure 34: Depth to the top of the Thorncliffe Aquifer Complex (or equivalent).

3.3.6 Newmarket Aquitard

The Newmarket Aquitard (or equivalent) separates the Oak Ridges Aquifer Complex from the underlying Thorncliffe Aquifer Complex. The top of the Newmarket Aquitard is shown on **Figure 35**. For the Newmarket Aquitard maps, the silt infill of the tunnel channels has been combined with the Newmarket to form one continuous aquitard. Thus the maps reflect both types of fine grained sediments; till and silt. The highest elevations of this surface occur beneath the Oak Ridges Moraine where the aquitard appears to drape over a high on the upper surface of the Thorncliffe Aquifer Complex. The thickness of the Newmarket Aquitard is shown on **Figure 36**. The aquitard is generally less than 60 m thick with the greatest thickness occurring near Stouffville and along the ridges flanking the Holland Marsh. **Figure 37** shows the depth from ground surface to the top of the Newmarket Aquitard. The aquitard is found at depths of up to 100 m below ground surface along the core of the ORM.

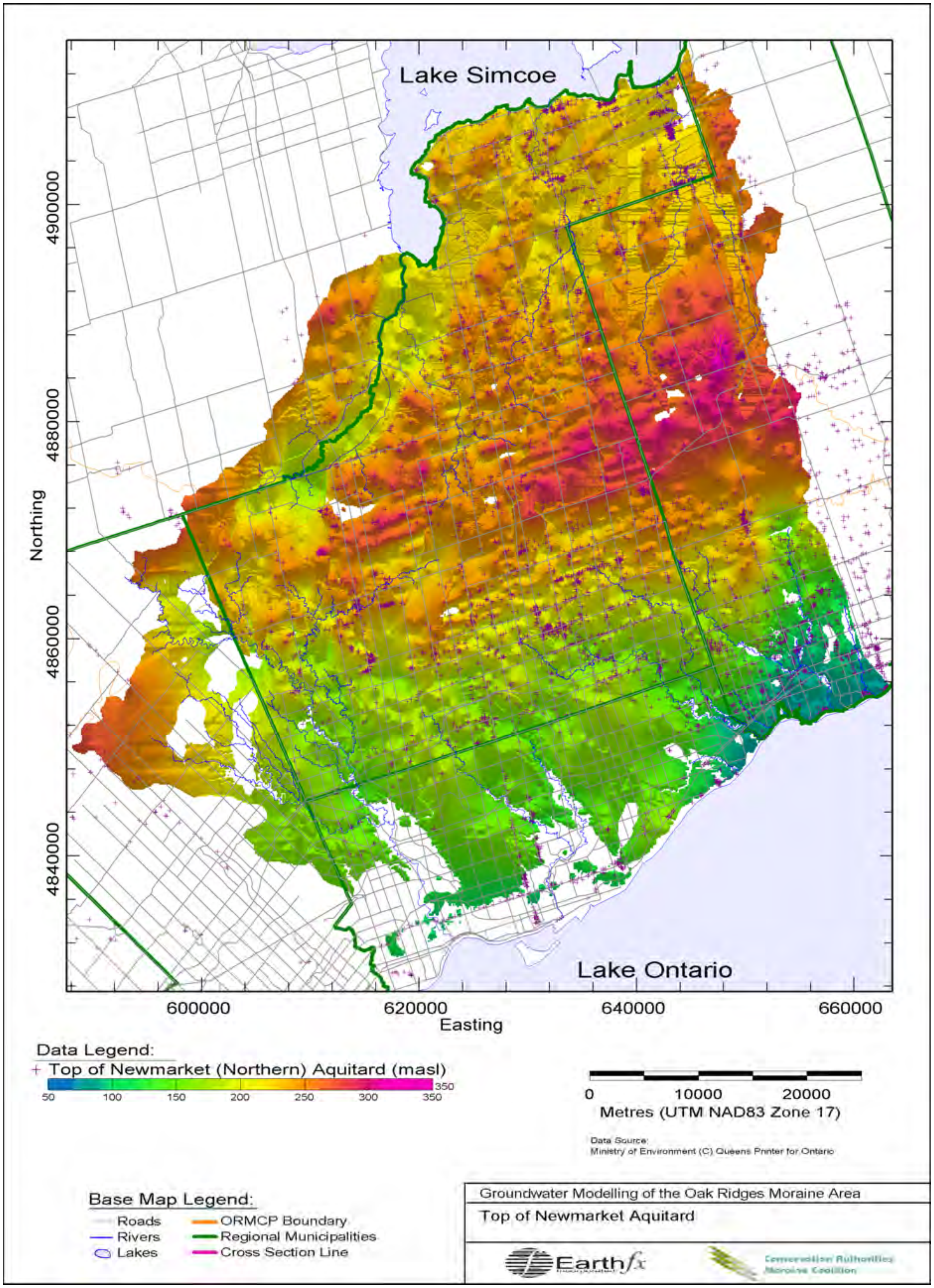

Figure 35: Elevation of the top of the Newmarket Aquitard (and tunnel channel sediments).

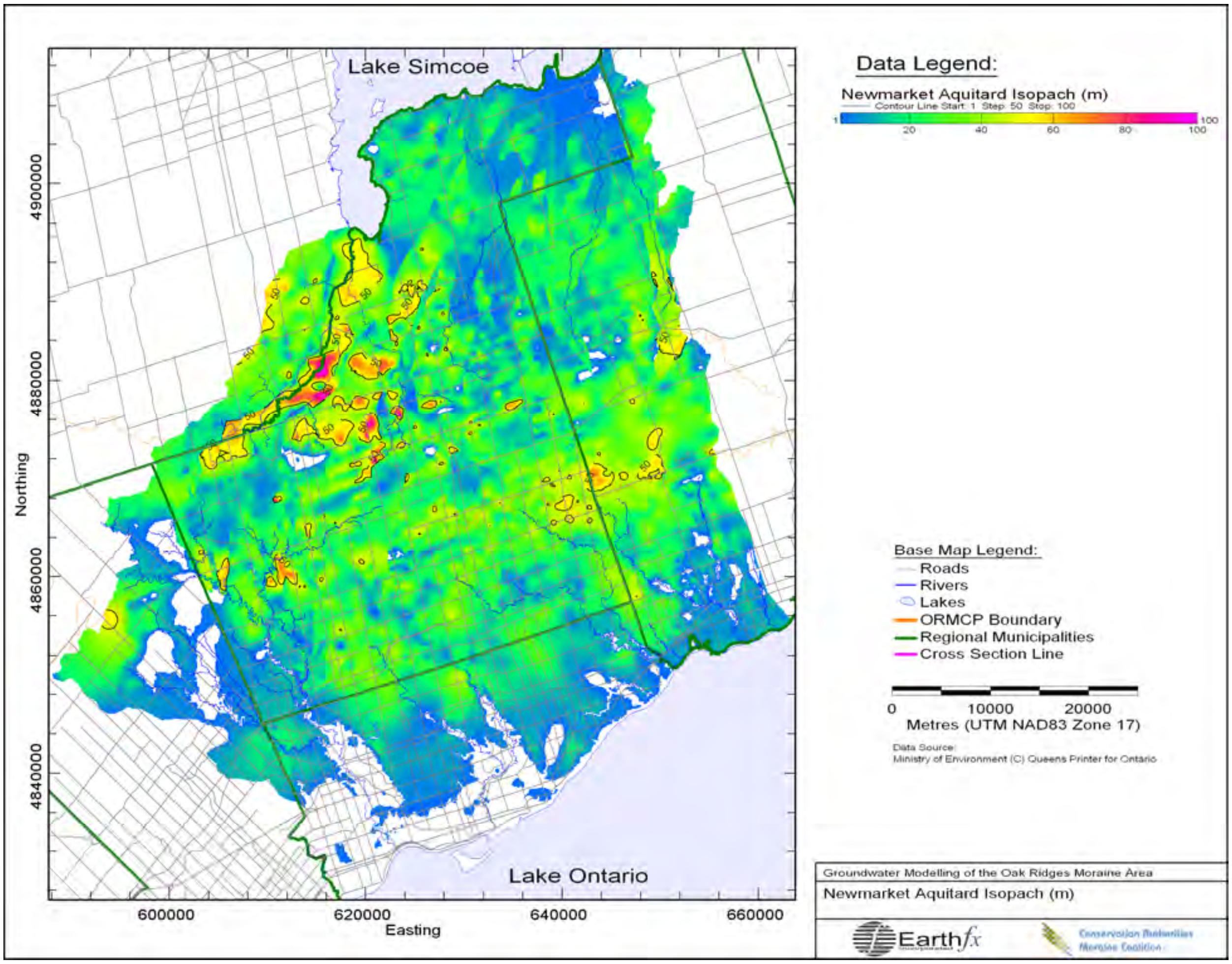

Figure 36: Isopach of the Newmarket Aquitard (and tunnel channel sediments).

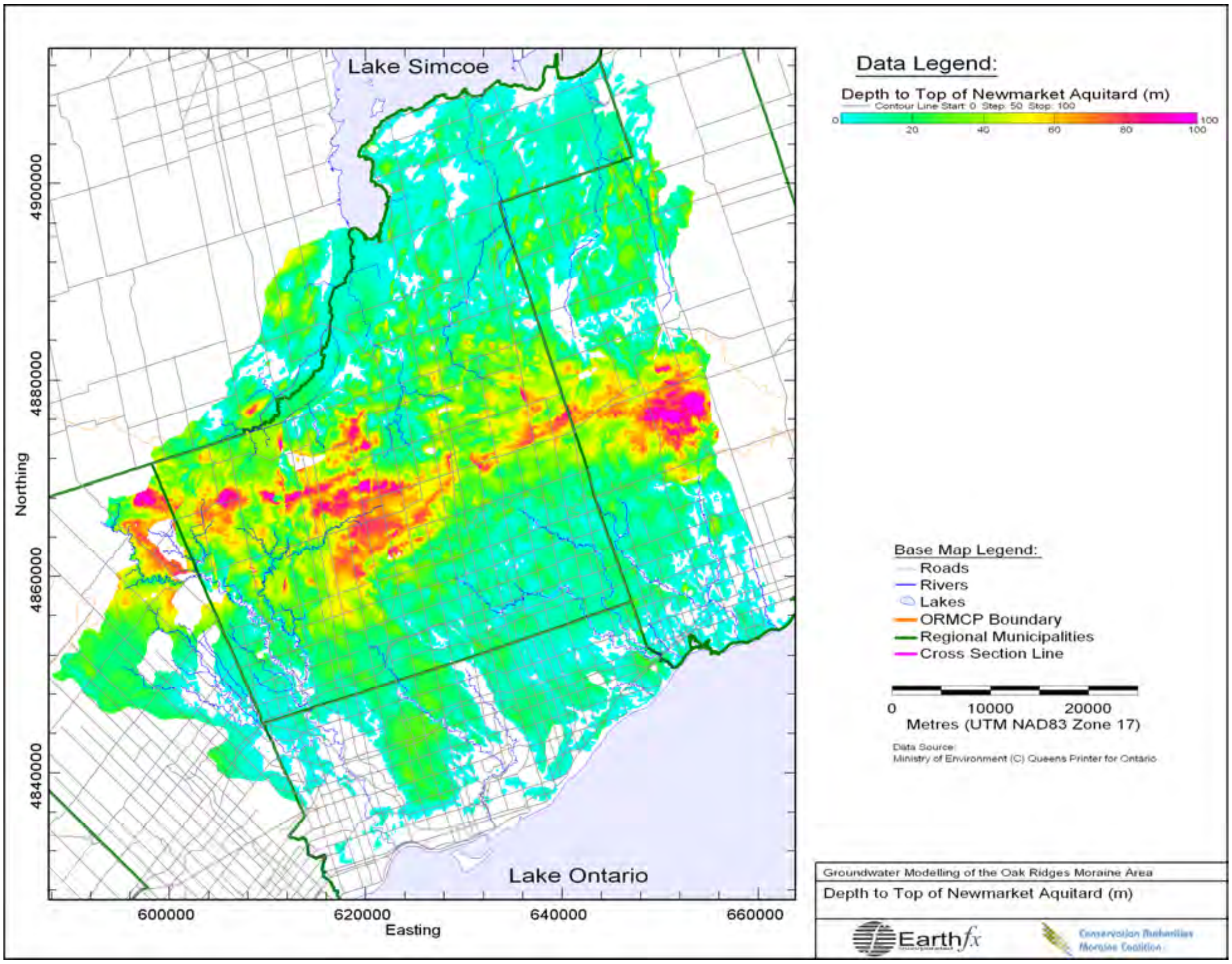

Figure 37: Depth to top of Newmarket Aquitard (or top of tunnel channel sediments).

Hydrogeologic investigations conducted by MM Dillon Limited (MM Dillon Limited, 1990; Interim Waste Authority, 1994a-e) and continued by Gerber (Gerber, 1999; Gerber and Howard, 1996, 2000; and Gerber et al., 2001) suggest that the Newmarket Aquitard can be considered a dual porosity medium with bulk hydraulic conductivity (K) controlled by non-matrix structures or pathways (**Figure 38**; Gerber et al., 2001). Horizontal pathways include sand and gravel interbeds and boulder pavements marking erosional surfaces identified in the Newmarket Till in outcrop and shallow seismic reflection profiles (Boyce et al., 1995 and Boyce et al., 1997). Vertical pathways include fractures, sand dykes, and steeply-dipping shear surfaces. Isotopic data (^{2}H, ^{18}O and ^{3}H) and regional water balance/groundwater flow modeling (Gerber, 1999) suggest vertical bulk K values on the order of 5×10^{-9} to 10^{-10} m/s. Matrix K estimates from triaxial permeability and slug testing, in contrast, yield much lower estimates ranging from 10^{-11} to 10^{-10} m/s. Vertical leakage through the Newmarket Till to the underlying Thorncliffe Aquifer is estimated at 30-40 mm/yr on a regional basis. The amount of vertical leakage will obviously differ where the till has been removed by meltwater erosion (tunnel channels) and will depend on the nature of channel infill sediments.

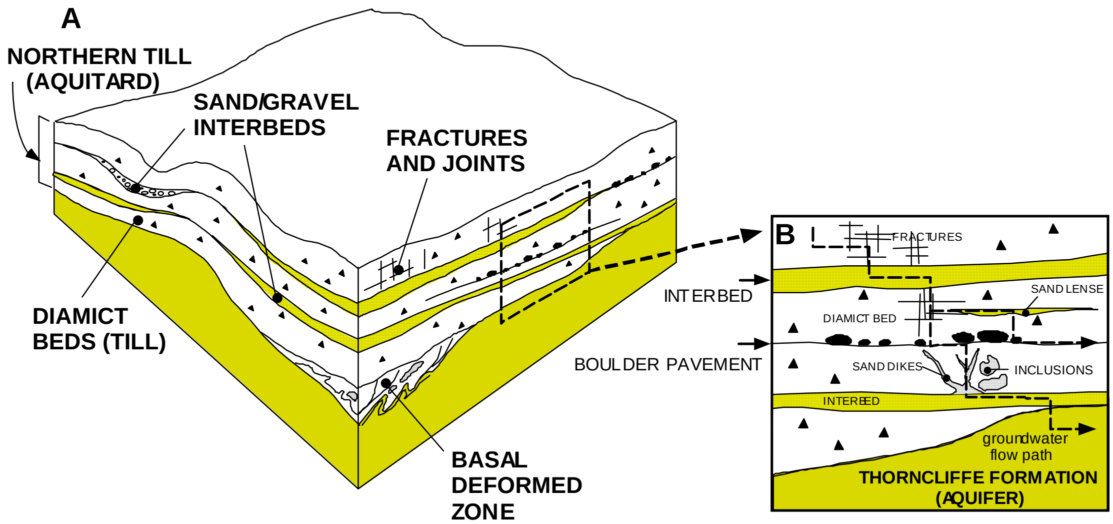

Figure 38: Conceptual model of the internal architecture of the Newmarket/Northern Till aquitard (from Gerber et al., 2001).

3.3.7 Tunnel Channel Sediments

A series of channels exist, most noticeably to the north of the Oak Ridges Moraine, where the Newmarket Till has been partially or completely eroded. The interpreted location of these erosive channels is shown on **Figure 39**. The sediments that infill these channels are quite variable, ranging from sand and gravel to silt and clay. Typically, the coarser sediments are found near the bottom of the channels with sediments fining upwards to silts. The nature of the infill sediment is important, particularly where the Newmarket Till has been completely eroded, in that the hydraulic conductivity of the upper silts will control the degree of vertical hydraulic communication between the adjacent aquifer units (**Figure 40**).

For mapping purposes, the silt portion of the tunnel channel sediments have been included with the Newmarket Aquitard. Thus, **Figure 35** shows the top of the tunnel channel sediments within the area delineated on **Figure 39**. Likewise, **Figure 36** shows the thickness of the upper silt portion of the tunnel channel sediments within the area delineated on **Figure 39**. **Figure 37** shows the depth from ground surface to the top of the tunnel channel sediments within the tunnel channel areas.

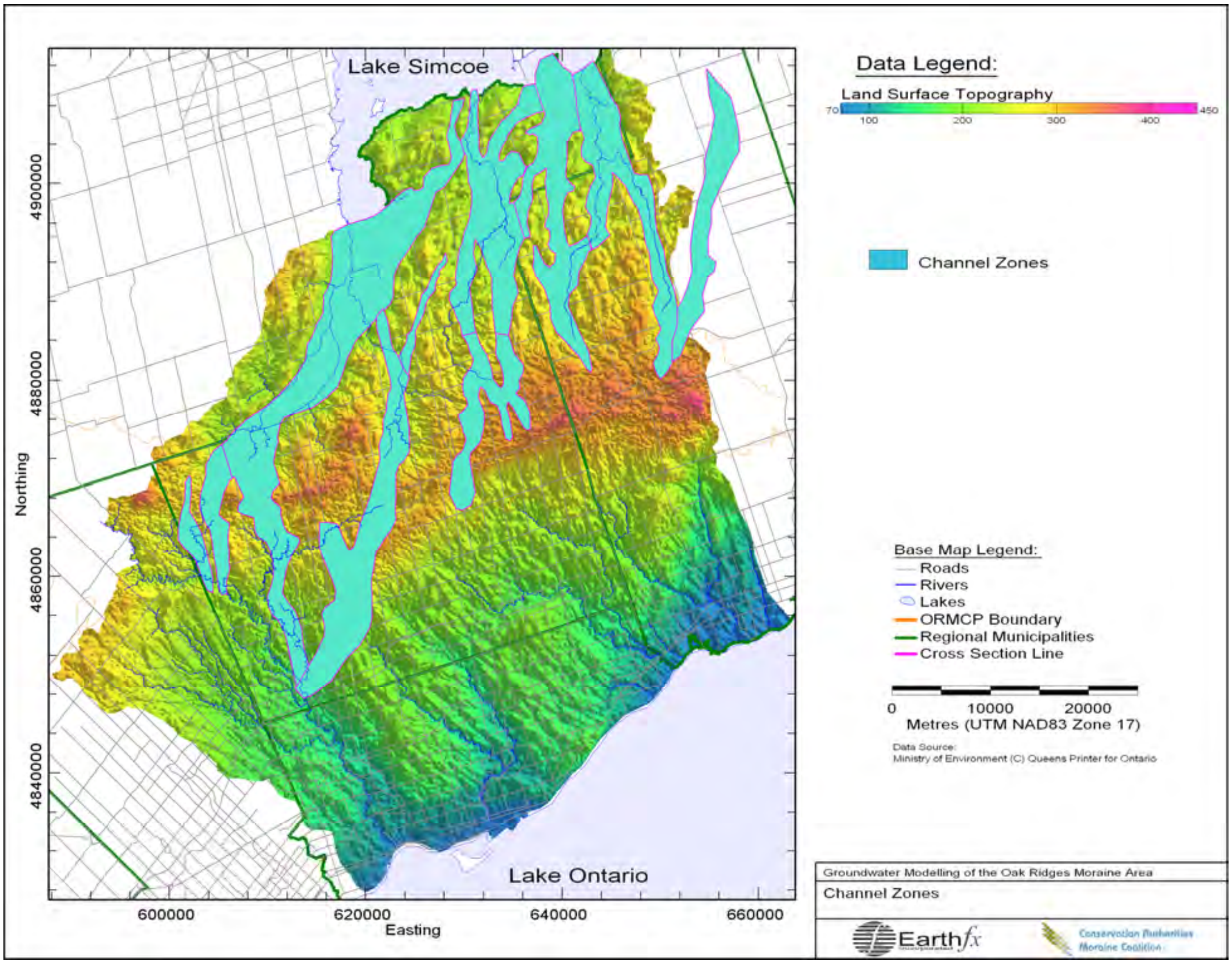

Figure 39: Channel zones.

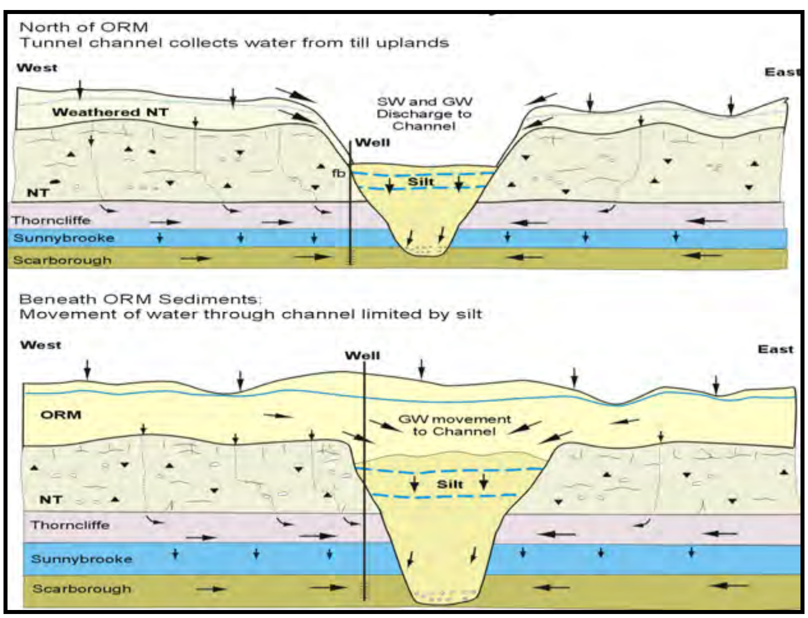

Figure 40: Conceptual function of the tunnel channel sediments.

3.3.8 Oak Ridges Aquifer Complex

The interpolated top of the Oak Ridges Aquifer Complex is shown on **Figure 41**. Sand bodies situated beneath the surficial tills along the flanks of the ORM are also included with the moraine deposits. The degree of hydraulic connection with the moraine sediments generally decreases with distance from the core of the ORM. ORAC sediments are up to 100 m thick along the core of the moraine, as shown in **Figure 42**. Remote from the ORM, the sands are generally less than 10 m thick.

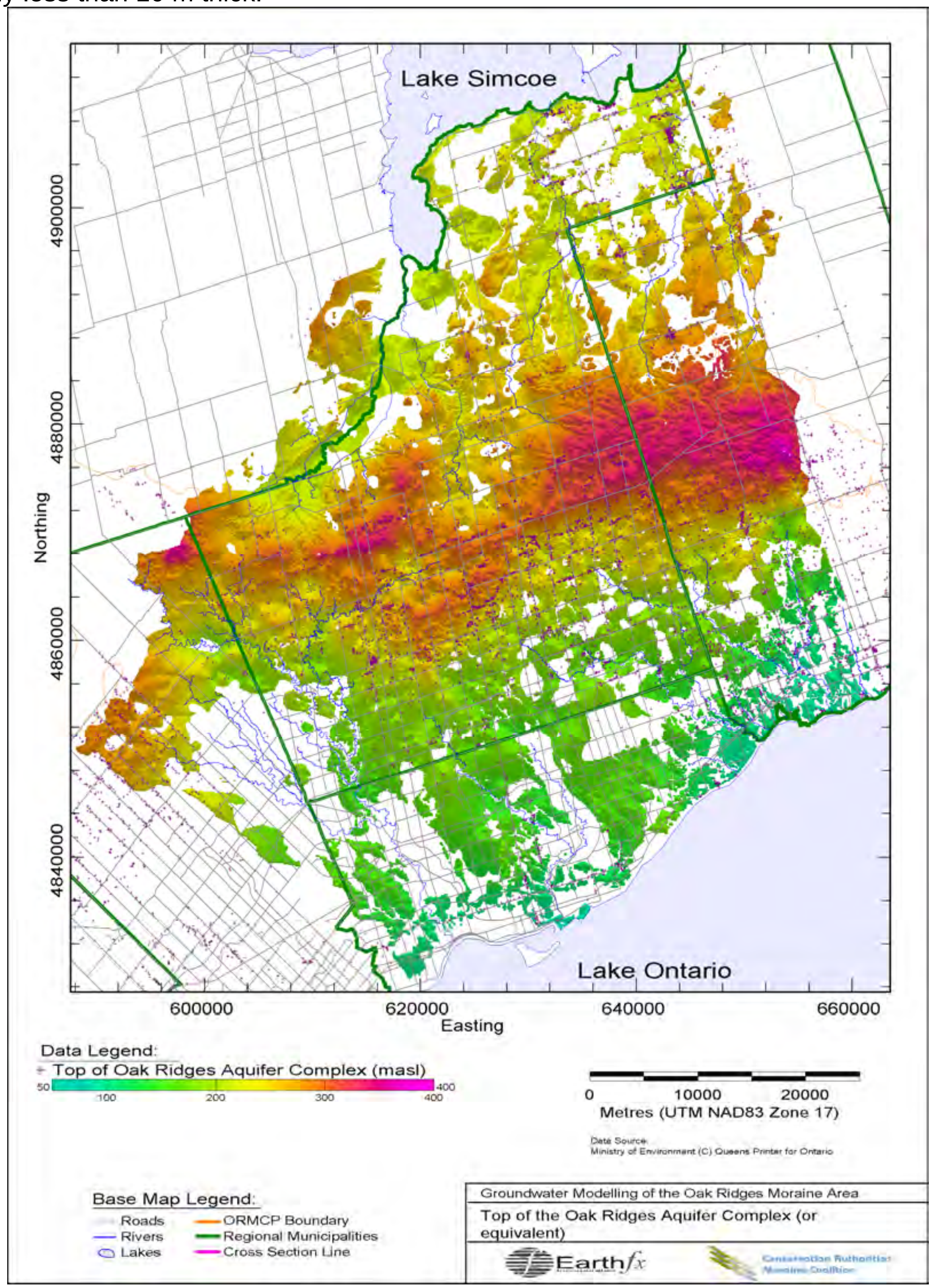

Figure 41: Top of the Oak Ridges Aquifer Complex (or equivalent).

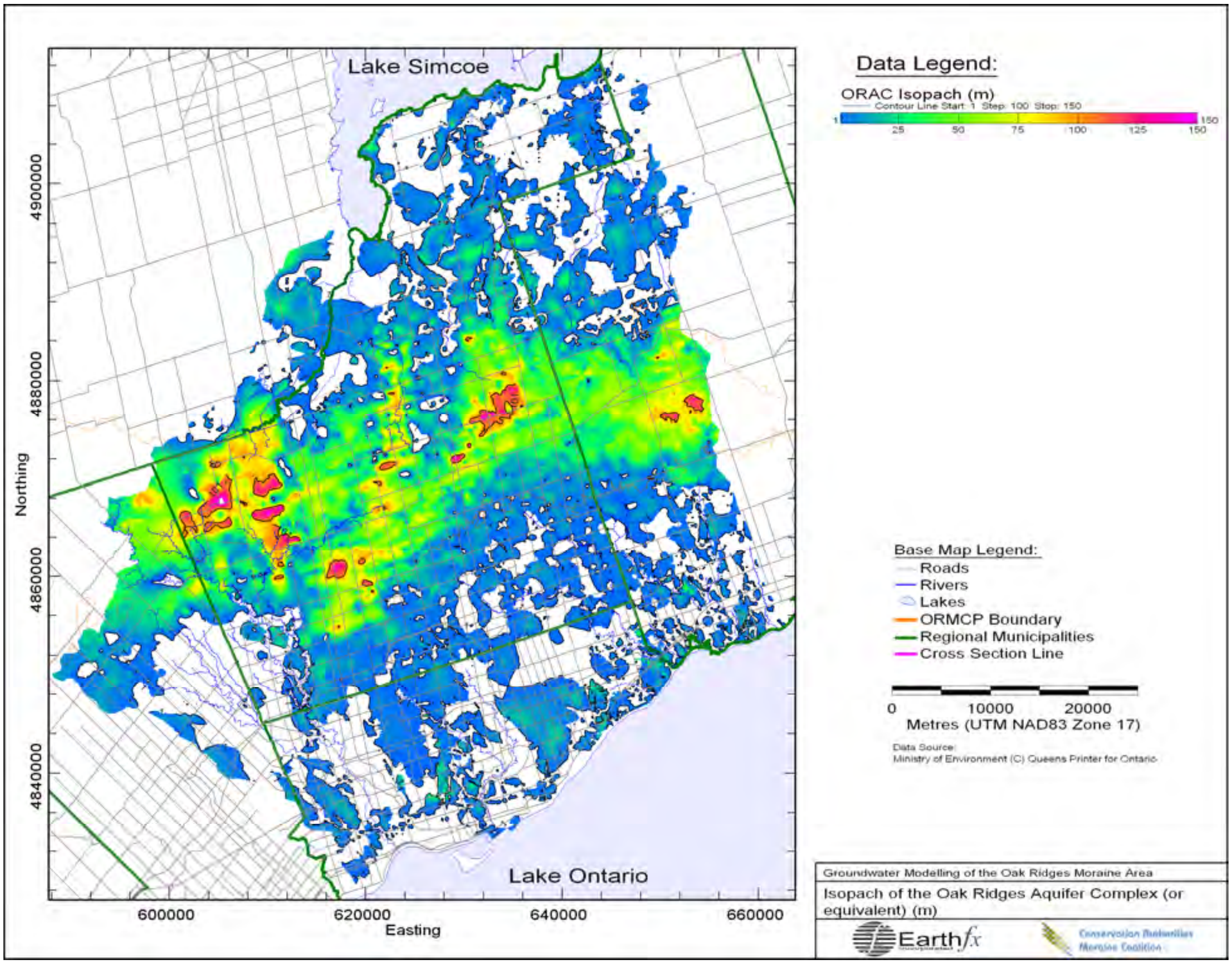

Figure 42: Isopach of Oak Ridges Aquifer Complex (or equivalent).

3.3.9 Halton/Kettleby Aquitard

The most recent till units occur largely at ground surface on either side of the ORM. The interpolated top of these till units, which have been grouped into the Halton/Kettleby Aquitard, is shown on **Figure 43**. These most recent, near surface till deposits are generally less than 25 m thick, as shown on **Figure 44**.

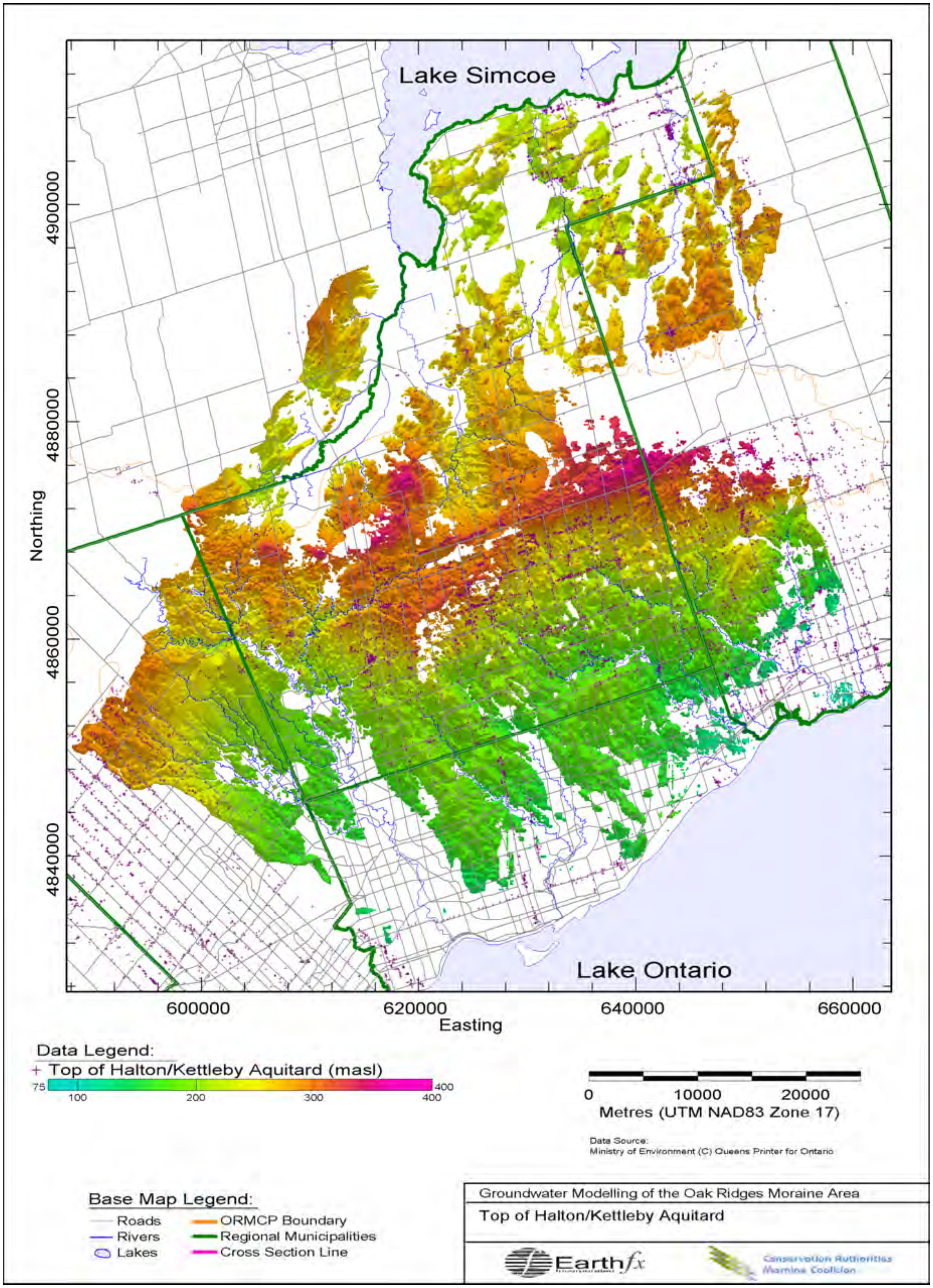

Figure 43: Elevation of the top of the Halton/Kettleby Aquitard.

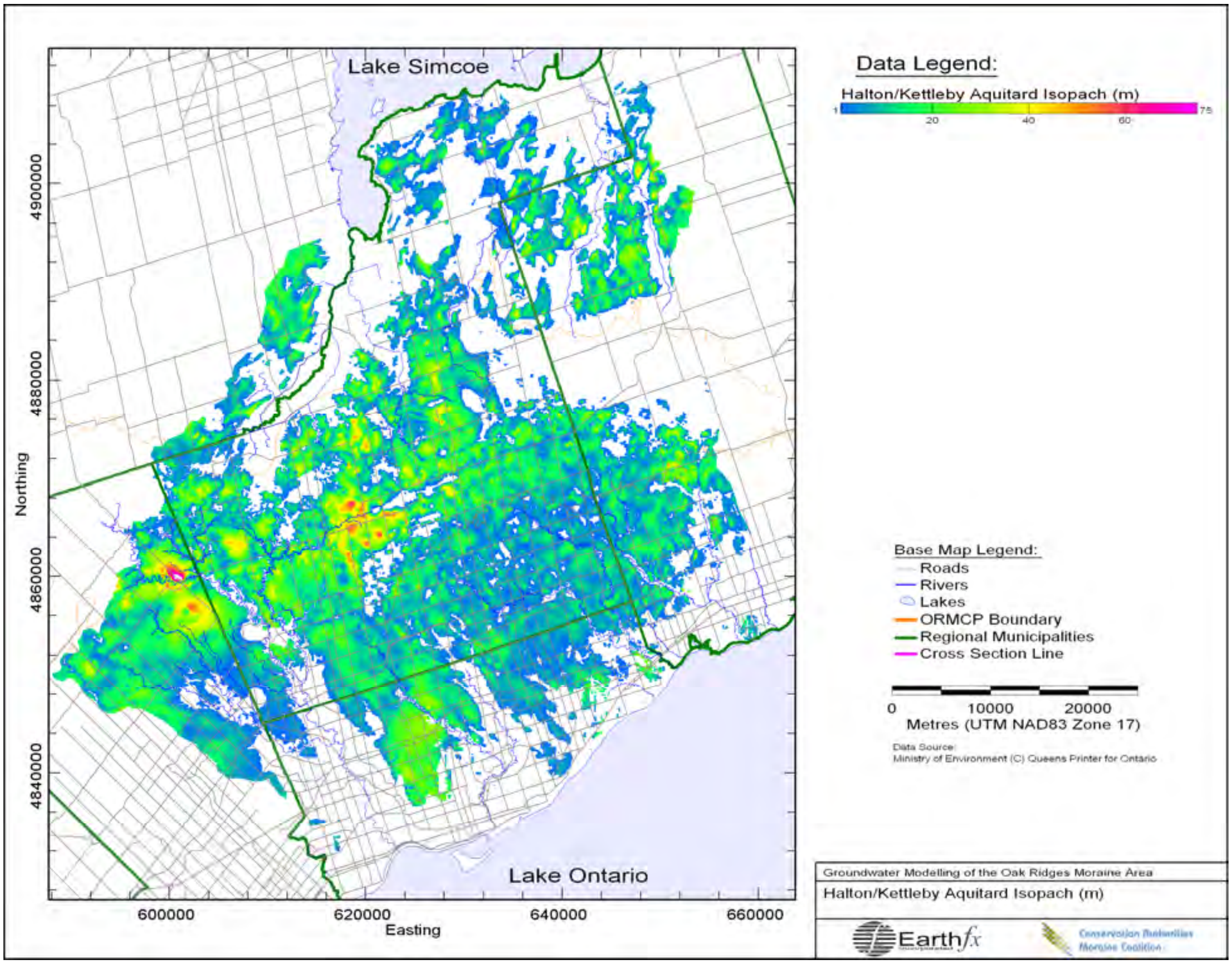

Figure 44: Isopach of the Halton/Kettleby Aquitard.

3.3.10 Cross-Sections

The key features of the hydrostratigraphic model are illustrated in a series of five cross sections. Cross section locations are shown on **Figure 45**. **Figure 46** represents a north-south cross section along the York-Durham Line which is typical of the eastern half of the Core Model study area. To the north of the ORM, the Sunnybrook Aquitard and the Scarborough Aquifer are largely absent as the stratigraphy drapes onto the bedrock high. To the south of the ORM, the sedimentary deposits dip to the south towards Lake Ontario and lie upon the bedrock surface that also slopes towards Lake Ontario. This section also illustrates the thickening of the Thorncliffe Aquifer Complex beneath the ORM.

Figure 47 shows a north-south cross section along Yonge Street. This section shows features typically present within the western half of the Core Model study area. The tunnel channel breaches of the Newmarket Aquitard are visible in the north half of this section. The interpreted base of these channels is difficult to estimate but, where present, a basal coarse-grained gravel was selected to demarcate the channel base. While not visible on this section, the base of the tunnel channels rises in the direction of flow towards the south. Also illustrated on this section is the thickening of the Scarborough Aquifer Complex within bedrock valleys.

The depth of interpreted tunnel channel erosion and deposition is also illustrated in west-east cross sections along Mt. Albert Road (**Figure 48**) and along Aurora Road (**Figure 49**). It should be noted that within the southern part of York Region and south of the ORM, the tunnel channels are either not present or have not eroded the Newmarket Aquitard to the same extent as occurs north of the ORM (**Figure 50**). The thickening of the Scarborough Aquifer Complex within bedrock valleys is apparent on all three west-east cross sections.

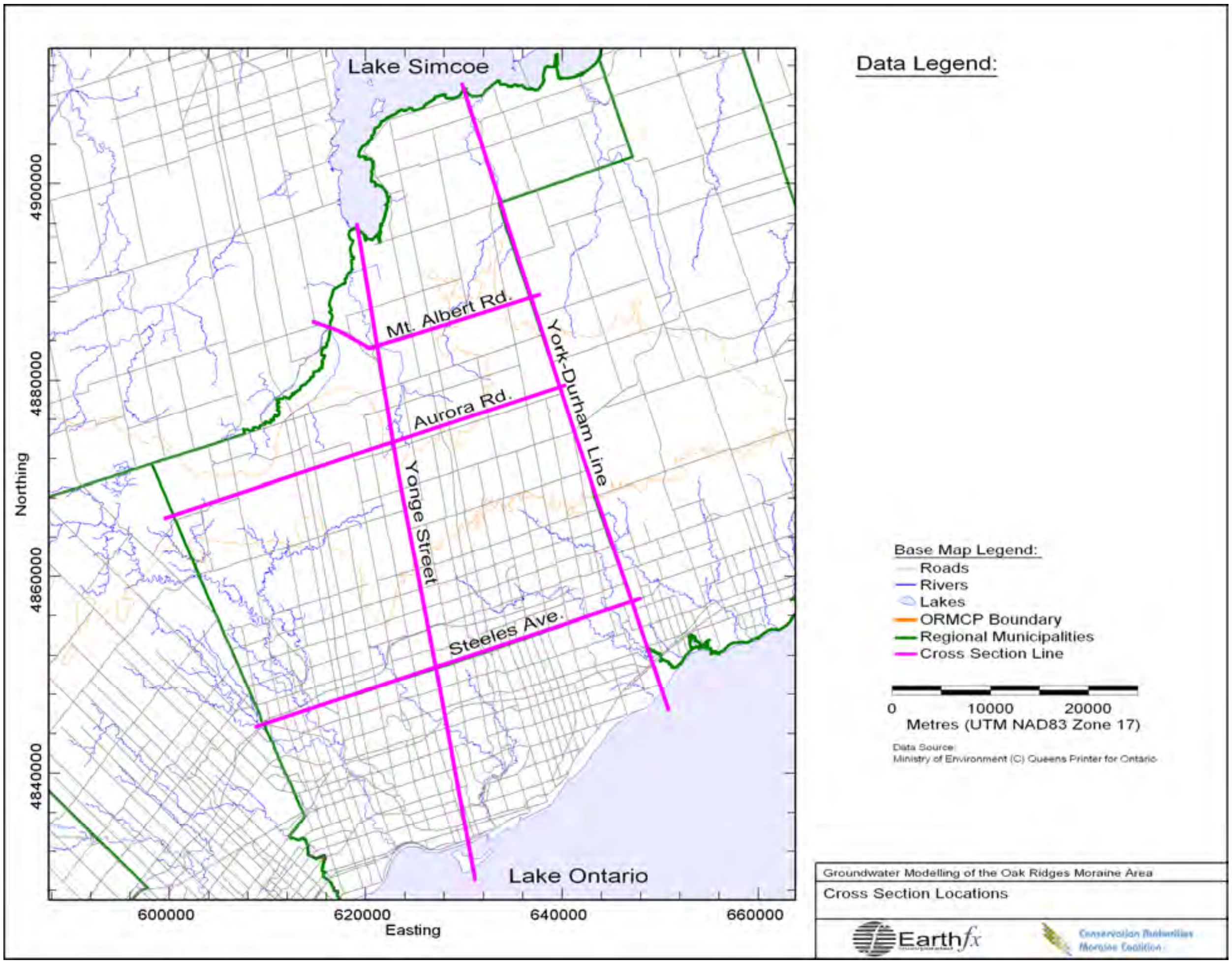

Figure 45: Cross section locations.

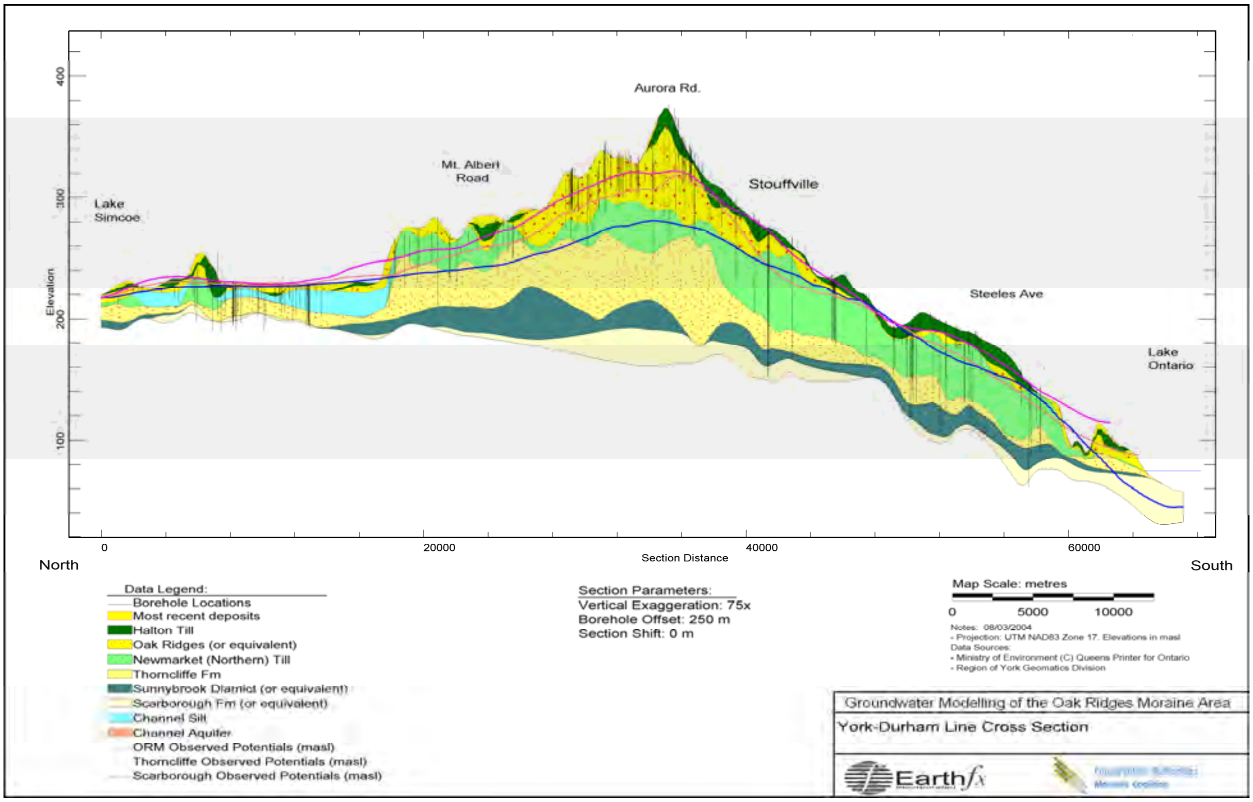

Figure 46: North-south cross section along the York-Durham line.

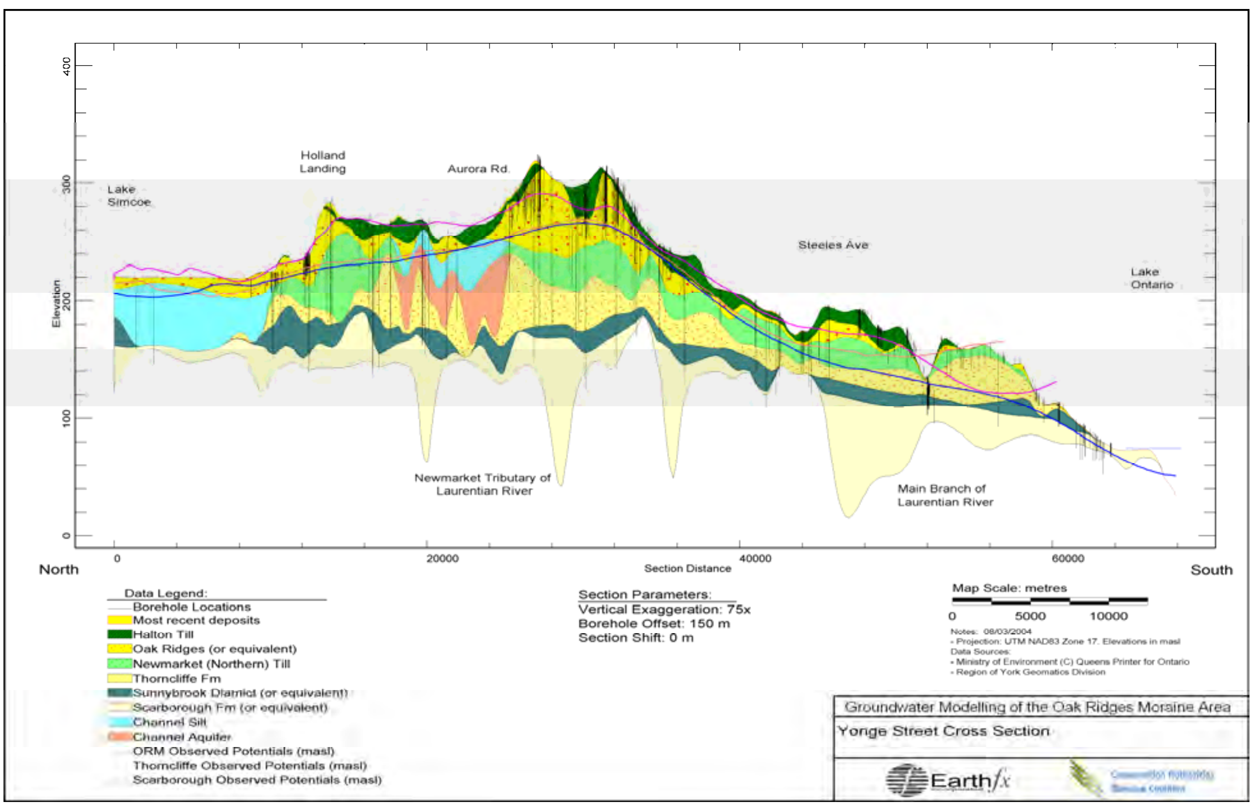

Figure 47: North-south cross section along Yonge Street.

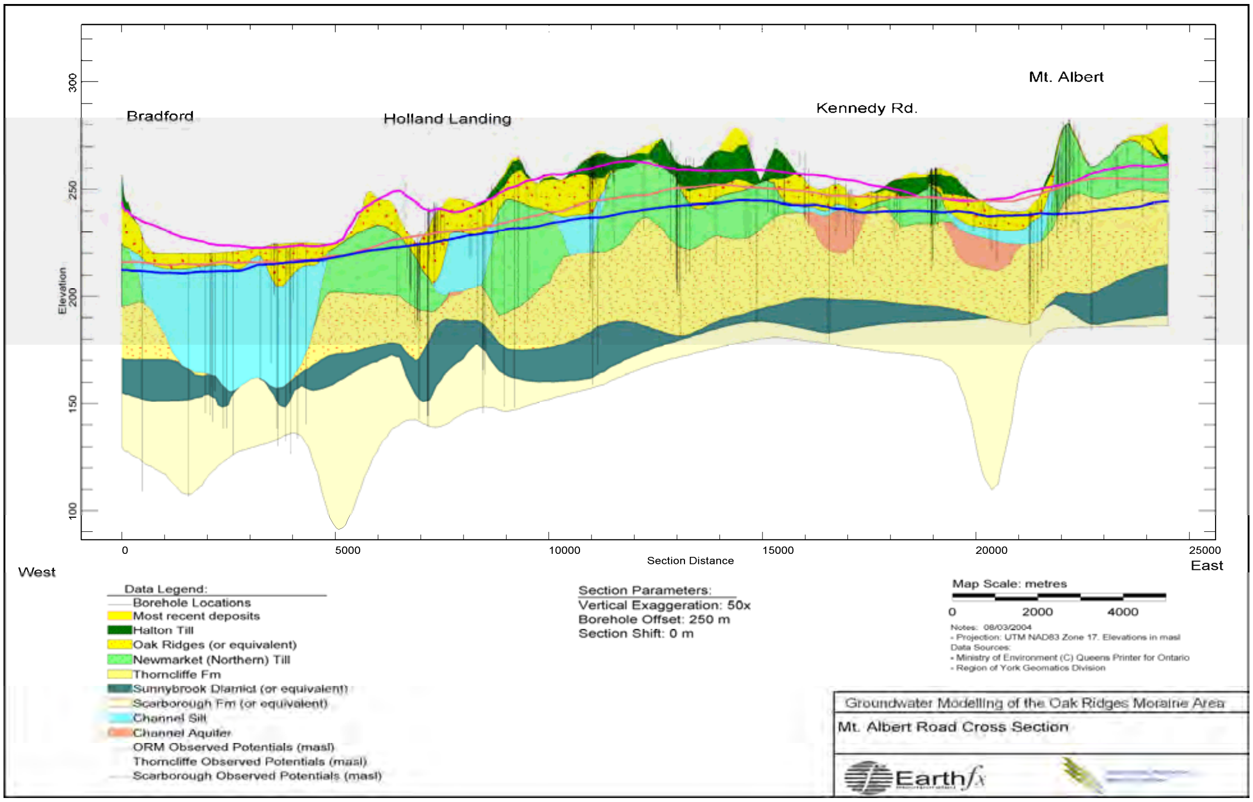

Figure 48: West-east cross section along Mt. Albert Road.

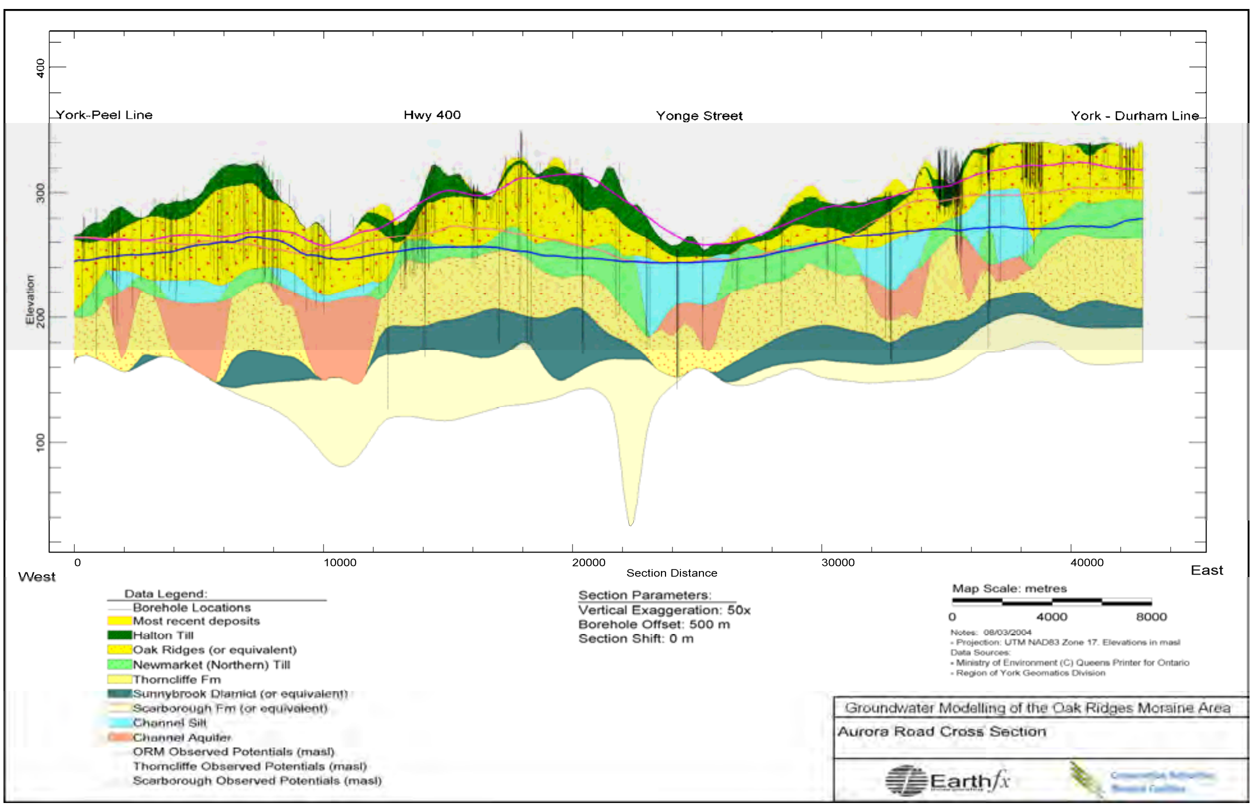

Figure 49: West-east cross section along Aurora Road.

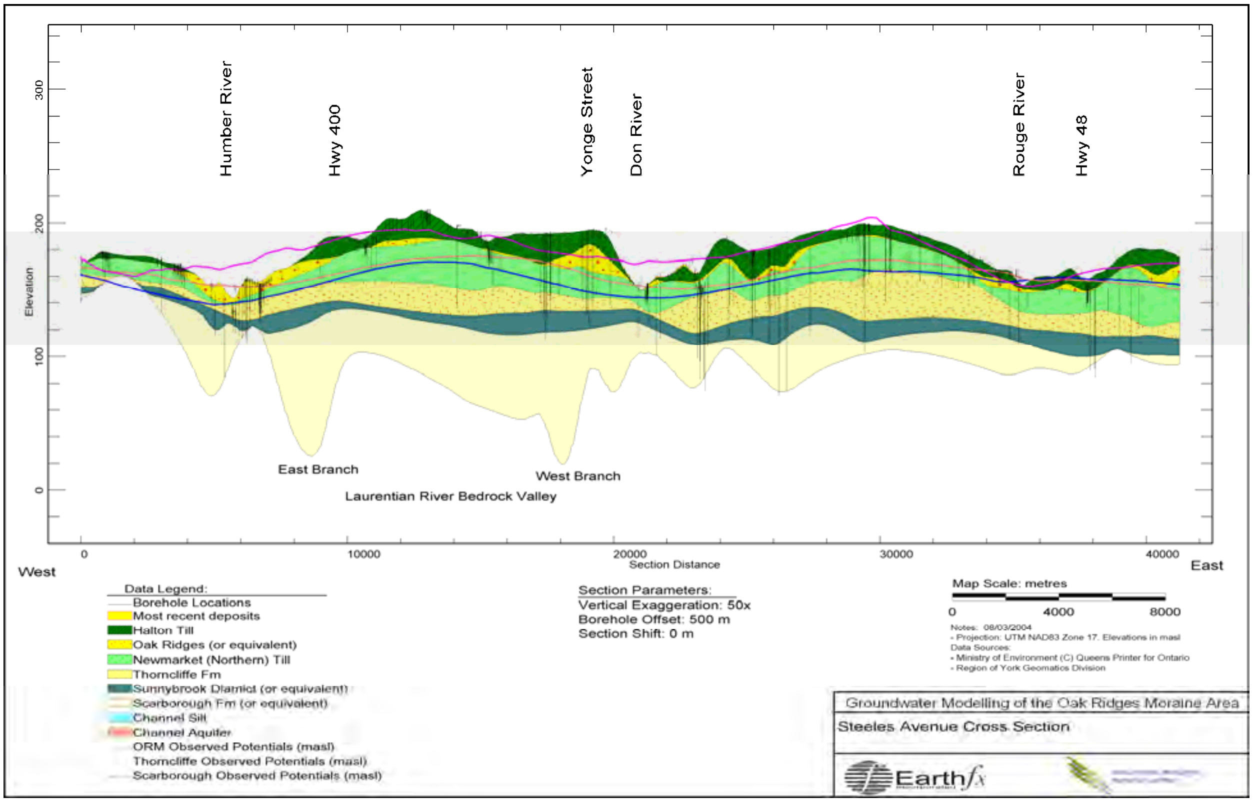

Figure 50: West-east cross section along Steeles Avenue.

3.3.11 Transmissivity Maps

Transmissivity is defined as the ability of an aquifer to transmit water and is equal to the hydraulic conductivity of the aquifer multiplied by the aquifer thickness. Aquifer thickness values were obtained as a result of the refinement of the Core Model hydrostratigraphy. Hydraulic conductivity values were obtained through the process of numerical model calibration (defined further on in the report).

Figure 51 presents a map of the transmissivity of the ORAC showing the high transmissivity areas associated with the thick granular deposits of the Oak Ridges Moraine and the equivalent sediments north and south of the moraine. Figure 52 presents a map of the transmissivity of the Thorncliffe Aquifer Complex showing the high transmissivity areas associated with thicker granular deposits of the Thorncliffe Formation. These areas frequently coincide with the tunnel channels. Figure 53 shows the transmissivity of the Scarborough Aquifer Complex showing the presence of higher transmissivity zones within the bedrock valleys.

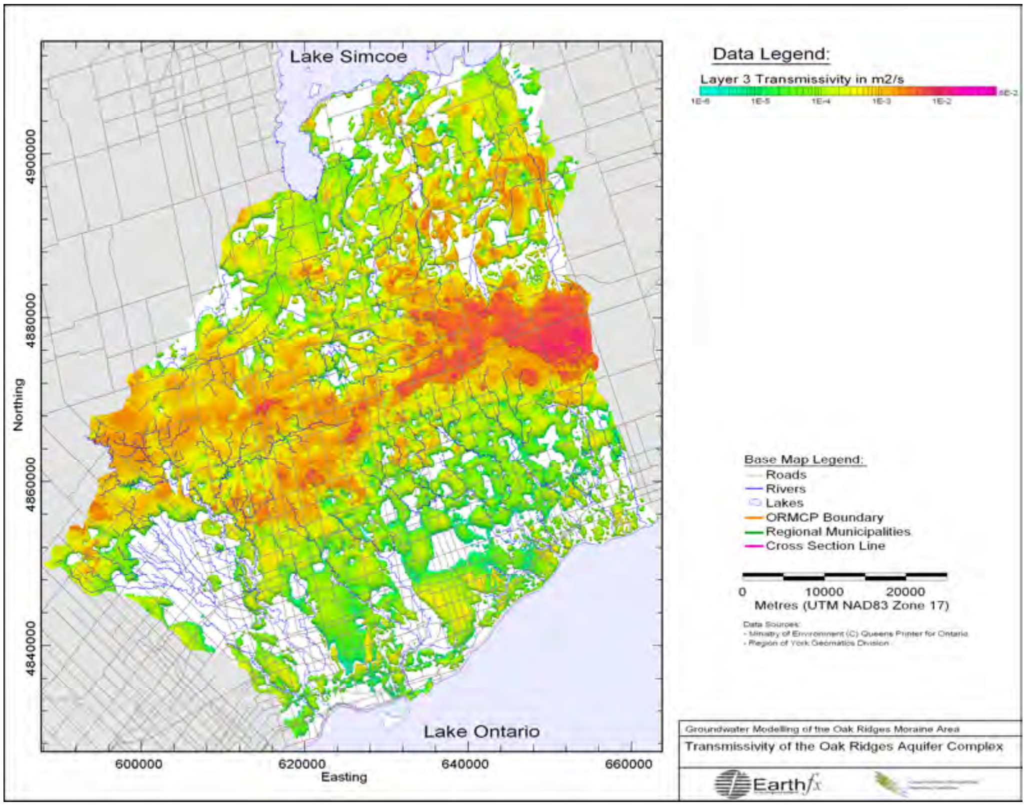

Figure 51: Transmissivity of the ORAC (or equivalent).

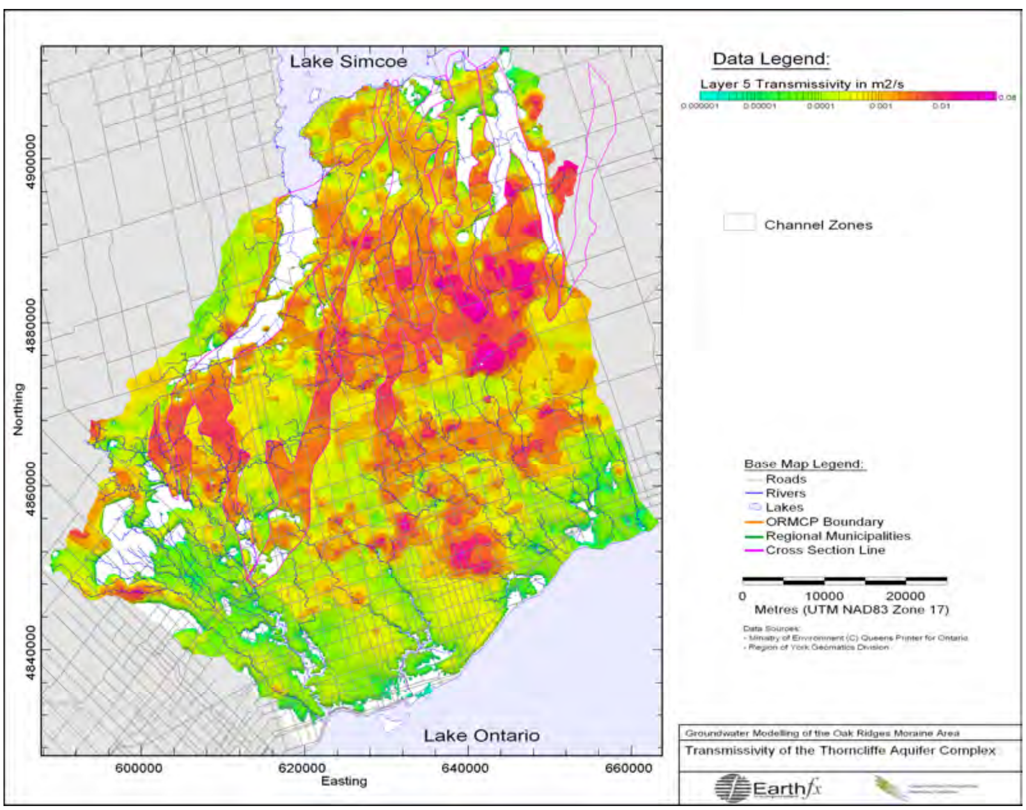

Figure 52: Transmissivity of the Thorncliffe Aquifer Complex (or equivalent).

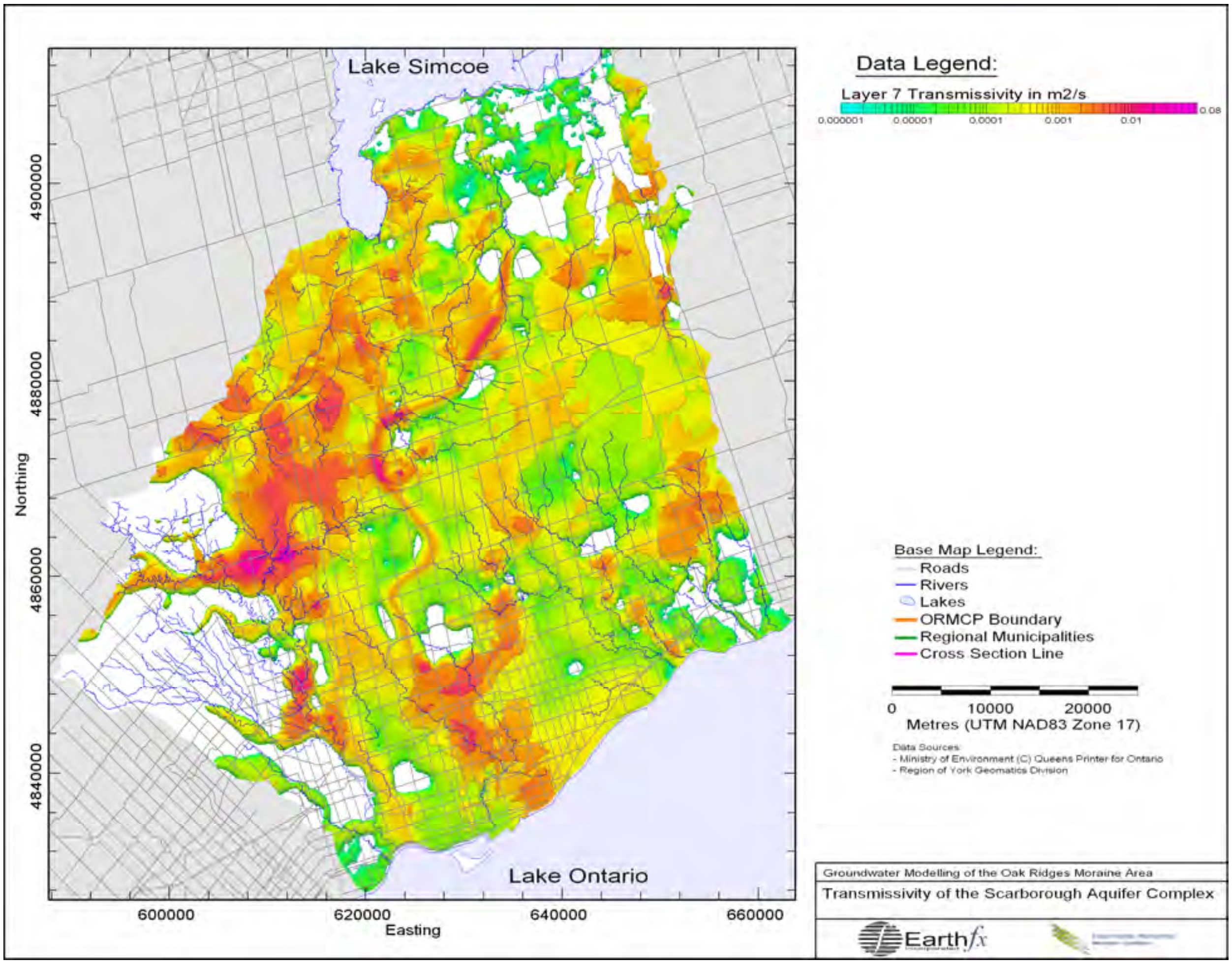

Figure 53: Transmissivity of the Scarborough Aquifer Complex (or equivalent).

3.3.12 Discussion

The complex hydrostratigraphy of the Oak Ridges Moraine provided many challenges to the construction of a regional hydrostratigraphic flow model. Simple interpolation of sparse well picks was not sufficient to create a model that accurately reflected the known sedimentary processes within and below the moraine. A new hydrostratigraphic methodology, built on the GSC stratigraphic approach, was developed with an emphasis on incorporation of hydrogeologic indicators as well as stratigraphic data. The approach was time consuming, iterative and database intensive, but resulted in significant understanding of the hydrostratigraphy of the ORM area.

The approach suggested that simply adding more wells will not necessarily produce better surfaces: the key was to integrate and understand the data, and build upon an understanding of the conceptual processes that shaped the subsurface. Database integration, flexible visualization, efficient layer picking tools, and the capture of expert intuition using 3-D constraint polylines were all essential to this process. The final result was a hydrostratigraphic model that not only honoured the well data, but also the conceptual understanding of the processes that formed the moraine.

Sensitivity analysis using the three-dimensional numerical groundwater flow model, created based on this hydrostratigraphic model and discussed in the Section 4, could be conducted to determine whether areas with poor stratigraphic control are hydrogeologically sensitive and in need of detailed field investigations (e.g. geophysically logged and/or cored boreholes or seismic surveys).

The hydrostratigraphic framework constructed for this project has built upon the Version 1 stratigraphic framework provided by the GSC. The three-dimensional delineation of the hydrostratigraphic layers presented here is considered to the best estimation at the time of the study. The database, particularly the MOE water well records, contains areas of ambiguous and often conflicting data. It is expected that future refinement of the layers will occur with further use and inspection on a more site-specific scale and as new data becomes available.

New data should be incorporated into the existing database so that the interpretation can be progressively refined. The hydrostratigraphic model also benefits from results of the numerical groundwater flow model where fluxes and hydrogeologic response can provide a feedback mechanism to assist in refining the hydrostratigraphic layers. Geologic and hydrostratigraphic analyses, coupled with numerical groundwater flow modeling, form an iterative and complimentary process.

4 Groundwater Model Development

4.1 Scope of Groundwater Modelling

4.1.1 What is a Numerical Model?

Numerical groundwater modelling is a process in which computer programmes (model codes) are used to solve the equations controlling groundwater flow to determine groundwater levels (also referred to as aquifer heads or potentials) at all points in an aquifer system. The process begins by representing the aquifers and aquitards in the subsurface as a series of interconnected blocks.

Values are assigned to represent the hydrogeologic properties of each block. Initial estimates for the values may be obtained from subsurface borehole information and aquifer testing data. These estimates are usually refined in the process of model calibration. By using many small blocks, or cells, an accurate representation of the variation in aquifer and aquitard geometry and property values can be constructed (see **Figure 54**).

Areal recharge and discharge to streams are usually represented as inflows and outflows from the upper model layers. Conditions along the boundaries of the model (for example, the water levels in a large lake at the edge of the model area) also affect or control the groundwater levels within the model area. Calibration of the model is done by refining the initial estimates of aquifer properties, recharge and discharge rates, and boundary conditions within reasonable ranges until a good match between simulated and observed water levels and flow rates is achieved. The calibrated model can then be used in a predictive mode to determine groundwater response to changes in model inputs.

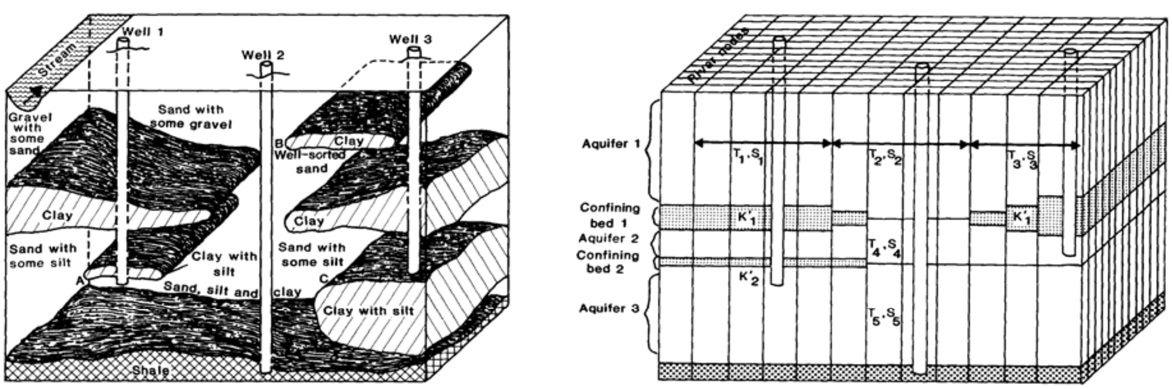

Figure 54: (a) Geologic conditions and (b) representation in a finite-difference model (After Anderson and Woessner, 1992).

4.1.2 Model Construction Methodology

The following general procedure was used to construct, calibrate and apply the model:

1. Gather available information on geology, hydrogeology, and surface water resources.

2. Review, synthesize, and interpret the information using traditional hydrogeologic analysis techniques such as geologic correlation on cross sections and mapping of water levels and aquifer properties.
3. Develop a conceptual understanding of the subsurface conditions. The conceptual model includes assumptions about the aquifer and aquitard layer geometry, aquifer and aquitard hydraulic properties, flow patterns, boundary conditions, and response of water levels to imposed stresses such as pumping.
4. Build a digital representation of the conceptual model by extrapolating the geologic and hydrologic data to create a continuous three-dimensional system.
5. Assign initial estimates for the aquifer and aquitard properties and represent conditions along the model boundaries.
6. Calibrate the numerical model to match field observations.
7. Test the quality of the calibration by conducting sensitivity analysis and verify the calibration by checking the model's ability to match multiple scenarios (such as non-pumping and pumping conditions).
8. Apply the calibrated model to predict the impact of various changes to the groundwater system (e.g. reduction in recharge due to urbanization; proposed changes in wellfield pumping rates) or to delineate capture zones for municipal wells.

4.2 ORM Model Development Overview

A regional-scale groundwater flow model was developed for the entire Oak Ridges Moraine and surrounding area. The primary objective of this modelling effort was to develop a tool to help understand the hydrogeology of the study area and the primary factors controlling the rate and movement of groundwater. Other objectives included using the model to (1) determine an overall water balance for the study area, (2) determine the sensitivity of the groundwater system to recharge variation, (3) quantify impacts of increased water takings on stream flow, and (4) provide a framework for detailed wellhead capture zone analysis. Longer term objectives are to use the model to provide guidance on groundwater management and monitoring in the ORM and to minimize the impact of urban development and other changes in land use on the groundwater and surface water systems.

Model development progressed in two stages. A regional model was constructed based on the original interpretation of the ORM geology by the GSC. The regional model area, shown in **Figure 3**, is approximately 250 km long and 160 km wide and extends well beyond the ORM limits to reach natural hydrologic boundaries. The model area is bounded by the Niagara Escarpment to the west and by the eastern edge of the Trent River watershed to the east. The southern boundary is defined by Lake Ontario while the northern boundary is defined by Georgian Bay, Lake Simcoe, the Kawartha Lakes, and several watershed boundaries.

Results from the regional model were used to develop a refined sub-regional model for the core of the study area. The study area for the sub-regional model encompasses all of York Region and extends partly into neighbouring Peel and Durham Regions (**Figure 3**). The Core Model extends southward from York Region to cover the City of Toronto and almost all of the watersheds in the TRCA from Duffins Creek and Carruthers Creek in the east to Mimico Creek and most of the Humber River watershed in the west.

4.2.1 Previous Models

Several investigators have built sub-regional numerical models for parts of the study area. For example, Gerber (1999) studied the Duffins Creek watershed; Meriano (1999) modelled the Rouge River basin and Smart (1994) studied the Humber, Don, Rouge, Duffins, and Lynde Creek watersheds. The largest-scale study was by Mowatt (2001), who modelled an area similar to that of the Core Model. Most studies, with the exception of Mowatt (2001), used the regional groundwater divide in the ORM as a model boundary. The current study integrates and builds on these previous efforts.

4.3 Conceptual Flow Model

Prior to building the numerical groundwater flow models, it was necessary to develop an initial comprehensive understanding of the groundwater flow system. This understanding, often referred to as a conceptual flow model, encompasses the physical and hydrogeologic setting of the study area and the hydrologic factors that govern groundwater flow. Key issues addressed in developing the conceptual model included:

1. bedrock and overburden stratigraphy;
2. physical conditions along the boundaries of the flow system;
3. initial estimates of aquifer and aquitard properties;
4. configuration and continuity of the major aquifers and aquitards;
5. rates of recharge and groundwater discharge; and
6. aquifer heads (i.e. historic and current groundwater levels) and flow patterns.

Description of the geologic setting of the study area and the development of the conceptual geologic and hydrostratigraphic models is found in Sections 2 and 3. The GSC provided digital mapping of key units used to build the regional groundwater flow model of the ORM. Refinement and subdivision of these units provided the basis for the numerical groundwater flow model of the core area.

Natural hydrologic boundaries, such as Lake Simcoe, Lake Ontario and major watershed divides, were used to define the extent of the area modelled and to determine the conditions specified on the external boundaries of the Regional Model and Core Model. The aquifers and confining units, which are derived mostly from glacial materials, are extremely variable. The success of the model depended on the accurate understanding and representation of the variations in aquifer properties (e.g. aquifer thickness and hydraulic conductivity), since these variations influence the lateral movement of groundwater. Also important were variations in aquitard properties which control the vertical movement of water between aquifers. Initial estimates of aquifer properties used in the Regional Model were derived from the limited amount of aquifer performance test data and from the results of previous modelling studies. Better estimates of the distribution of aquifer properties in the Core Model were obtained through analysis of the lithologic and well performance data. Property estimates were refined during the process of model calibration.

The rate of groundwater recharge varies over the study area and is controlled by the spatial distribution of precipitation, soil properties, topography, vegetation, and land use. The initial estimates for the rates and distribution of recharge for the Regional Model were obtained from previous groundwater models and watershed studies and by additional water budget analyses. These recharge estimates were further refined while developing and calibrating the Core Model.

Potentiometric surface and water-table maps were prepared using static water levels in the MOE water well database (see Section 5). The data showed a number of significant features that needed to be matched by the numerical model, including:

- the water-table mound beneath the Oak Ridges Moraine which creates a regional groundwater divide;
- the observation that the potentiometric surfaces in the lower aquifers were subdued replicas of the water-table;
- the influence of the shallow streams on the flow system and the extent to which surface water divides also serve as groundwater divides.

Based on the preliminary water-table and potentiometric surface maps, it was interpreted that groundwater discharges primarily as baseflow to streams and, to a lesser degree, as underflow across model boundaries (e.g. to Lake Ontario or Lake Simcoe), and through groundwater pumping. Data on water use and stream baseflow were compiled and analyzed to determine rates of groundwater discharge in the Regional Model and Core Model.

Groundwater is exchanged between the different aquifers as leakage across the aquitards. Leakage rates can vary locally depending on changes in the thickness and hydraulic conductivity of the confining units. Leakage is downward in the vicinity of the Oak Ridges Moraine where recharge rates and aquifer heads are highest. The magnitude of the head differences (greater than 30 m in some areas) indicates that the confining units are of very low permeability and that they restrict the rates of vertical movement of water between the aquifers. Areas of lower vertical gradients which coincide with the location of tunnel channels suggested that the model would have to reflect higher leakage rates in areas where the confining units have been removed. Upwards leakage from the lower aquifers occurs in the immediate vicinity of streams and springs and, to a lesser extent, close to lake shorelines, all areas where water levels in the upper aquifer are depressed.

Once this preliminary conceptual understanding of the groundwater flow system was obtained, construction of the numerical model proceeded. The process of model development provided additional insight into the physical processes governing flow in the study area and, in turn, helped to refine the conceptual understanding of the hydrogeology.

4.4 Numerical Groundwater Flow Modelling

4.4.1 Approach

Steady-state groundwater levels (also referred to as aquifer potentials or hydraulic heads) within the study area are controlled by many factors including stratigraphy, the magnitude and spatial variation in hydraulic conductivity, and the rate and distribution of recharge and discharge. The groundwater flow models developed in this study incorporated information on the geometry and physical properties of the aquifers and aquitards and information on aquifer stresses (i.e. recharge and discharge) in order to solve the groundwater flow equation and determine aquifer potentials at all points within the model area.

The resultant groundwater levels were interpreted to determine the rates and direction of groundwater flow. Water budgets were computed based on model results to quantify the difficult-to-measure fluxes such as underflow to Lake Ontario and groundwater discharge to streams. Model runs with different pumping rates were used to determine the likely changes in heads and groundwater discharge to streams under different stress conditions.

The following sections describe the governing steady-state groundwater flow equation and the groundwater flow model code selected for this study. Limitations of the model and simplifying assumptions used in model development are also discussed.

4.4.2 Groundwater Flow Theory

Groundwater flow is governed by Darcy's Law, which states that flow is proportional to the hydraulic gradient and to the hydraulic conductivity of the aquifer material and is given by:

$$q = K \frac{dh}{dx} \qquad \text{(Eq. 4.1)}$$

where q is the specific discharge or rate of flow per unit area, K is the hydraulic conductivity, and dh/dx is the hydraulic gradient (change in hydraulic head per unit length). Groundwater flow is also governed by the Law of Conservation of Mass which states that, under steady-state conditions, all inflows to an area are balanced by outflows. When the mass balance equation is combined with Darcy's Law, it yields the governing equation of groundwater flow. The groundwater flow equation for two-dimensional flow in a confined aquifer with recharge, discharge, and leakage from above and below can be written mathematically (Bear, 1979) as:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)+\left[\frac{K'_u}{B'_u}\left(H_U-h\right)\right]+\left[\frac{K'_O}{B'_O}\left(H_O-h\right)\right]+N-\sum_{k=1}^{Nwell}Q'_k=0 \qquad \text{(Eq. 4.2)}$$

where:

	T_{xx}	=	transmissivity in the x direction;
	T_{yy}	=	transmissivity in the y direction;
	h	=	hydraulic head;
	K'	=	vertical hydraulic conductivity of an overlying (or underlying) confining unit
	B'	=	thickness of the overlying (or underlying) confining unit;
	H_o/H_u	=	head in the aquifer layer overlying/underlying the confining unit;
	N	=	rate of groundwater recharge;
	Q'_k	=	pumping rate (per unit area) at well k

A similar equation can be written for each aquifer in a layered sequence of aquifers and confining units. When an aquifer layer is unconfined, the transmissivity terms T_{xx} and T_{yy} are replaced by the effective transmissivity, equal to K_{xx}(h-b) and K_{yy}(h-b)where b is the base of the aquifer layer and K_{xx} and K_{yy} are the hydraulic conductivities in the x and y directions .

Equation 4.2 forms the basis of the mathematical model developed for the study area. Model input, in the form of information on aquifer properties, recharge and discharge rates, and conditions along the study area boundaries, was assembled and Equation 4.2 was solved to determine aquifer potentials. Numerical methods were needed to solve Equation 4.2 because study area boundaries are irregular and aquifer/aquitard properties, aquifer geometry (stratigraphy), and rates of recharge and discharge vary spatially within the study area.

4.4.3 Modelling Code and Modelling Environment

4.4.3.1 MODFLOW Finite Difference Flow Model

There are several types of numerical methods and numerous computer codes available to solve the groundwater flow equation. The U.S. Geological Survey MODFLOW code was selected for use in this study because this code is recognized worldwide and has been extensively tested and verified. The MODFLOW code is extremely well-suited for modelling regional flow in multi-layered aquifer systems and can easily account for irregular boundaries, complex stratigraphy, and variations in hydrogeologic properties. The version of MODFLOW used in this study is documented in McDonald and Harbaugh (1988) and Harbaugh and McDonald (1996). MODFLOW solves Equation 5.2 when simulating two-dimensional or quasi-three-dimensional flow. MODFLOW uses the leakage terms in Equation 5.2 to represent vertical flow between units when simulating fully three-dimensional flow.

4.4.3.2 Solution Techniques

MODFLOW offers the option of several techniques to solve the system of simultaneous equations resulting from the algebraic approximation to Equation 5.2. The technique found to be the most robust was PCG2, an iterative partial-decomposition, conjugate gradient solver added to the MODFLOW code by Hill (1990). Convergence criteria for heads in the regional model were set to 1×10^{-7} m. This value is much smaller than the accuracy to which water levels are measured in the field but helped ensure that mass balance errors due to numerical roundoff errors would be low. Starting heads (i.e., the initial guesses for the steady-state water levels) were assigned based on the interpolated water-table map and then updated periodically to speed model convergence during the calibration process.

4.4.3.3 MODPATH

In addition to MODFLOW, the U.S. Geological Survey MODPATH code, as documented in Pollock (1989), was used to simulate groundwater flow paths and define capture zones and time-of-travel zones for York Region municipal wells. The MODPATH code uses the aquifer potentials determined by MODFLOW along with estimates of aquifer porosity to determine groundwater velocities. Particle tracks for specified time intervals can be extracted from MODPATH output to delineate time-of-travel zones for each well.

4.4.3.4 VIEWLOG Geologic Data Management System

The study made extensive use of VIEWLOG (VIEWLOG Systems Inc., Version 3) to view, analyze, and manage hydrogeologic data. VIEWLOG allowed a direct link to the extensive relational database that was constructed for the project. Along with the ability to facilitate geologic data analysis and spatial data management, VIEWLOG has an add-on module with pre-and post-processing functions for MODFLOW. The MODFLOW module was used to facilitate model construction and model calibration as well as interpretation and presentation of model results.

4.4.4 Model Limitations

A well-calibrated groundwater model is a powerful tool that can be used to provide insight into the factors that influence groundwater flow. The model can be applied to predict the effects of stresses, such as increased water takings, on groundwater levels and discharge to streams.

Hydrogeologic systems, however, tend to be complex due to the highly variable physical properties of the geologic materials and due to the time-varying (transient) nature of the stresses on the groundwater system. The sparsity of data available to fully characterize these systems and computer limitations often require making a number of simplifying assumptions to make it possible to solve the groundwater flow equations.

Although MODFLOW is capable of simulating both transient and steady-state flow; the models developed for this study simulated steady-state flow only. Transient effects, such as daily or seasonal fluctuations in aquifer potentials, rates of recharge, and surface water levels, have been removed from the models by using long-term average values for model parameters. For example, net aquifer recharge and municipal pumping were represented using annual average values. The steady-state models provide a good representation of annual average groundwater flow conditions, but they cannot represent some phenomena such as intermittent streams that might flow in response to high recharge rates in the spring, perched water-table conditions that occur only in the spring, or the short-term increase in drawdowns due to peak pumping of groundwater during the summer months. Future work is planned to enable the models to simulate both transient and steady state flow.

As noted, the physical properties of the stratigraphic layers are highly variable. Because there are only a limited number of boreholes available to characterize a particular area, there is always a level of uncertainty regarding how representative the measured values are of the average properties in the vicinity of the borehole and how properties change between boreholes. Other uncertainties can arise as to the quality of the borehole data and as to how well aquifer properties and groundwater recharge and discharge rates can be measured or estimated. Data limitations also affect the quality of the model calibration. For example, despite the millions of water level records in the database, there were few records in the City of Toronto. Lack of water level data in critical areas of the model can reduce the number of unique parameter zones that can be represented and can lead to non-unique model calibrations.

The physical properties of the streams have not been documented through field work in any consistent fashion. For the purposes of modeling, the streams were assigned widths and stream bed conductance values based on the Strahler classification system. Depending on the individual stream, this simplification may over or under represent the actual conductance of the streams that are draining the moraine.

Another point to be made with respect to the ORM models is the ability to accurately predict drawdown at a pumping well or in the immediate vicinity of the pumping well. The cell size of both models used on the ORM (100 m and 240m), results in drawdown estimations close to the well being under estimated. It is unlikely that the models would be used to predict drawdown at a pumping well itself, however if drawdown estimations are required for wells close to a pumping well there is a methodology that can be used to correct the predicted drawdown from the model results (Prickett and Lonnquist, 1971).

Because of data sparsity, many previous models used constant aquifer properties over large areas. This approach was adopted in the Regional Model but for the aquifers in the Core Model, local borehole data were incorporated to derive spatially-varied hydraulic properties.

Models can also be limited by the resolution selected. Typically, regional and sub-regional models cover large areas but at low resolution resulting in critical processes, such as stream-aquifer interaction, and local variation in aquifer properties not being well represented. Local-scale models, on the other hand, have high resolution but often do not extend to natural hydrologic boundaries and are often unable to simulate the larger-scale phenomena that control regional flow. By using more powerful computers and better data analysis capabilities, the models created for the study have a resolution typical of local-scale models but at the same time, extend out to the natural hydrologic boundaries of the study area.

Even with the higher resolution, the predictive capabilities of the numerical models are limited by the nature of the simplifying assumptions used in model development. As a general rule, a well-calibrated groundwater flow model can accurately simulate average water levels, gradients, and flow directions. Predictions of flow paths and well capture zones are less certain since real flow paths and capture zones can be significantly affected by small-scale (sub-grid) variations in geology and aquifer properties that cannot be represented in the model.

5 Model Calibration Targets

5.1 Interpretation of Historical Groundwater Potentials

Regional water level analysis can be difficult where knowledge regarding the geologic and hydrogeologic setting for the wells is not available. By first developing the detailed hydrostratigraphic model, it was possible to assign well screens to their proper hydrostratigraphic layer. Analysis of the water level data by hydrostratigraphic layer allowed correlation of complex water level patterns with features of the hydrostratigraphic model. This also afforded an opportunity to determine whether the water level patterns confirmed or conflicted with the assumptions made regarding the hydrostratigraphic layers.

The goal of the water level analysis was to evaluate water level patterns across the Core Model area and to provide targets for Core Model calibration. Water levels were analyzed at a larger scale to develop calibration targets for the Regional Model. Wellfield operations were not considered in either model because of the regional focus.

5.1.1 Well Screen Classification

The first step in the evaluation of the water level data was the assignment of well screens to specific aquifer layers. During geologic layer interpretation, well screen placement was given a high weight when identifying the aquifer and aquitard layers. Well screen assignment was made based on the position of the well screen relative to a particular layer top and bottom. It should be noted that there were many instances where wells were screened partially within aquitards and where long well screens straddled two aquifers, making it necessary to apply a level of judgement in the assignment process. Where no screens were reported in the well logs, the screen was assumed to be located at the bottom one metre of the well.

The position of the well screen relative to the Newmarket Aquitard was particularly important. In many cases, the well screens are located immediately below the base of the Newmarket Aquitard, i.e., in the uppermost portion of the Thorncliffe Aquifer Complex. This occurrence is common since only a short well screen located in the top of an aquifer is necessary to meet the needs of most domestic wells. Deeper wells drilled in the ORM frequently stop just into the top of the Newmarket Aquitard because drilling through the dense till is difficult. It should be recognized that the gridding process cannot exactly honour each well pick where multiple wells fall within the same 100-m cell. Because some well screens are located close to the geologic contact, they may appear to fall within the Newmarket Aquitard even though they were correctly picked. These discrepancies may be observed when drawing cross sections, however they did not introduce error into the water level analysis presented in this section.

Any analysis of the well screen data is limited by errors common to the well record data set, including survey errors, coding errors and incomplete reporting of well construction. These errors are discussed further in Appendix D.

5.2 Groundwater Level Analysis

5.2.1 Overview

Groundwater level patterns in the ORM study area reflect the complex aquifer layer geometry, influence of streams, and changing historical stresses. On first glance, it would appear that there are considerable well data; however, the data are unevenly distributed with respect to depth and time. Information from deep boreholes is limited, particularly under the ORM where drillers can find sufficient water at shallow depths.

Snapshots of both pumping and non-pumping (pre-development) conditions, on both a local and regional scale, were of particular interest for model calibration. Creating these snapshots was difficult because of variation in land use and wellfield operation over time and because of variability in MOE well record data quality.

This section presents water level data and discusses, in a general manner, the correlation between the water level patterns and the hydrostratigraphic interpretation. The focus of the analysis was regional and dealt with static water levels collected over large time periods. Local-scale and transient water level patterns are complex and need to be interpreted in conjunction with detailed histories of land development, water use changes, municipal wellfield operations, and analysis of climate data.

5.2.2 Water Level Error and Variation Analysis

The MOE water well records contain a measurement of the “static water level” in the well at the time of construction. Differences in static water levels between two nearby wells can be the result of many factors in addition to the natural gradients in the potentiometric surface. The source of these errors and the geostatistical methods used to evaluate the magnitude of these errors are discussed in detail in Appendix D.

5.2.3 Oak Ridges Aquifer Complex Water Levels

Interpolation of the water levels from wells screened in the Oak Ridges Aquifer Complex provided a reasonable estimate of the water table. Where the ORAC is capped by the Halton Till, however, significant upward gradients can be observed. In these areas, the ORAC water levels may be higher or lower than the true water table position which would lie somewhere within the till unit or at land surface.

Variogram analysis of the ORAC water level data (see Appendix D) showed that the variance in the data followed a Gaussian relationship (indicative of high correlation within short distances of the well and then a linear decrease in correlation with distance), reaching a sill of approximately 1600 m^2 at a range of approximately 20,000 m. The best fit variogram for the entire range of data is shown in **Figure 55**a. It is interesting to note that wells up to 20 km apart exhibit some degree of correlation. This is considerably longer than the correlation range of the geologic surfaces. The geologic surfaces reflect the complexity of the depositional process, whereas water level surfaces tend to be much smoother. There also may be a large degree of anisotropy in the data, as east-west correlation of the data (parallel to the axis of the ORM) is likely to be much stronger than the north-south correlation. This was not explored in this project.

The Gaussian theoretical variogram parameters were then adjusted to better fit the data from shorter distances (**Figure 55**b). This was done because the kriging procedure used sampled only a subset of nearby wells for the interpolation to the grid and would rarely need to "pull" data from as far as 20 km into the interpolation neighbourhood. The nugget value associated with the ORAC water levels is approximately 20 m^2, which suggests that a local-scale error of ±4.5 m is inherent in the data. This includes the variation due to both measurement errors and natural variation, as discussed in Appendix D. From a practical point of view, the level of intrinsic error present indicates that there is little justification for contouring the ORAC water levels with a contour interval of less than 5 m, as smaller-scale patterns in the water levels could simply be "noise".

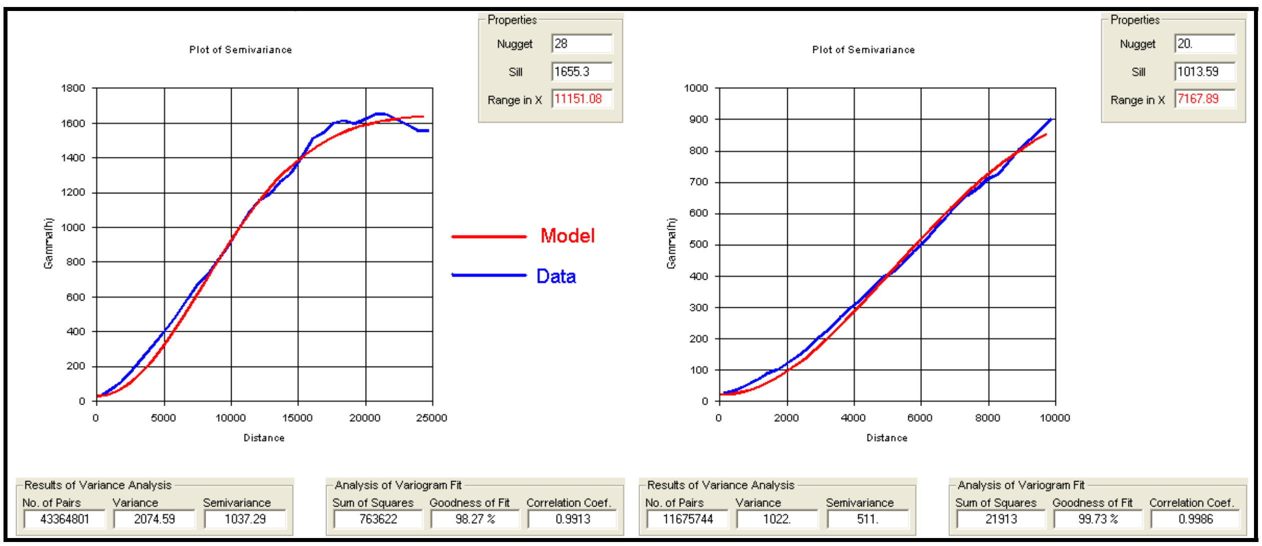

Figure 55: Variogram of Oak Ridges Aquifer Complex water levels (a) best fit to entire range and (b) best fit closer to origin

The kriged ORAC potentiometric surface is shown in **Figure 56**. The surface broadly reflects land surface topography. The influence of the major river systems can be clearly seen, particularly that of the Humber and Holland Rivers. Groundwater flow divides generally correspond to the surface water flow divides. The water table mounds are also affected by the presence of tunnel channels such that three separate mounds have formed, one east of the Yonge Street area, a second between the Yonge Street area and the Holland River Valley and a third to the west of the Holland River Valley. The highest water levels are observed in two areas, east of Aurora and north of Stouffville. Horizontal flow gradients are generally steeper on the south side of the moraine than on the north side. However, measured ORAC values within the City of Toronto are very limited, due partially to the lack of wells and partially to the lack of ORAC in the Toronto area, which makes the interpolated values south of Highway 401 of limited reliability.

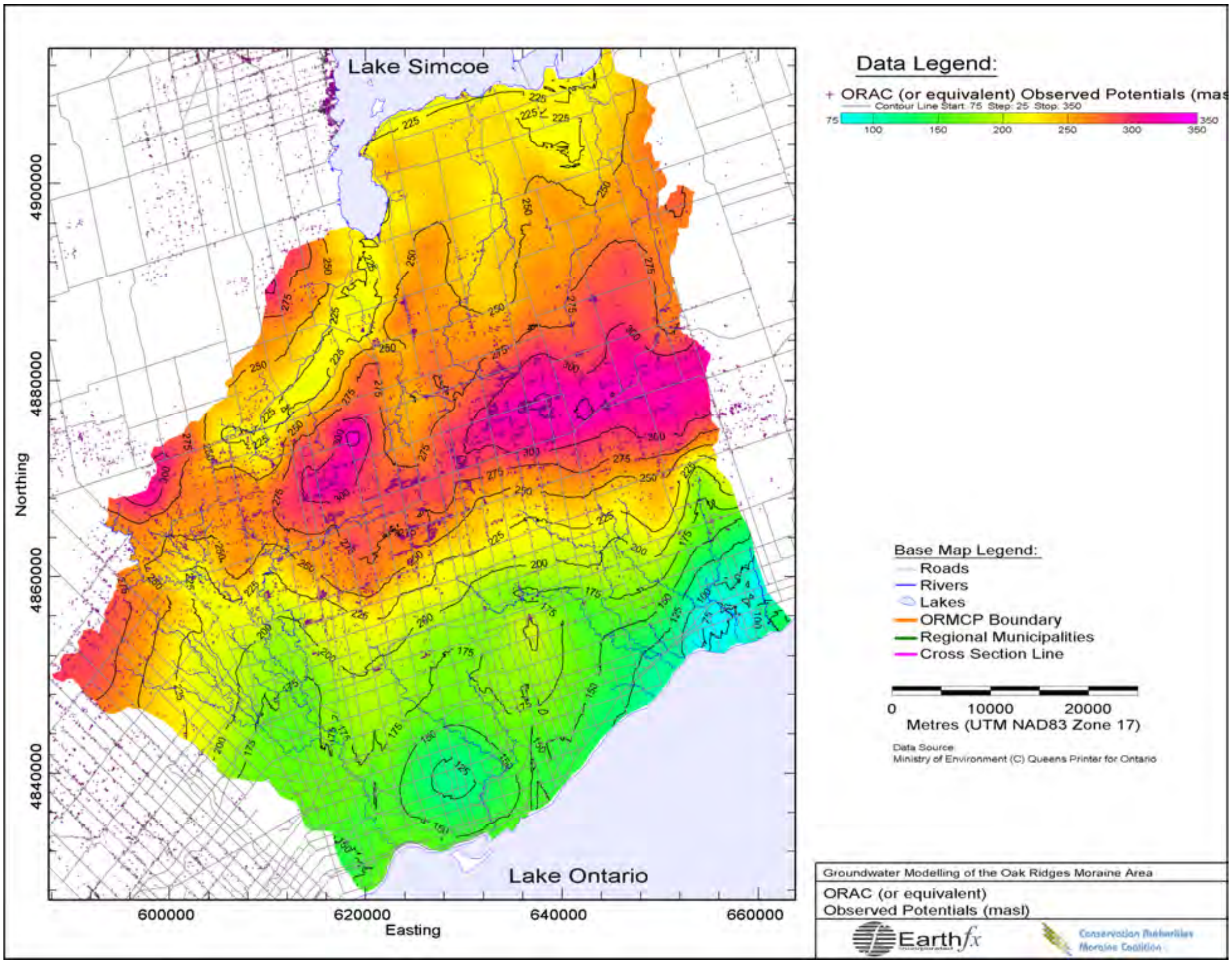

Figure 56: Interpolated static water levels in the Oak Ridges Aquifer Complex (or equivalent).

The standard error of the estimate graphically shows the relative confidence in the ORAC water level interpolation (**Figure 57**). Much of the study area has the same level of uncertainty and only in the south does the uncertainty rise significantly. The error map shows that the ORAC water level estimates in **Figure 56** are generally within ±4.5 m with a confidence level of 68% (one standard deviation) or ±9 m with a confidence level of 95% (two standard deviations).

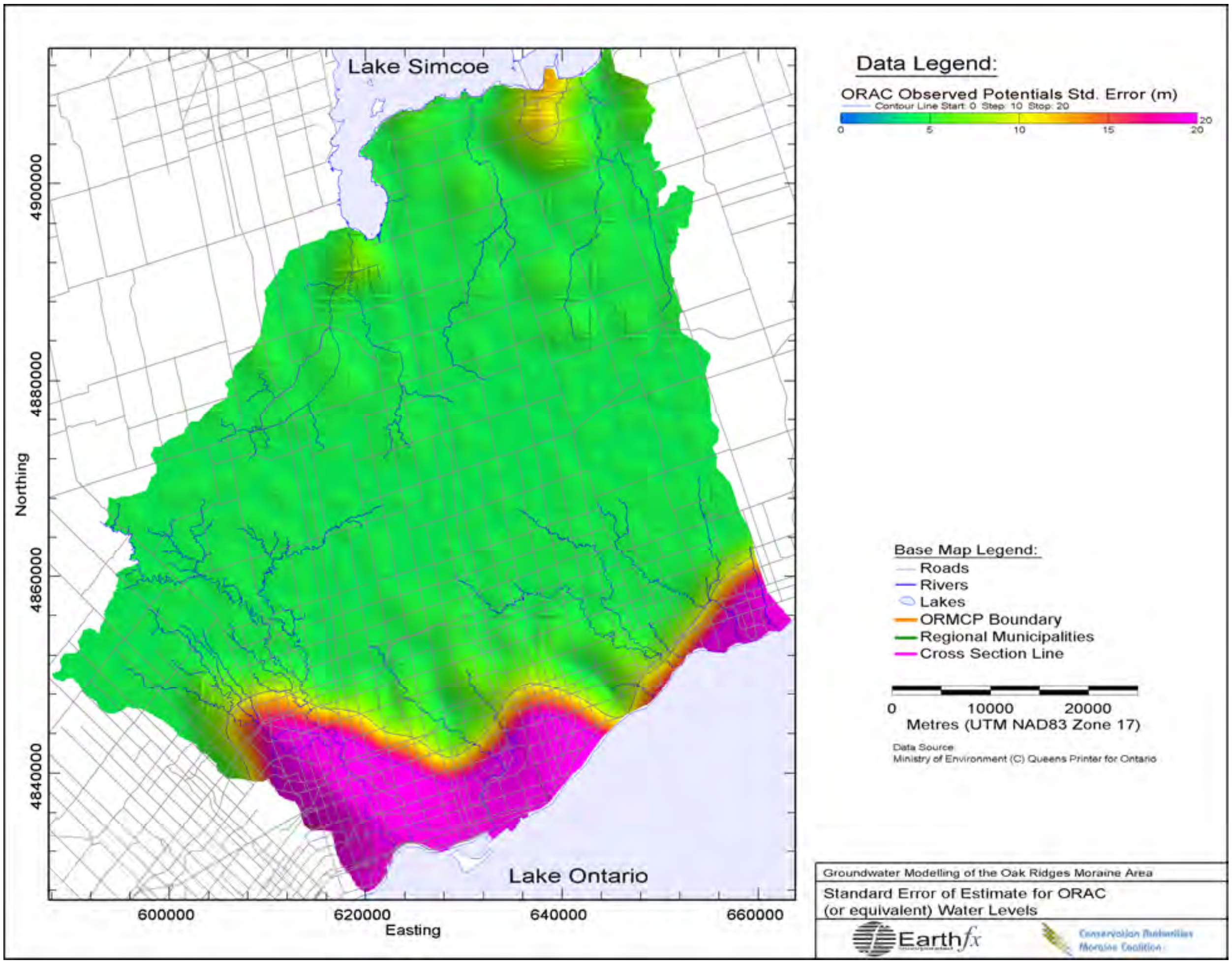

Figure 57: Standard error of estimate for the ORAC water levels

The depth-to-water map for the ORAC, shown in **Figure 58**, highlights the ridges that run through the moraine. The red zones (showing greater depth to water) generally correlate with the topographic ridges of the ORM. While the water table is expected to be lower under a narrow ridge, the low gradients shown in **Figure 56** reflect that the ridges contain coarser grained materials and thus are better drained. Some researchers have speculated that the core of the moraine may be an esker (D.R. Sharpe, personal communication) and the narrow band of deep water levels could support that hypothesis. It should be noted that the bright red zone in central Toronto is caused by the sparsity of water level data.

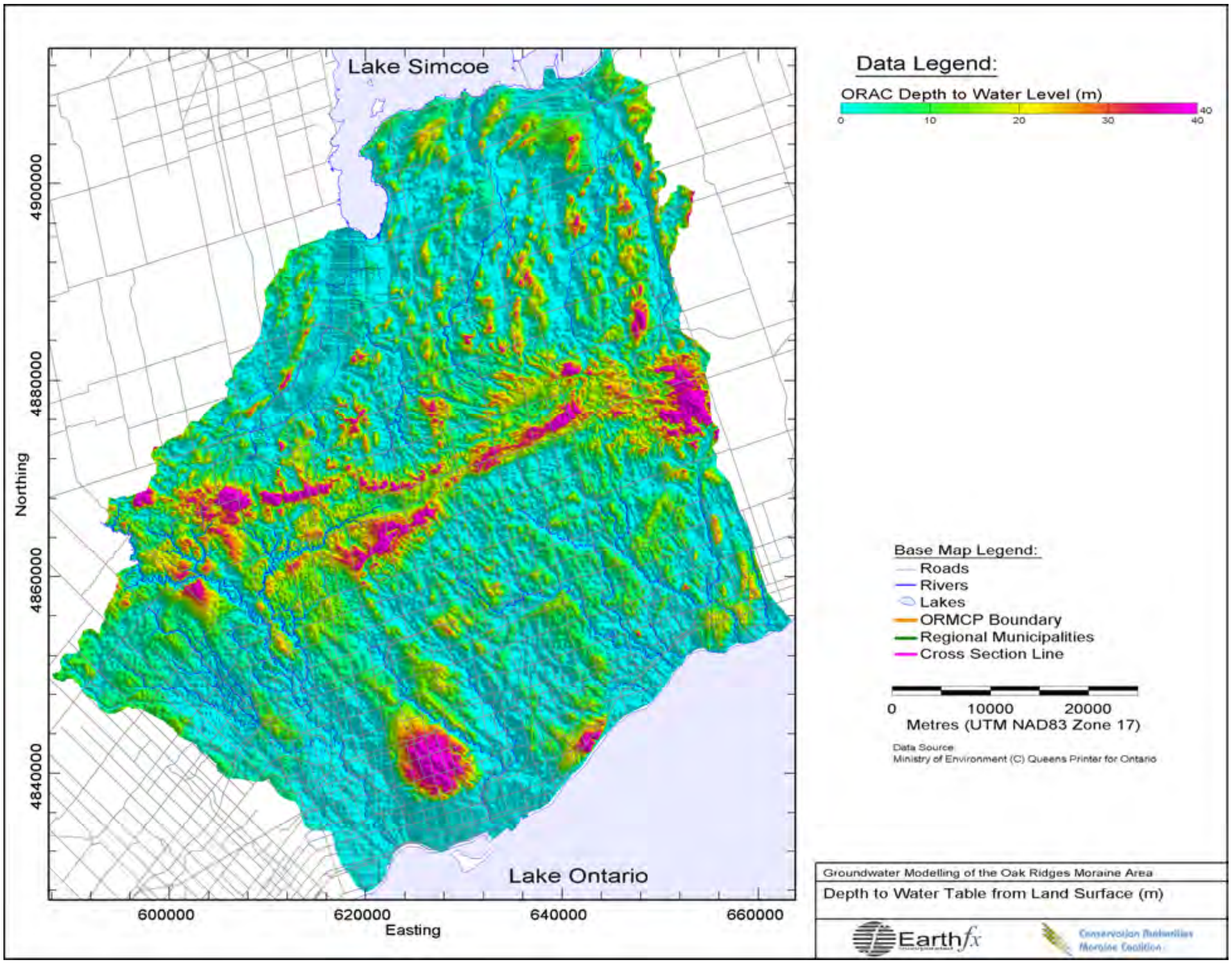

Figure 58: Depth to water in the ORAC (or equivalent).

The interpolated ORAC potentiometric surface was shown on the cross sections in Section 3 of this report (**Figure 45** through **Figure 50**). In some cases, the ORAC water levels appear above ground surface in the deeper valley systems. This condition can occur where the ORAC is confined by the Halton till (flowing wells have been observed in the valleys). In some cases, however, potentials above land surface are a result of the interpolation process that was based on a limited number of wells in the bottom of the valleys (i.e. the interpolation is not sufficiently constrained by real data points). While these surfaces could have been corrected by adding in topographic and stream stage data as constraints, the focus here was on presenting the best interpretation from the available data.

Due to the nature of the available water level data, that is the lack of synoptic water elevation data sets, there is no easy way to evaluate long term trends in water levels. Trends are best evaluated in conjunction with the higher quality monitoring data and historic pumping and climate information.

5.2.4 Thorncliffe Aquifer Complex Water Levels

Thorncliffe Aquifer Complex (TAC) potentials were interpreted using similar variogram analysis and gridding steps performed for the ORAC. Well coverage across the study area is good except within the City of Toronto.

Many of the wells penetrating the TAC are completed in the upper-most portion of the aquifer. Geophysical logging performed by the CAMC/YPDT group (Quantec/DGI Geoscience, in preparation) indicated that there are depositional sequences in the Thorncliffe Aquifer Complex indicative of significant vertical anisotropy at points within the aquifer. Vertical variation of potentials within the TAC may be of importance but was not considered in this study.

The variogram for the TAC water levels is similar to that of the ORAC potentials; however, the range of the variogram is considerably longer, suggesting even more lateral correlation in the data (**Figure 59**a), particularly in the east-west direction. The variogram range is 33 km, compared to 20 km for the ORAC. This is due, in part, to the greater influence of topographic features (such as streams), surficial geology, and recharge variations on the ORAC water levels as compared to the Thorncliffe Aquifer Complex water levels which are more subdued and smoother as a result. The variogram parameters were then adjusted to better fit the values near the origin (**Figure 59**b) and had a nugget of approximately 50 m^2. This suggests that a local-scale error of ±7 m is inherent in the data.

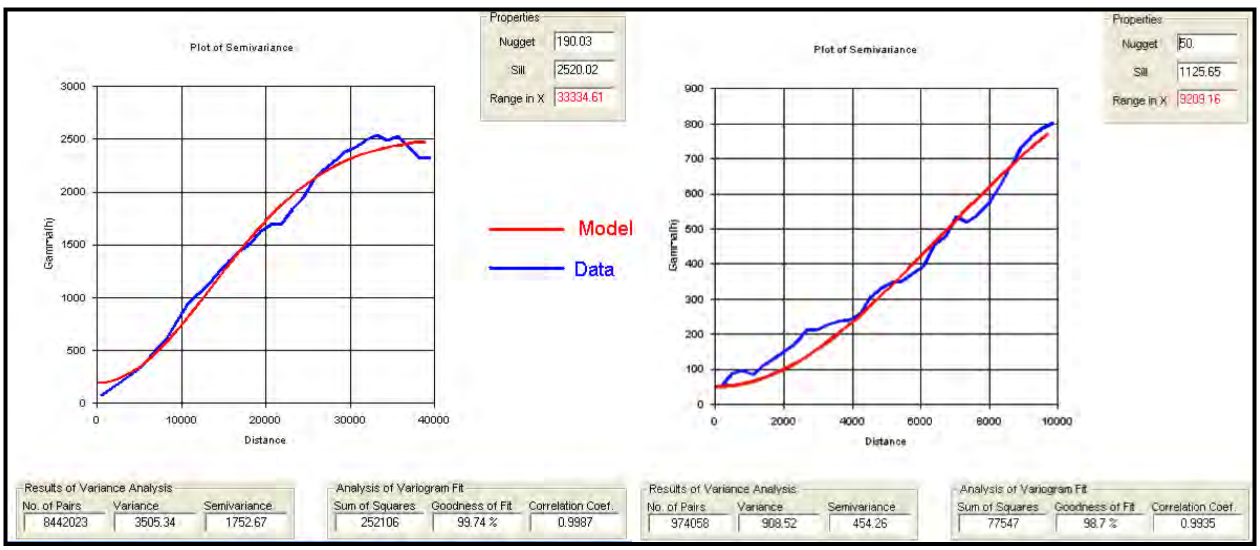

Figure 59: Variogram of Thorncliffe Aquifer Complex potentials (a) best fit to entire range and (b) best fit closer to origin

The standard error estimate for the TAC is similar to that of the ORAC. Given this similarity, the TAC error estimate is not shown. Regionally, much of the TAC standard error is within ±7 m with a confidence level of 68% (or ±14 m with a confidence level of 95%).

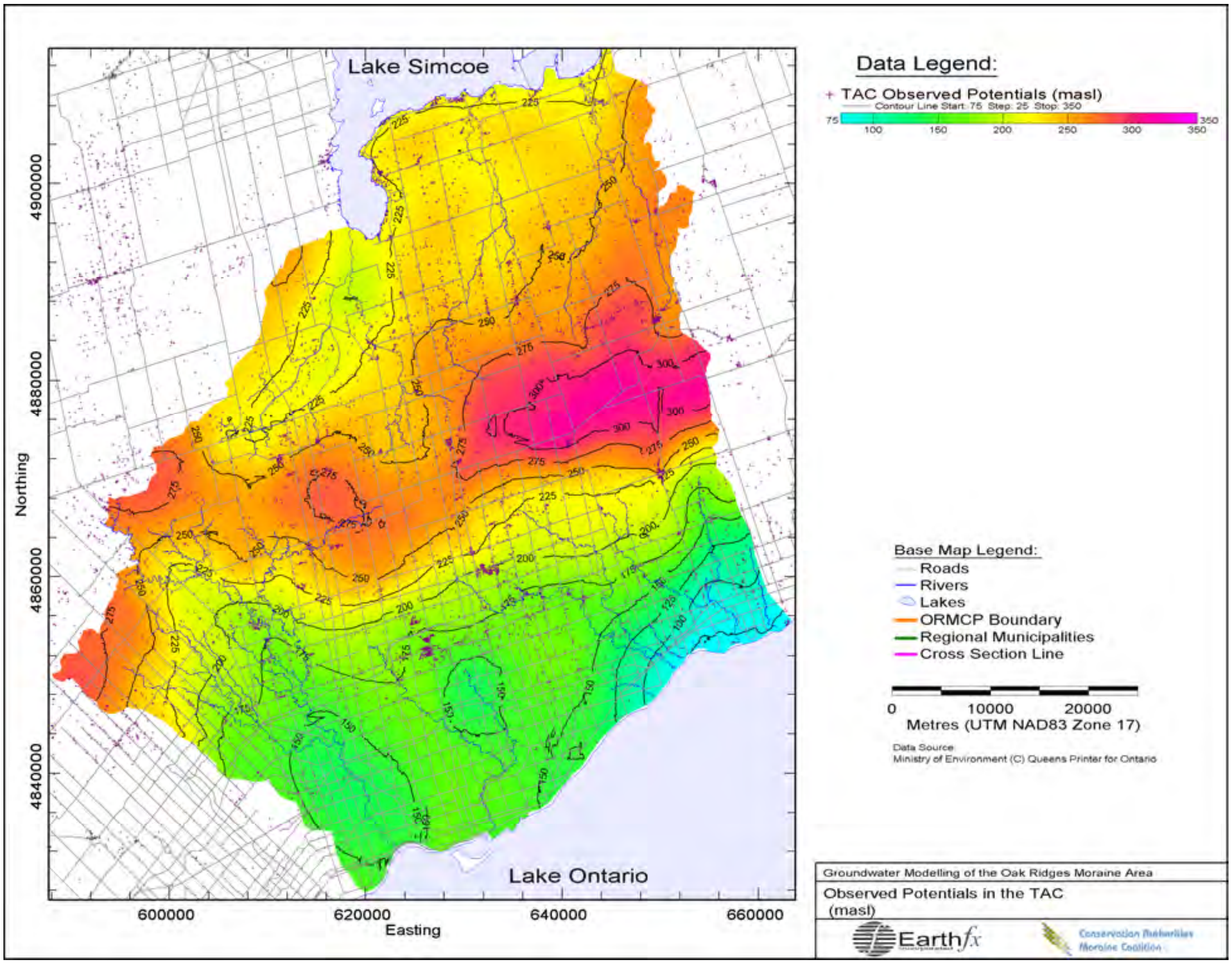

Figure 60: Interpolated static water levels in the Thorncliffe Aquifer Complex.

Interpolated potentials for the Thorncliffe Aquifer Complex are shown in **Figure 60**. The TAC water levels are generally a muted reflection of the potentials in the ORAC and show a similar, but subdued, influence of topography and the major watershed divides. As in the ORAC, there are three separate mounds, one east of the Yonge Street area, a second between the Yonge Street area and the Holland River Valley and a third to the west of the Holland River Valley. Horizontal flow gradients are generally steeper on the south side of the moraine than on the north side. The distribution of standard error for the TAC potentials was very similar to that for the ORAC (**Figure 57**) and is not reproduced here.

The interpolated TAC potentiometric surface was shown on the cross sections in Section 3 of this report (**Figure 45** through **Figure 50**). Head differences between the ORAC and the TAC are shown in **Figure 61**. The largest positive head difference (red coloured areas indicate downward gradients) occurs just west of Newmarket. The Newmarket Aquitard is generally thicker in this area (see **Figure 36**) which, together with municipal pumping in the TAC, might explain the large head difference.

Smaller head differences generally occur within the channel zones, however, the magnitude of these differences are not unlike those observed in other areas south of the moraine. Overall, this suggests that increased leakage likely occurs in the channel zones but the channels are not acting as “open” windows between the aquifers. Silt layers deposited within the channels are likely limiting the downward flow. Model simulations have been used to further evaluate this issue, as discussed further on in this report.

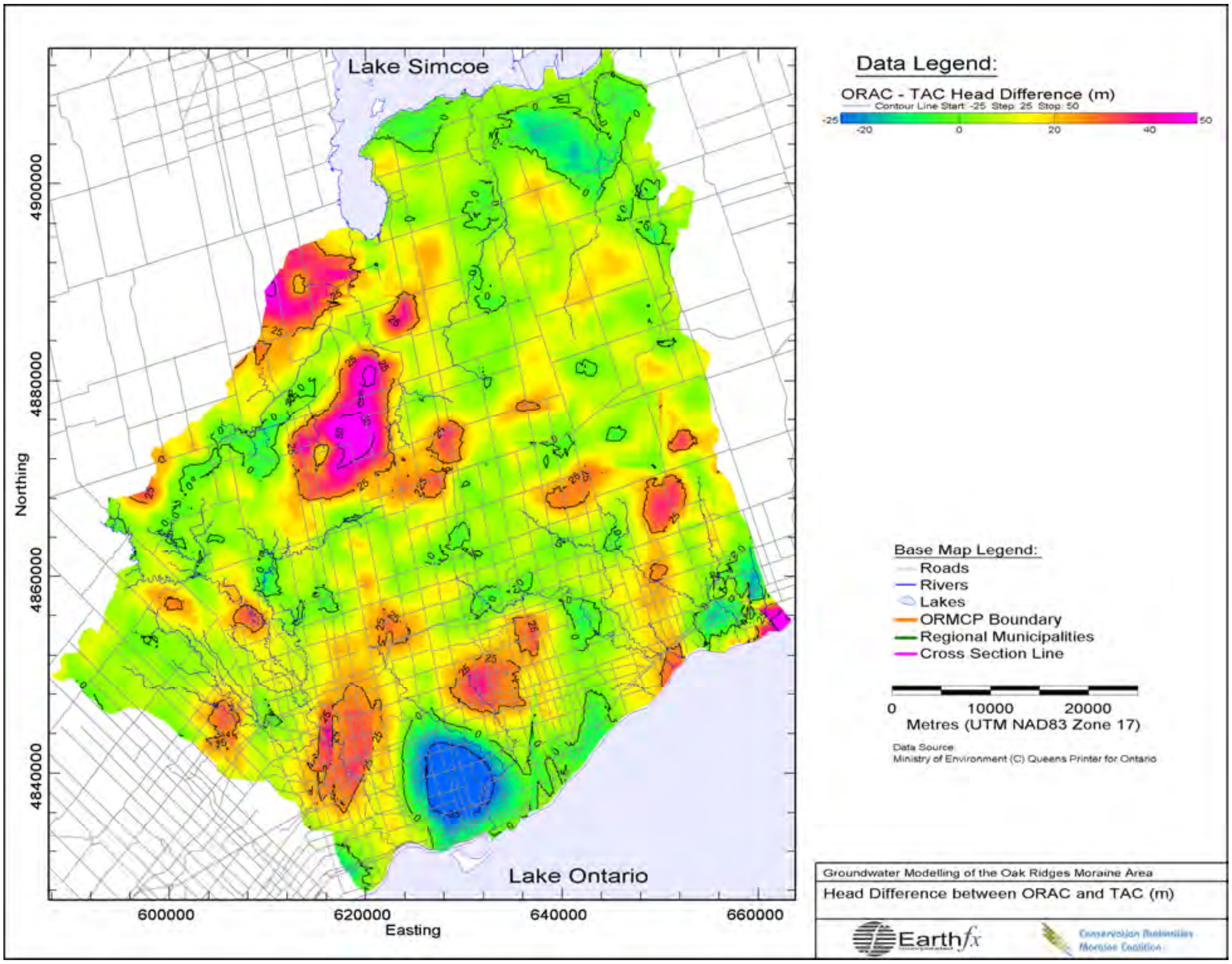

Figure 61: Head differences between the ORAC and Thorncliffe Aquifer Complex.

5.2.5 Scarborough Aquifer Complex Water Levels

Interpretation of the Scarborough Aquifer Complex potentials followed the same variogram analysis and gridding procedure followed for the ORAC and TAC. Well coverage across the study area is very limited in the eastern portion of the study area under the ORM but is reasonable in other locations. Well coverage within the City of Toronto is somewhat better than for the ORAC and TAC.

The variogram for the Scarborough Aquifer Complex water levels (**Figure 62**) was similar in shape to that for the TAC data. The range of the variogram (60 km), however, is considerably longer than that for the Thorncliffe Aquifer Complex (33 km) suggesting an even higher degree of spatial correlation (**Figure 62**a). The variogram parameters were then adjusted to better fit the values near the origin (**Figure 62**b) and had a nugget of approximately 70 m^2. This suggests that a local-scale error of ±8.4 m is inherent in the data.

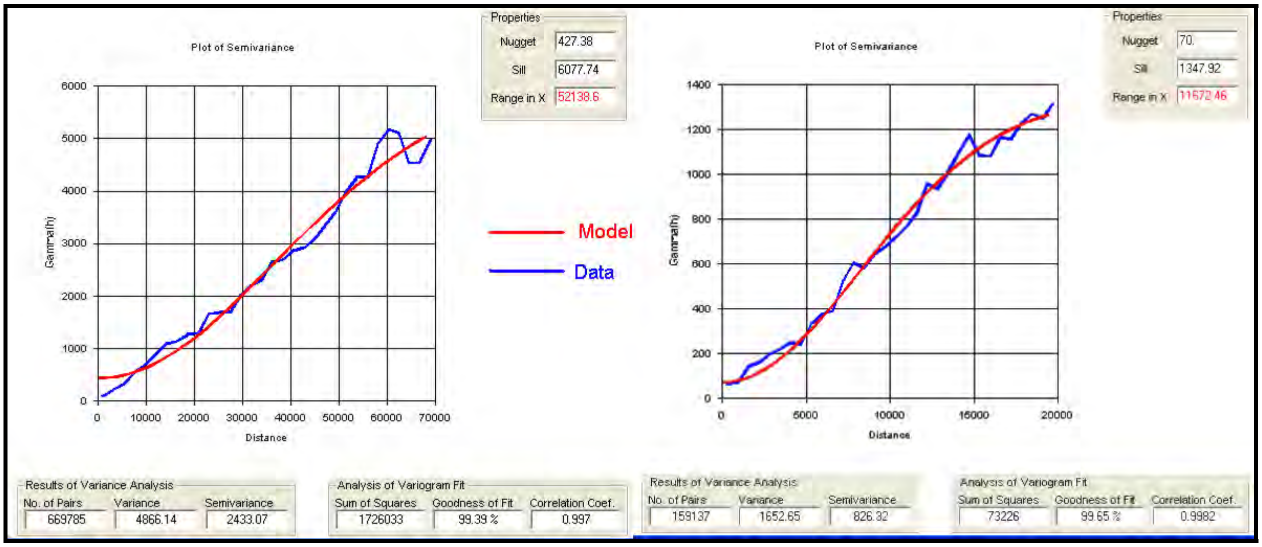

Figure 62: Variogram of Scarborough Aquifer Complex potentials (a) best fit to entire range and (b) best fit closer to origin

Interpolated potentials for the SAC are shown in **Figure 63**. The distribution of standard error for the SAC potentials was similar to that for the ORAC (**Figure 57**) and is not reproduced here. Regionally, much of the SAC standard error is within ±8.4 m with a confidence level of 68% (or ±16.8 m with a confidence level of 95%).

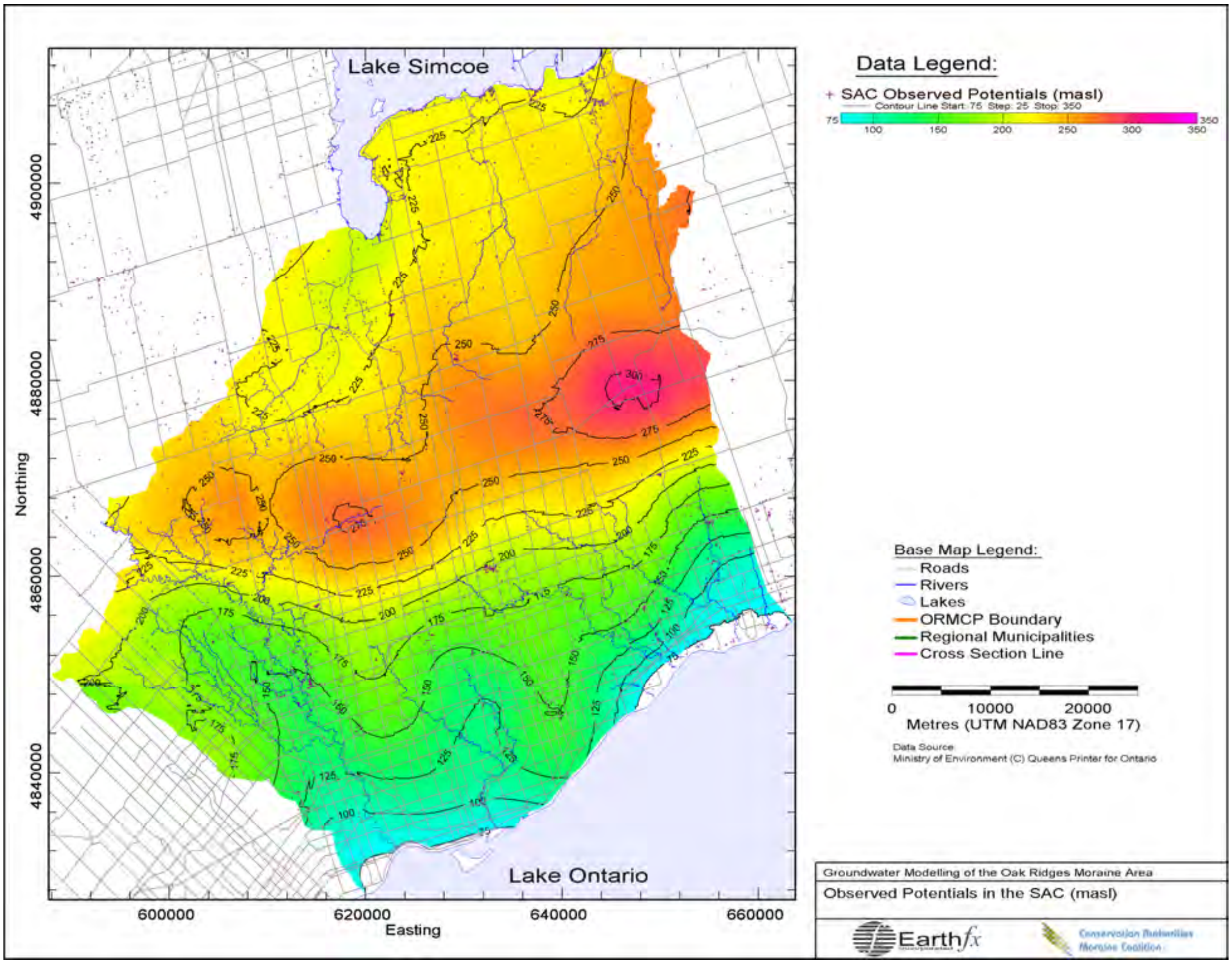

Figure 63: Interpolated static water levels in the Scarborough Aquifer Complex.

The Scarborough Aquifer Complex water levels are generally a muted reflection of the potentials in the aquifers above and broadly show the influence of the moraine and the major watershed divides. There is a subtle indication of the effects of the bedrock valley systems in the water level data and flow directions. The lack of a clearer influence on water levels may be due, in part, to the scarcity of wells in the deeper valleys.

The interpolated SAC potentiometric surface was shown on the cross sections in Section 3 of this report (**Figure 45** through **Figure 50**). Head differences between the TAC and SAC are shown in **Figure 64**. The zone of high downward gradient in the east-central part of York Region (the purple/red area under the ORM) is based on very limited well data. The general pattern shows downward head differences outside of the tunnel channel areas and small (near-zero) head differences within many of the channel zones. Areas within the channels that exhibit larger downward head differences may be areas where the intervening Sunnybrook Aquitard has not been breached. Other areas within the channels, such as in the Holland River Valley, show small upward head differences indicating discharge of water from the SAC back to the TAC.

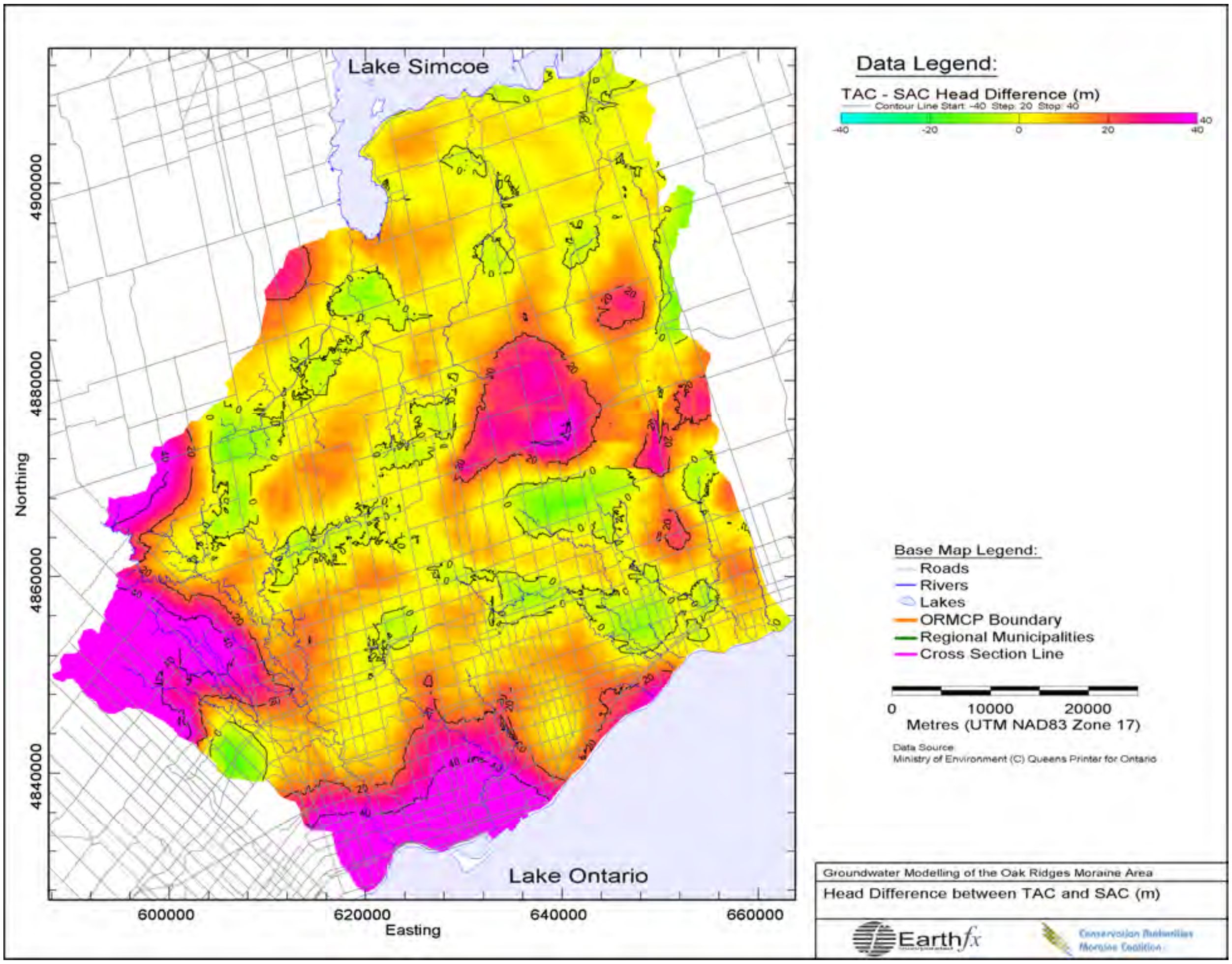

Figure 64: Head differences between the TAC and Scarborough Aquifer Complex.

5.2.6 Discussion

This section presented water level data and, in a general manner, the correlation between the water level patterns and the hydrostratigraphic interpretation. The focus of the analysis was regional and dealt with static water levels collected over long time spans. It is important to note that local-scale and transient water level patterns are complex and need to be interpreted in conjunction with detailed histories of land development, water use changes, municipal wellfield operations, and analysis of climate data.

Overall, the ORM topography dominates the regional water level patterns and results show that the mound underlying the ORM and the regional flow divides persist within all the aquifer layers (although data are sparse for the Scarborough Aquifer Complex in the ORM area). The mounds are less pronounced in the deeper units due to head loss through the confining units. The potentiometric mounds are affected by the presence of tunnel channels such that three separate mounds have formed, one east of the Yonge Street area, a second between the Yonge Street area and the Holland River Valley and a third to the west of the Holland River Valley.

Potentials in the ORAC aquifer are strongly influenced by the topography, including the presence of streams and watershed divides. The watershed boundaries and influence of streams are also broadly visible in the lower aquifer systems, particularly in the south and north of the study area where these units are closer to, or are at land surface. The influence of the Humber and West Holland Rivers is particularly pronounced.

Some correlation between the channels and the regions of lower water level gradient is apparent in that generally, areas of higher downward head differences exist away from the tunnel channel areas where there is a more distinct separation between the aquifers. Smaller downward gradients or upward gradients exist within the tunnel channel zones. The channel zones appear to allow more exchange of groundwater between aquifers than in areas where the Newmarket Till is present. The occurrence of silt sequences in the tunnel channel fills, however, limits the rate of vertical flow.

Based on the available data, the Laurentian Channel does not appear to exhibit a large influence on the water level patterns, however this influence may also be hard to discern because of the very limited number of wells in the valleys and relatively lower gradients in the deeper system.

The variogram analysis indicates that there is an intrinsic variation in the water level data on the order of 4.5 to 8.4 m, depending on the aquifer. There are many factors that contribute to this variation, including measurement error, seasonal variation and pumping. This intrinsic error must be recognized when using the water level data and calibrating the numerical models. Despite this high level of intrinsic error, some patterns remain visible in the data. The variogram analysis clearly suggests that the water-level patterns can be correlated over some distance.

5.3 Surface Water Calibration Targets

This section presents a brief overview of the surface water system in the study area and discusses streamflow measurements that were used to aid in calibrating the groundwater models. Calibration to match groundwater discharge to streams (baseflow) was critical, because it provided an additional constraint on recharge and flow allocation between the shallow and deeper aquifer systems.

5.3.1 Drainage

Due to its predominantly sandy surface soils and hummocky topography, the Oak Ridges moraine serves as the primary recharge area to underlying aquifers. The moraine forms a surface water and groundwater divide between water flowing north to the Trent-Severn River System (which includes Lake Simcoe and the Kawartha Lakes) and water flowing south to Lake Ontario. While few streams are located on the moraine itself, springs along the lower slopes of the moraine provide baseflow to streams that drain the till plains to the north and south.

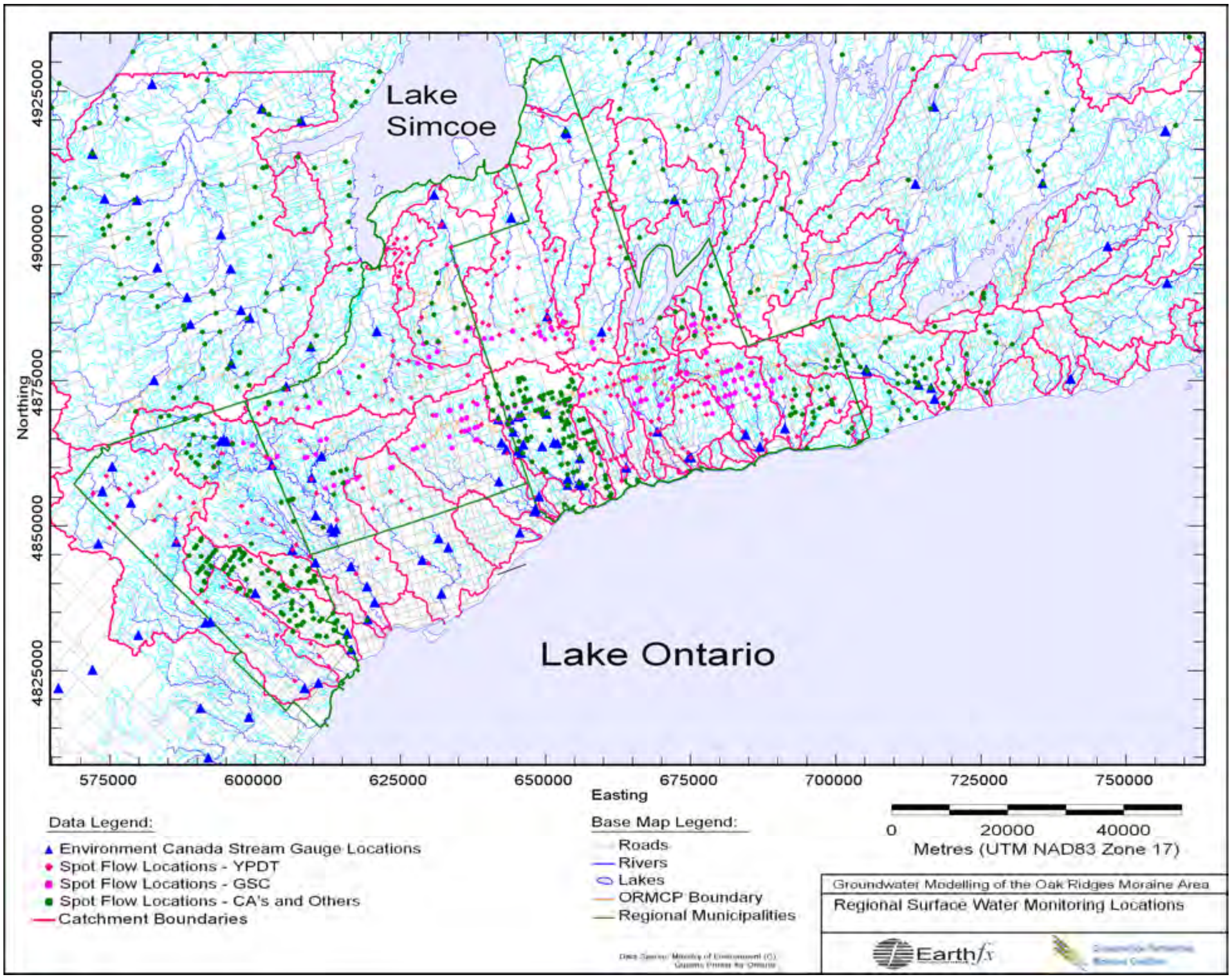

Figure 65: Streams in the ORM area, major watersheds, and surface water flow monitoring locations.

Within the Core Model area, major streams draining south to Lake Ontario include the Humber River, Don River, Rouge River, and Duffins Creek. The Holland River, Black River, Pefferlaw Brook, and the Beaverton River drain north to Lake Simcoe. To the west of the core area, the Credit River and Etobicoke Creek drain to the south while the Nottawasaga River drains north to Georgian Bay. The Credit River and Nottawasaga River get a portion of flow from the ORM, but most of the flow is derived from tributaries draining the Niagara Escarpment. Major streams to the east of the Core Model area include Lynde Creek, Oshawa Creek, Bowmanville Creek, Wilmot Creek, Graham Creek, the Ganaraska River, Coburg Brook, Barnum House Creek, Shelter Valley Creek, and Colborne Creek which drain directly to Lake Ontario. Other streams, such as the Nonquon River, Cross Creek, Pigeon River, Cavan Creek, Baxter Creek, Squirrel Creek, Salt Creek, and Cold Creek all drain directly to the Trent River or to lakes (e.g. Lake Scugog, the Kawartha Lakes, and Rice Lake) or the Otonabee River all of which are part of the Trent canal system. The watersheds and surface water network within the Regional Model area are shown in **Figure 65**; the watersheds and surface water network within the Core Area are shown in **Figure 66**.

The surface water network was classified by MNR based on the Strahler classification system (**Figure 67**), which formed the basis for assigning estimates of stream properties in the models. In the Strahler classification scheme, headwater tributaries are assigned a value of 1. If two same-class tributaries combine (e.g. two Class 1 tributaries), the downstream segment is given the next highest classification. If a higher and a lower class tributary combine (e.g. a Class 2 and a Class 1), the downstream tributary is given the same number as the higher-number tributary.

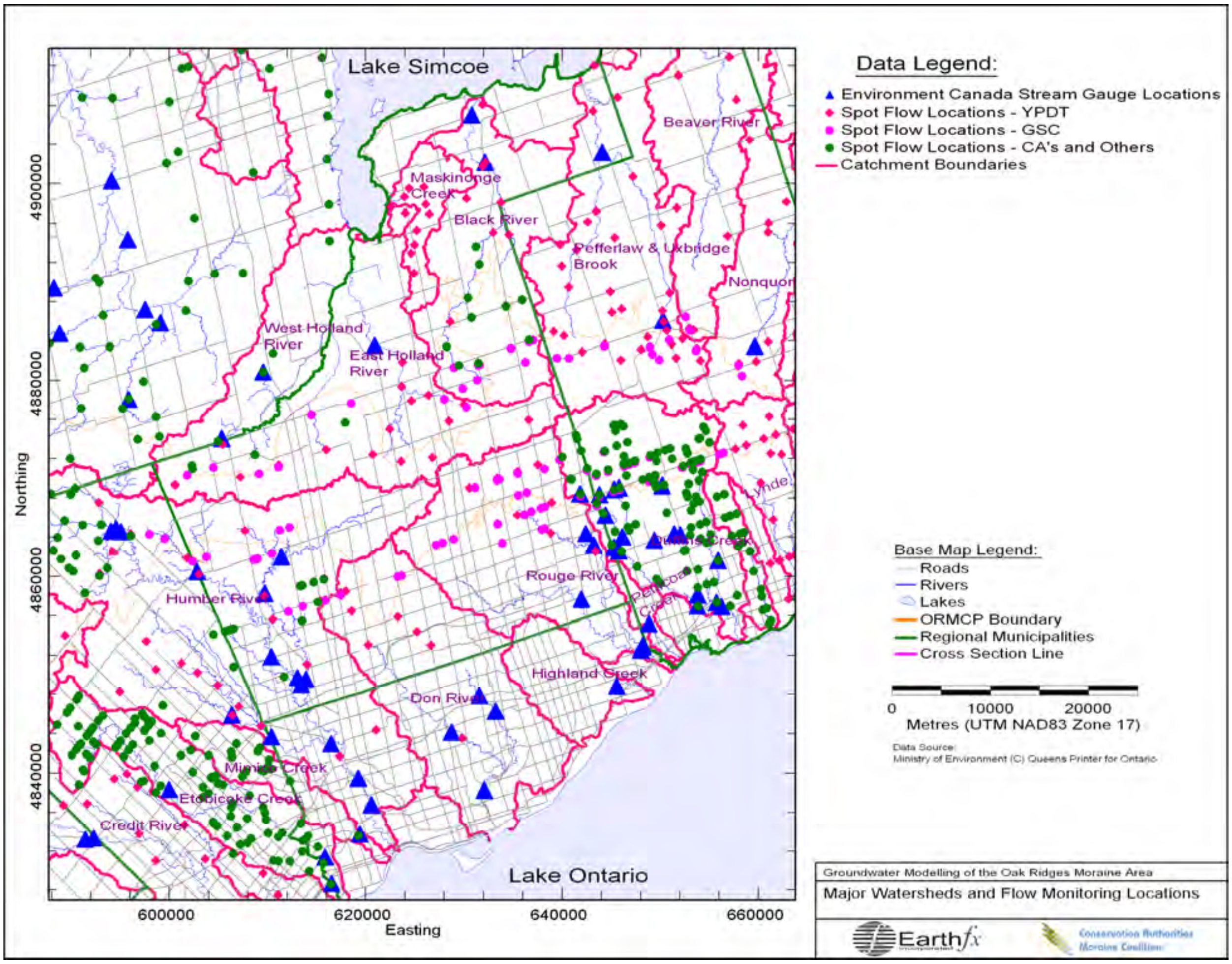

Figure 66: Major Watersheds with flow monitoring locations in the Core Model area.

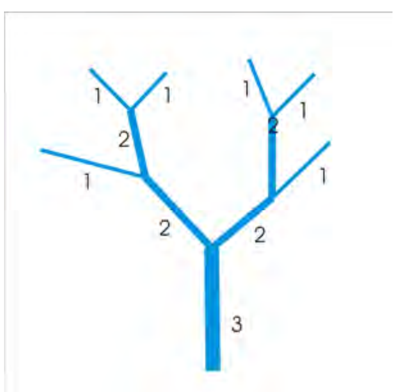

Figure 67: Strahler classification scheme example.

Many of the streams flowing south of the moraine are in deeply incised valleys that penetrate through the Newmarket Aquitard into the deeper sediments. North of the moraine many of the streams are located in broad, relatively flat valley systems that were formed by sub-glacial erosional processes. Many of these streams exhibit sluggish flow and drain wetland areas adjacent to the stream channels. This is partially related to the topographic variation which is much greater from the crest of the moraine southward to Lake Ontario than it is to the north towards Lake Simcoe.

5.3.2 Baseflow

Figure 66 shows the location of long-term HYDAT stream gauges monitored by Environment Canada. Flow in a stream is composed of two components: (1) overland runoff and (2) baseflow, which is primarily groundwater discharge to the stream. From a groundwater modelling perspective, quantifying the baseflow is important in that it provides a “measured” flux value that can be compared to estimates derived from the numerical model. Baseflow separation techniques can be applied to estimate the relative contribution of groundwater discharge to streamflow. For these discussions, annual average groundwater contribution to streams was estimated from long-term streamflow measurements using a baseflow separation technique developed by Clarifica Inc. and employed on several streams in the TRCA area (Clarifica, 2002). The method is described in Appendix D. **Figure 68** shows an example of baseflow separation at the Holland River at Holland Landing gauge.

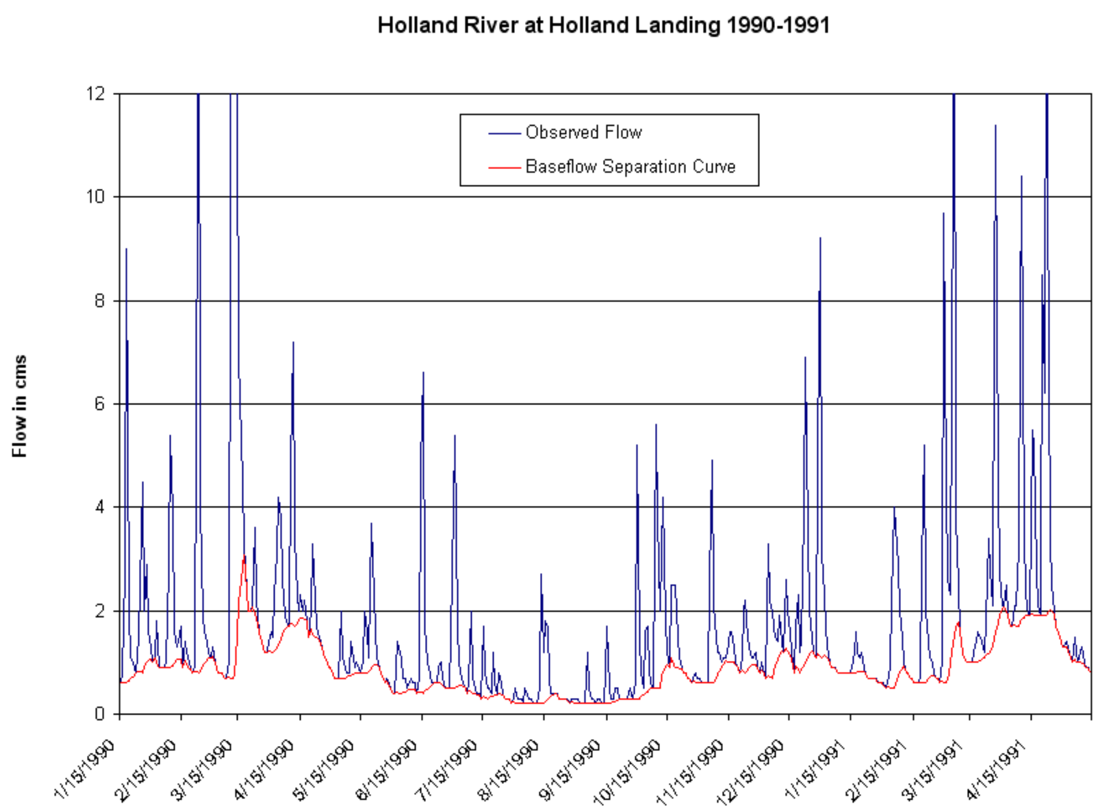

Figure 68: Typical baseflow separation curve

Table 3 lists estimated baseflow at all Environment Canada HYDAT gauges with sufficient record. Also shown are the model simulated values at the same locations. Further discussions of the calibration of the Regional Model to the computed baseflows are found in Section 6.

Table 3: Observed and simulated flows at HYDAT stations

Station ID	Station Name	Annual Average Flow (m^3/s)	Calculated Baseflow (m^3/s)	Simulated Baseflow Regional Model (m^3/s)	Simulated Baseflow Core Model (m^3/s)
148298	Black River at Baldwin	2.26	1.41	1.62	1.53
148299	Holland River a Holland Landing	1.32	0.69	0.64	0.39
148300	Schomberg River near Schomberg	0.29	0.13	0.17	0.24
148302	Black River at Sutton	2.55	1.62	1.84	1.70
148308	Pefferlaw Brook near Udora	3.00	2.00	1.96	1.89
148309	Uxbridge Brook at Uxbridge	0.36	0.30	0.29	0.32
148310	Pefferlaw Brook near Udora	3.25	2.19	1.96	1.89
148422	Etobicoke Creek near Summerville	1.36	0.42	0.50	
148423	Humber River at Weston	6.05	3.08	3.13	2.88
148424	Little Don River near Lansing	0.99	0.43	0.52	0.44
148425	Don River at York Mills	0.86	0.37	0.22	0.13
148426	Duffins Creek at Pickering	2.82	1.63	1.19	1.53
148427	Humber River above East Humber River	3.04	1.70	1.82	1.11
148428	West Humber River near Thistletown	0.84	0.30	0.53	0.60
148429	East Humber River near Pine Grove	1.20	0.65	0.49	0.75
148430	East Humber River near Kleinburg	1.19	0.53	0.31	0.42
148431	Humber River at Woodbridge	3.37	2.30	2.32	1.88
148433	Highland Creek near West Hill	1.10	0.44	0.06	0.10
148434	Little Rouge Creek at Rouge Hill	1.72	0.65	0.44	0.46
148435	Rouge River at Rouge Hill	1.59	0.60	1.03	0.87
148437	Etobicoke Creek at Brampton	0.72	0.65	0.71	
148438	Lynde Creek near Whitby	0.91	0.45	0.52	
148439	Duffins Creek above Pickering	1.20	0.76	0.52	0.75
148440	Rouge River near Markham	1.51	0.70	0.87	0.76
148441	Cold Creek near Bolton	0.48	0.30	0.20	0.42
148442	Don River at Todmorden	3.96	1.60	1.31	0.95
148443	Humber River at Elder Mills	2.47	1.59	1.79	1.09
148444	West Duffins Creek at Green River	1.13	0.62	0.38	0.47
148445	Black Creek near Weston	0.80	0.28	0.18	0.11
148446	Little Rouge Creek near Locust Hill	0.81	0.36	0.40	0.38
148447	Little Don River at Don Mills	1.52	0.73	0.59	0.48
148448	Etobicoke Creek below QEW	2.22	0.71	0.65	
148449	West Humber River at Highway 7	1.03	0.30	0.40	0.50
148450	East Humber River at King	0.60	0.34	0.13	0.18
148451	Mimico Creek at Islington	0.80	0.21	0.18	0.14
148452	West Humber River below Claireville Dam	1.29	0.34	0.48	0.60
148453	Stouffville Creek below Stouffville	0.18	0.12	0.03	0.05
148454	Katabokokonk Creek above Locust Hill	0.03	0.01	0.01	0.00
148456	West Duffins Creek above Green River	0.63	0.39	0.25	0.30
148457	Reesor Creek above Green River	0.40	0.22	0.08	0.11
148458	Reesor Creek near Altona	0.18	0.08	0.03	0.05
148463	Michell Creek below Claremont	0.23	0.10	0.04	0.06
148467	Duffins Creek at Ajax	2.58	1.48	1.20	1.53
148469	Rouge River at Scarborough	1.29	0.54	1.03	0.87
148470	Little Rouge Creek at Scarborough	0.73	0.31	0.44	0.46
148471	Petticoat Creek near Dunbarton	0.16	0.05	0.00	0.01
148472	West Duffins Creek near Pickering	1.08	0.61	0.53	0.62
148480	Oshawa Creek at Oshawa		0.70	0.48	
149293	Ganaraska River Near Osaca		0.87	0.39	

The HYDAT gauge network does not afford coverage of all major streams. Some key streams north of the ORM are not monitored at all and many large tributaries to gauged streams are not monitored. Gauge location also affects the utility of the data. If the only gauge on the stream is located near the downstream discharge point, it is difficult to determine the distribution of groundwater discharge to the upstream tributaries. Conversely, if the gauge is located too far upstream (for example, the only gauge on the West Holland River is at Schomberg), then groundwater discharge in the downstream reaches cannot be quantified. Some gauges, especially those in the urban areas, are influenced by sewage treatment plant (STP) discharges and by discharge of groundwater leaking into storm sewers. Approximately 0.4 m^3s, was subtracted from the initial baseflow estimate of 2.0 m^3s at the Don River at Todmorden gauge in **Table 3** to account for STP discharge. STP discharge to the Holland River is less regular and the baseflow estimates were not corrected.

Figure 65 and **Figure 66** show locations where historical spot streamflow measurements were taken by the GSC, TRCA, and LSRCA to supplement the gauge network. A separate project to collect additional spot flow measurements at ungauged streams was carried out on behalf of the YPDT partnership. Conestoga-Rovers and Associates (CRA) collected 295 spot flow measurements during the summer of 2002 in 25 watersheds across the study area (Conestoga-Rovers & Associates, 2003). Spot flow measurements help to determine the relative increase in flow along the stream channel and can identify areas of greater groundwater discharge. The model was not calibrated to match the spot flow measurements; however, model predicted baseflows were compared against the spot flow values to see that a reasonable agreement was achieved.

6 Regional ORM Area Groundwater Flow Model

6.1 Model Grid

Constructing the numerical model started with the design of the regional model grid and preparation of input data files. MODFLOW uses the finite-difference method and requires that the study area be subdivided horizontally and vertically into a grid of small rectangular cells.

The finite-difference grid used to represent the study area is made up of square cells, each 240 m on a side. Although a larger model grid cell-size would have been adequate for regional flow modelling, the smaller cell size was selected to better represent stream-aquifer interaction. The grid extents are shown on **Figure 69** but since the number of lines needed to show all cells in the model grid would render the figure unreadable, only a coarse grid is shown in which each coarse grid cell is actually composed of 25 (5x5) model grid cells. The model grid consists of 1014 rows by 656 columns with five layers, for a total of over 3.3 million cells. Cells outside the study area, shown in dark grey on **Figure 69**, were designated as inactive and water levels were not determined for these areas.

MODFLOW works in a local, grid coordinate system based on row and column numbers. The VIEWLOG pre-processor helps to translate geo-referenced map data into MODFLOW input. A local origin for the model grid was selected at UTM coordinates 580,000 E and 4,825,000 N. All digital maps and well data for the study area were referenced using UTM NAD83 (Zone 17) grid coordinates.

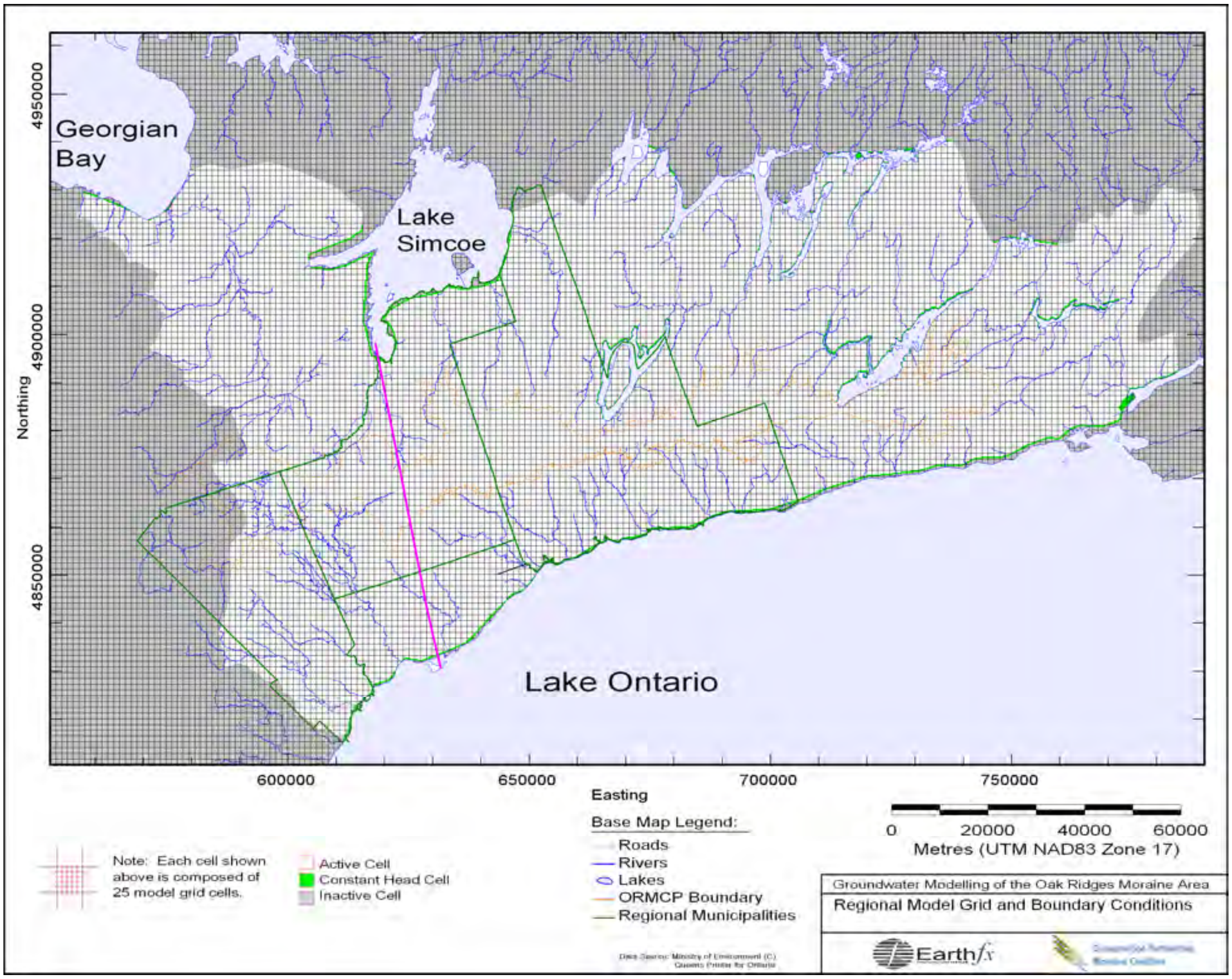

Figure 69: Model grid and boundary conditions for Layer 5. (Note that each cell shown on this grid contains 25 model cells).

6.2 Model Layers

MODFLOW requires that the study area be subdivided vertically into several layers, where each layer can represents a hydrogeologic unit (such as a till layer or a sand and gravel layer) or sub-unit (see **Figure 54**). Top and bottom elevations for each layer are assigned to each cell.

Regional hydrostratigraphy was based on the geologic layering defined by the Geologic Survey of Canada. Surfaces were modified slightly since MODFLOW also requires that all layers be continuous. Where GSC layers pinched out (i.e. their thickness was equal to zero), layer top or bottom elevations were adjusted to assure the Lower Sediments had a minimum of 4.0 m thickness (2 m for each model layer) and that the ORAC and Newmarket Aquitard had a minimum of 0.3 m thickness.

Layers in the regional model included:

Layer 1: Oak Ridges Aquifer Complex (ORAC)
Layer 2: Newmarket Aquitard

Layer 3: Upper Part of Lower Sediments
Layer 4: Lower Part of Lower Sediments
Layer 5: Weathered Bedrock

The Halton/Kettleby Aquitard was not represented as a separate model layer but as a thin surficial deposit along the southern flanks of the Oak Ridges Moraine that primarily restricts recharge to the underlying aquifers. The extent of the Halton Till was defined by GSC surficial geology mapping and recharge was adjusted accordingly in these areas. The Lower Sediments were split into two layers to approximate the intermediate and lower aquifer (Thorncliffe Aquifer Complex and Scarborough Aquifer Complex). The vertical conductance between the two layers was modified to represent the Sunnybrook Aquitard. A north-south section through the centre of the study area along Yonge Street is presented in **Figure 70** to illustrate the extent and relative thickness of the five layers (location of the Yonge Street section line is shown on **Figure 69**).

Land surface defined the top surface of the regional model. Land surface topography was obtained from a 10 m Digital Elevation Model (DEM) prepared by the Ontario Ministry of Natural Resources (MNR). The DEM was re-sampled to the model grid. A shaded relief map of land surface topography is shown in **Figure 2**.

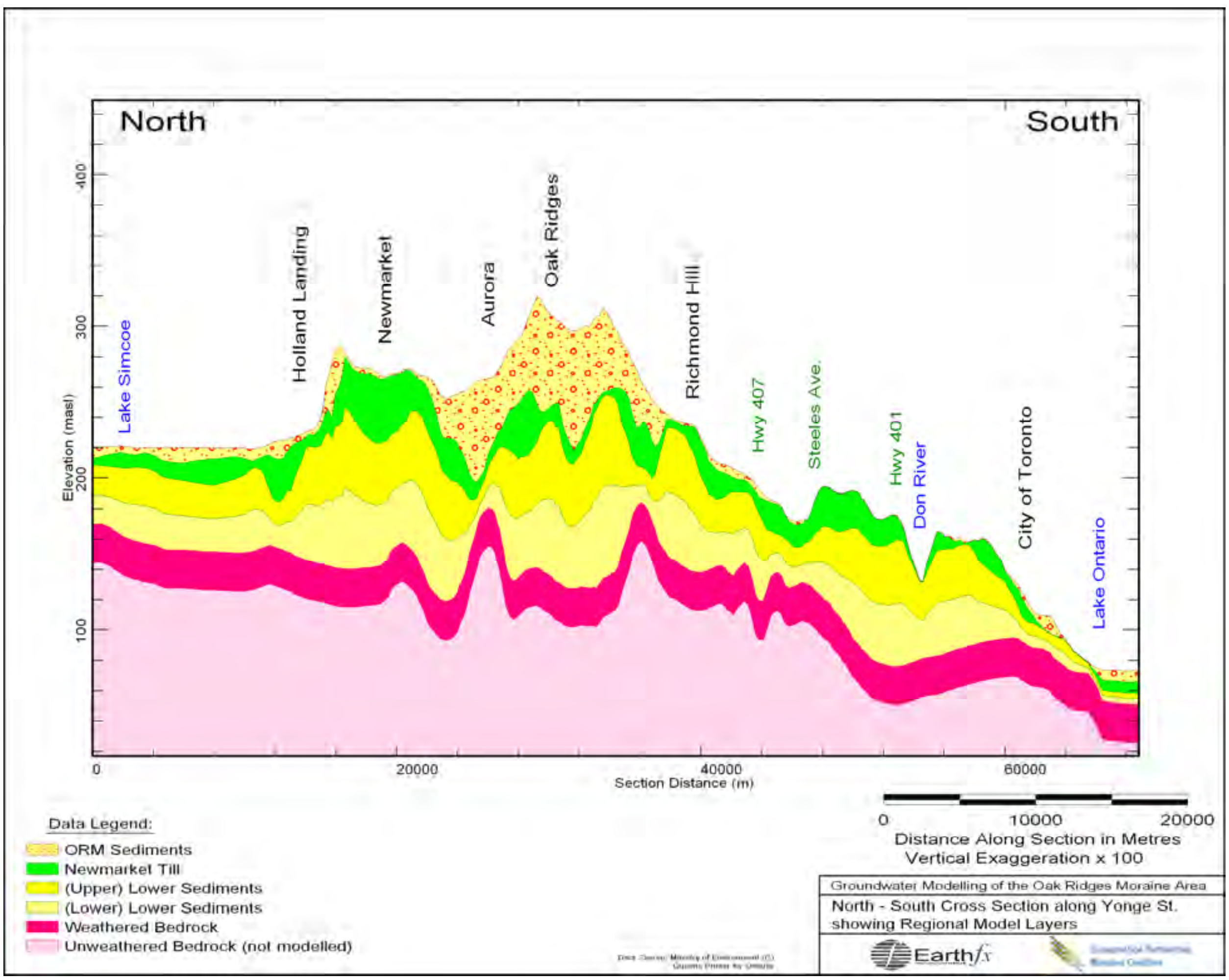

Figure 70: North-South Section through the Regional Model

6.3 Model Boundaries

Boundaries of the active model area were defined as shown in **Figure 69**. The model area is bounded to the west predominantly by the Niagara Escarpment and to the east by the divide between the Trent River and Moira River watersheds. The model extends southward from Georgian Bay, Lake Simcoe and the Kawartha Lakes to Lake Ontario. Cells outside the model boundaries were designated as inactive and were excluded from model calculations.

MODFLOW can represent three general types of conditions along the physical boundaries of the model. All three boundary condition types, constant head; no-flow, and head-dependent discharge boundaries, were employed. Boundary conditions for Layer 5, the weathered bedrock layer, are shown in **Figure 69**. Boundary conditions for Layers 2, 3, and 4 varied slightly (see Appendix D). The active area for Layer 1 was defined by the GSC ORM thickness.

6.3.1 Constant Head Boundaries

Constant head boundaries are typically applied to represent natural hydrologic boundaries at which aquifer potentials are expected to remain at a constant level. Cells bordering Lake Ontario, Georgian Bay, Lake Simcoe and the Kawartha Lakes were treated as constant head boundaries in all five layers. Two large lakes within the model boundaries, Rice Lake and Lake Scugog, were also treated as constant head boundaries. The water elevations at the constant head cells were determined from topographic maps and are provided in **Table 4** below.

Table 4: Elevations assigned at constant-head cells.

Lake Name	Elevation (masl)		Lake Name	Elevation (masl)
Lake Ontario	75.2		Sturgeon Lake	249
Lake Simcoe	219		Pigeon Lake	246
Georgian Bay	180		Chemung Lake	246
Lake Scugog	250		Clear Lake	232
Rice Lake	186		Percy Reach	112

Specifying the head at the boundary allows the model to determine the rate of underflow into or out of the model area. Post-simulation mass balances were analyzed to ensure that the simulated flow rates across the boundary remained within reasonable ranges.

6.3.2 No-Flow Boundaries

The rate of flow across a model boundary can be specified as a known value. This allows the head at the boundary to vary while the rate of underflow remains constant. No-flow boundaries are a special type of specified-flow boundary where the rate of lateral flow across the model boundary is assumed to be small or equal to zero. Typically, no flow boundaries are applied to represent groundwater divides or contacts with impermeable geologic units. A no-flow boundary condition was applied along the western boundary of the model to represent the Niagara Escarpment. (Inflow from valleys dissecting the Niagara Escarpment was not considered in this version of the Regional Model but was accounted for in the Core Model). A no-flow boundary condition was also imposed along the east side of the model to represent the eastern boundaries of the Trent River watershed. A combination of inter-stream divides (no-flow boundaries) and streamlines below major tributaries (also no-flow boundaries) were used to represent parts of the northern boundary located between the major lakes.

A no-flow boundary condition was applied at the base of the lowest model layer. This boundary condition assumes that the bedrock below a 15-metre thick weathered zone was much less permeable than the weathered zone and did not contribute significantly to the flow system. The thickness of the weathered bedrock zone was selected based on work by Haefeli (1972).

As noted earlier, geologic units are not continuous everywhere in the model area. Where uppermost layers were missing, the layer thickness was set to zero and the cells were designated as “inactive”. No flow can occur to or from inactive cells. An option in the MODFLOW recharge package was selected to allow recharge to an inactive cell to be passed down to the uppermost active cell. For example, if a cell in Layer 1 was inactive because Layer 1 was not present, the recharge was automatically applied to the underlying cell in Layer 2. As noted earlier, lower layers were assigned a minimum 0.5 m thickness.

Cells in the model can go “dry” during a simulation if the water table drops below the base of an active layer. This can occur as the model is iterating towards a solution of the flow equation. Dry cells are treated internally by MODFLOW as inactive cells since they no longer contribute flow to the rest of the model area. The number of dry cells and their locations varied in each model simulation in response to changes in model input data. The MODFLOW “re-wetting” option (McDonald et al., 1991) was used to allow a dry cell to become active again if potentials in neighbouring cells were higher than the base of the dry cell. Re-wetting parameters were modified during the course of the calibration to improve model stability and to speed the process of model convergence.

6.3.3 Groundwater-Surface Water Interaction – Head-Dependent Boundaries

Groundwater flow, especially in the ORM aquifer is strongly influenced by the presence of streams. Discharge of groundwater from aquifers provides baseflow to all streams in the study area. Streams can also “lose” water to the aquifer in lower reaches and possibly, where nearby wells induce recharge from the stream. One of the primary goals in constructing the model was to be able to represent and evaluate local-scale changes such as the effect on streamflow due to increased pumping or decreased recharge caused by urbanization.

MODFLOW uses several types of head-dependent discharge boundaries to simulate groundwater/surface water interaction where water is gained from (or lost to) a partially penetrating stream as leakage across the streambed. These boundaries are referred to in MODFLOW terminology as “rivers”, “drains”, and “general head-boundaries”. In all cases, the streambed is assumed to be less permeable than the surrounding aquifer due to deposition of fine-grained sediments or organic material.

The head-dependent flux, Q_{HD}, for each grid cell is calculated based on Darcy’s Law as:

$$Q_{HD} = \frac{K'}{B'} \cdot L_S \cdot W_S \cdot (H_S - h) \qquad \text{(Eq. 6.1)}$$

where: K’/B’ = Streambed leakage factor (hydraulic conductivity divided by bed thickness);
W_S = Streambed width (an approximation to the wetted perimeter)

L_S	=	Stream length within each cell;
H_S	=	Surface water stage (elevation of the stream surface); and
h	=	Head in the aquifer below the streambed.

MODFLOW “drains” were used to simulate discharge to the rivers and streams in the study area. The key assumption regarding drains is that leakage occurs in only one direction, from the aquifer to the drain (**Figure 71**). Leakage directly from streams back to the aquifer was thought to be a small part of the overall water balance and was not considered in this version of the Regional Model (but is accounted for in the Core Model).

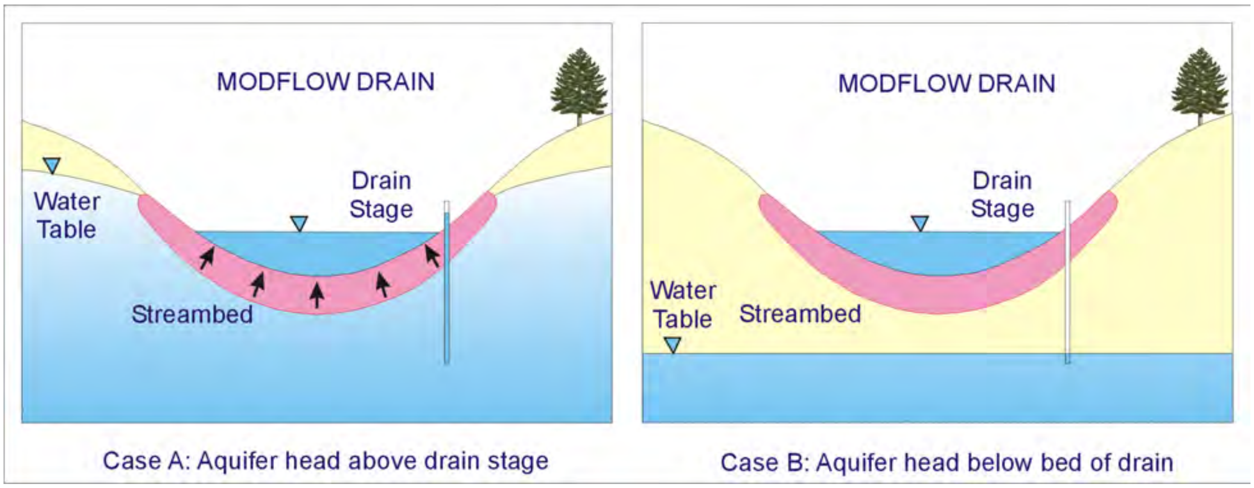

Figure 71: Cross section showing leakage between drain and aquifer.

When aquifer heads drop below the controlling elevation of the drain, the drain is presumed to go dry and no flow occurs from the drain back to the groundwater system. A MODFLOW parameter, called the “drain conductance”, groups the bed properties of the drain and geometry terms in Equation 6.1 (i.e. $K'W_sL_s/B'$). Drain conductances and drain elevations were specified for each drain segment that passed through a model cell.

The dendritic stream networks in the study area are complex and contain many channel segments. Some simplification was necessary to automate the process of assigning stream properties to each river and drain segment. In the Regional Model, stream reaches were each assigned a Strahler classification number (see **Figure 67**). Each stream reach was assigned an average width and bed thickness based on its Strahler number. Stream widths varied from one metre for a Class 1 tributary to 50 m for a Class 8. Uniform values for streambed hydraulic conductivity (K’) were used in the Regional Model. These values were adjusted slightly during model calibration to better match observed baseflows but remained in the range of silt to silty-fine sand.

Line segments representing all streams on the base map for the study area were imported into VIEWLOG (**Figure 72**). VIEWLOG was then used to compute the length of each stream reach within each model cell. Controlling drain elevations were estimated from the 30-m DEM. VIEWLOG calculated the conductance values and, after processing each drain segment, created the input data file for MODFLOW. A total of 136,359 stream reaches consisting of 148,800 drain segments were used in the Regional Model.

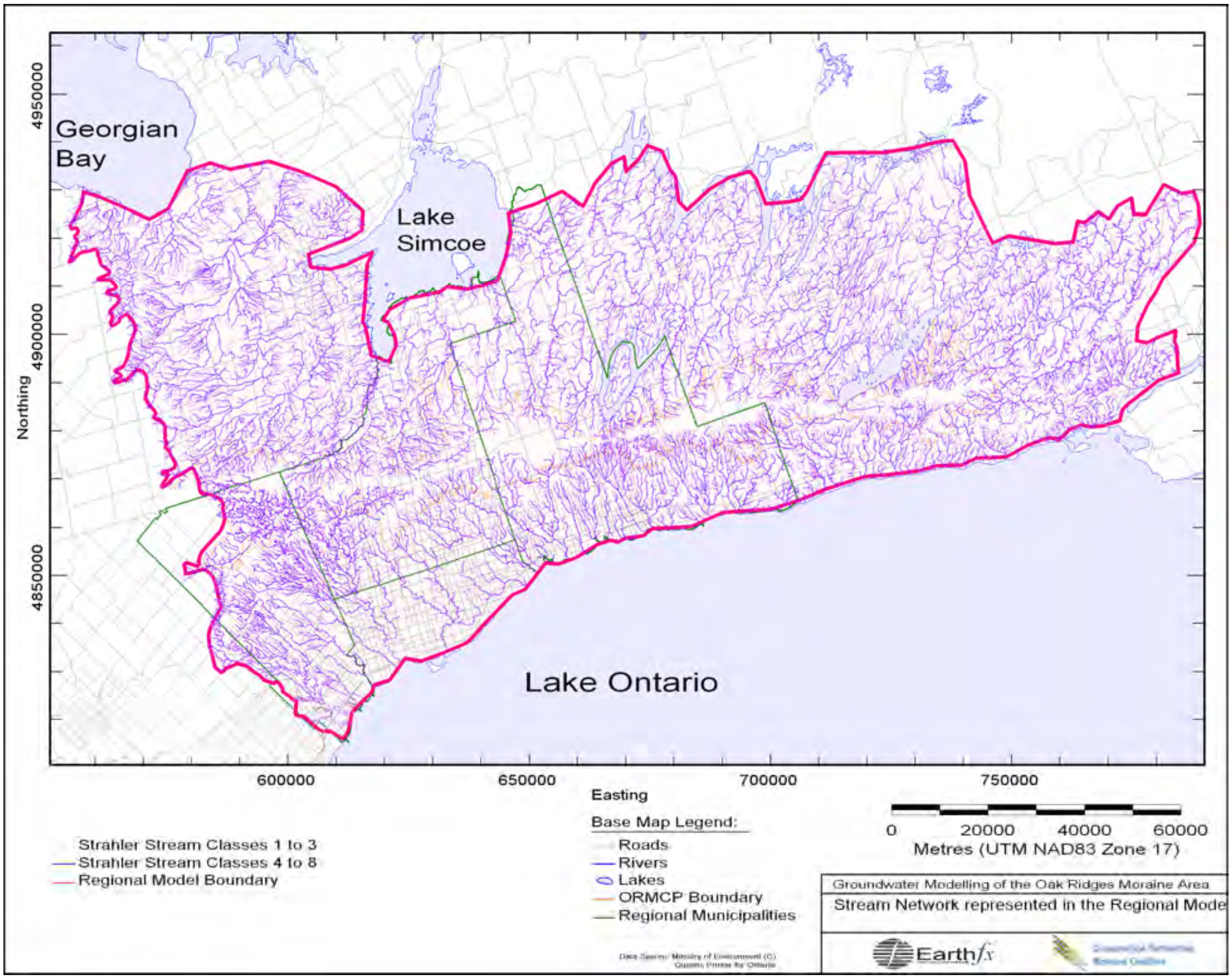

Figure 72: Location of the 36,359 stream reaches simulated in the Regional Model.

6.3.4 Groundwater Recharge and Discharge

Average precipitation measured at 129 Environment Canada climate stations in the study area with periods of record greater than five years during 1980 to 2002, ranged between 696 millimetres per annum (mm/a) and 1172 mm/a and averaged 886 mm/a. **Figure 73** shows locations of the climate stations used in this analysis and a colour-scale plot of the observed values interpolated to the model grid using the kriging technique. Higher values (>900 mm/a) occur locally, for example south of Georgian Bay, West of Lake Simcoe, near Trenton, and in the area between Lake Scugog and Rice Lake. Data in these areas are relatively sparse and it is difficult to determine the true lateral extent of these high rainfall areas. Lower values (<900 mm/a) were observed in the Toronto area and southern York Region which may be affected by the proximity to Lake Ontario, the generally lower topography, or microclimates in the urban areas. Recharge was not reduced in the urban areas in the initial simulations with the Regional Model which was primarily used to simulate pre-development conditions. Recharge was reduced in the Core Model area to account for this apparent reduction in precipitation in the urban areas as well as for the increased runoff due to impervious areas.

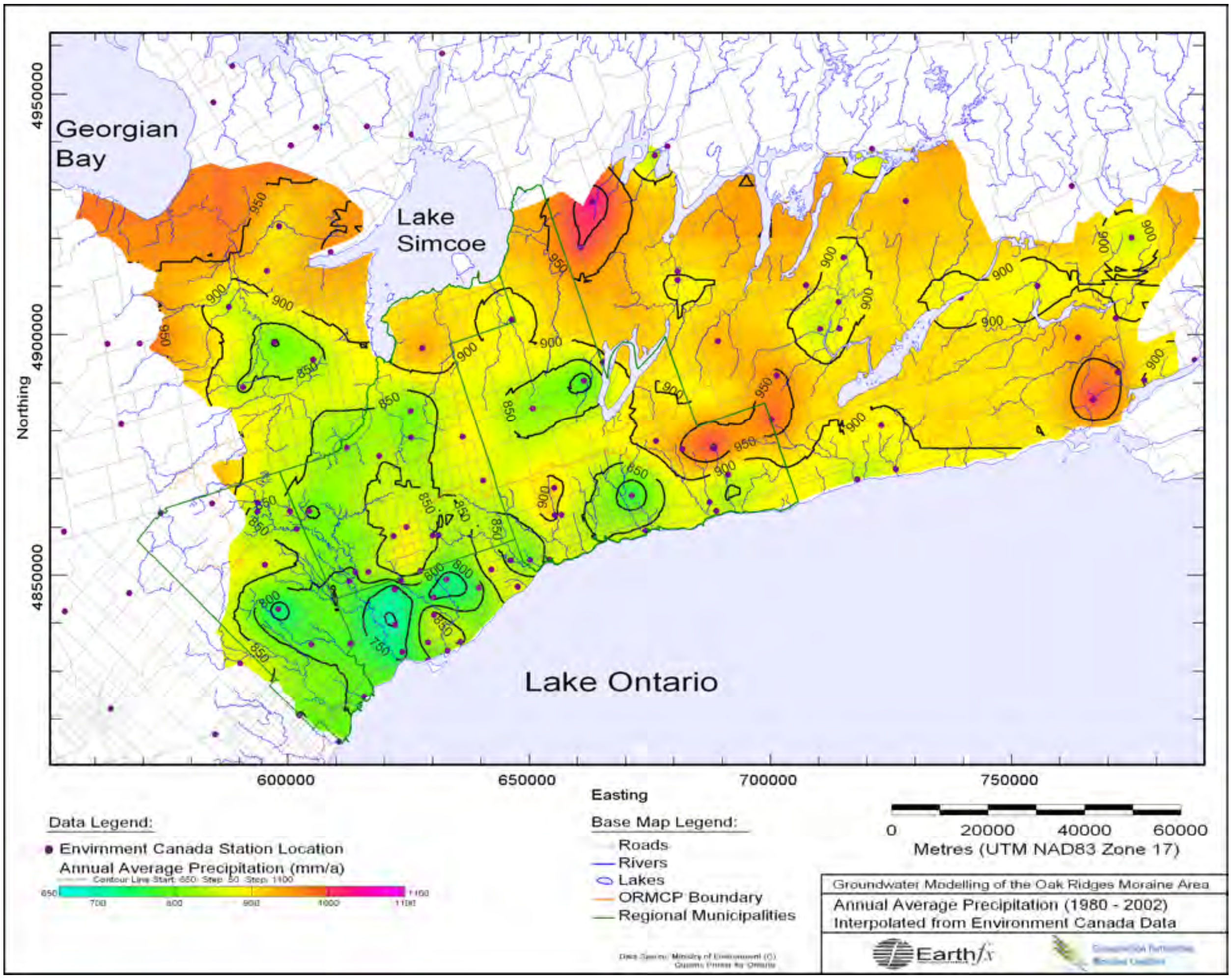

Figure 73: Annual average precipitation 1980-2002

Applying the Thornthwaite water balance equation (Thornthwaite and Mather, 1955), the annual potential evapotranspiration (PET) was estimated to vary between 575 to 603 mm/a (Environment Canada, 2002), with an average value of 580 mm/a covering most of the study area. The average water surplus can be approximated as the measured precipitation minus the actual ET. Part of the water surplus will end up as surface runoff to area watercourses and the balance will infiltrate through the soil profile and eventually recharge the upper portion of the groundwater system. The Thornthwaite method is a very simple method of calculating PET and water surplus and therefore does not account for local variations in precipitation, snowmelt, soil type, topography, and land use which can affect actual ET, runoff and recharge.

Previous studies and analyses of climate, land use, and soil properties were reviewed to provide initial estimates of the spatial distribution of groundwater recharge. The primary influence on the recharge distribution used in the Regional Model was assumed to be surficial geology as mapped by the GSC (**Figure 12**). The initial estimates of annual average net recharge were supplied as input to the MODFLOW model and adjusted during model calibration. Calibrated values are listed in **Table 5** and the spatial distribution of applied recharge is shown in **Figure 74**. Recharge rates were highest over the ORM due to the sandy soils and hummocky topography (360 mm/a) and lowest in areas covered with lake sediments or organic deposits

(60 mm/a). Areas east and west of Lake Simcoe in the northern part of the model lie outside the area mapped by the GSC and were assigned a uniform value of 60 mm/a.

Table 5: Annual average recharge values used in the calibrated Regional Model

Surficial Material	Value (mm/a)
Bedrock	60
Lower Sediments	120
Newmarket Till	90
Halton/Kettleby Till	90
Moraine Deposits	360
Glacial River Deposits	320
Glacial Lake Deposits - Silt and Clay	60
Glacial Lake Deposits – Sand and Gravel	240
Organic Deposits	60
River Deposits – Sand and Gravel	60
Other Recent Deposits	60
Unclassified Surficial Geology	60

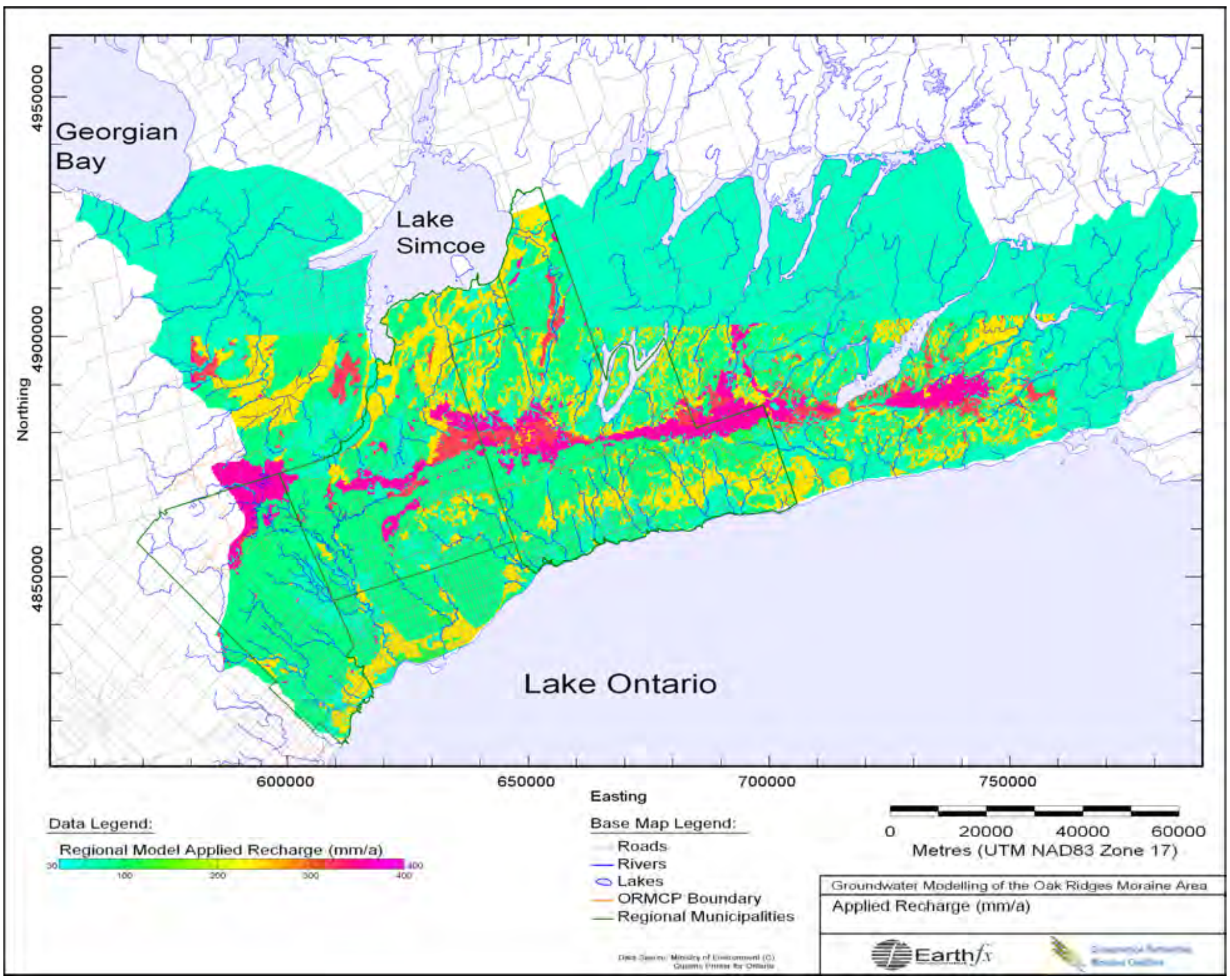

Figure 74: Distribution of recharge in the Regional Model

6.3.5 Groundwater Extraction

Groundwater is extracted from the aquifers in the study area for municipal water supply, agricultural use, industrial use, golf course irrigation, and private (domestic) water supply. No pumping was simulated in the Regional Model as this model was used primarily to simulate pre-development conditions. Pumping was considered in the Core Model analyses.

6.4 Model Parameter Values

6.4.1 Aquitard Properties

There is only limited information on the hydraulic properties of the confining units (Halton/Kettleby Aquitard, Newmarket Aquitard, and Sunnybrook Aquitard) and insufficient information to systematically vary the properties except, for example, to note that the Halton Till becomes more clay rich to the west. Accordingly, uniform properties were initially assigned to the confining units based on the available field data and the results of previous modeling studies. These estimates were varied during the model calibration process, however the hydraulic conductivity remained spatially uniform within each aquitard layer. Exceptions included areas where the Newmarket Aquitard was less than two m thick; these areas were assigned a higher hydraulic conductivity to represent zones in which the till may have been eroded away. (Further refinement of the erosional surface of the Newmarket Aquitard was conducted as described in Section 4). Calibrated horizontal and vertical hydraulic conductivity values are presented in **Table 6**.

Table 6: Hydraulic conductivity values for aquitards in the calibrated Regional Model

Aquitard	Layer	Horizontal Hydraulic Conductivity (m/s)	Vertical Hydraulic Conductivity (m/s)
Newmarket Aquitard > 2 m thick	2	5.0×10^{-8}	5.0×10^{-9}
Newmarket Aquitard < 2 m thick	2	5.0×10^{-8}	5.0×10^{-8}
Sunnybrook Aquitard	3 - 4	NA	5.0×10^{-9}

Calibrated values for hydraulic conductivity of the Newmarket Aquitard are higher than results of permeability tests on core samples. This is consistent with results by Gerber (1999) who noted that fractures and sand bodies within the Newmarket Till contribute to a higher effective vertical permeability.

Model results tended to be extremely sensitive to the vertical hydraulic conductivity of the Newmarket Aquitard and Sunnybrook Aquitard. A slight decrease in permeability below the calibrated value caused heads to increase sharply in the upper units and resulted in insufficient flux to maintain heads in the lower aquifers. Model stability was also degraded at lower hydraulic conductivity values. Conversely, a slight increase in vertical permeability caused the head difference between the two bounding aquifers to decrease to near zero and the model was unable to match the observed head differences between aquifer layers.

6.4.2 Aquifer Properties

MODFLOW offers the option of either specifying aquifer transmissivity (T) or hydraulic conductivity (K) values. Because great effort had been expended in defining layer geometry, it was decided to specify hydraulic conductivities and let the model calculate transmissivity values internally based on layer thickness. Initial estimates of hydraulic conductivity for the aquifer layers in the Regional Model were based on results of aquifer testing and results of previous modelling studies.

Table 7: Hydraulic conductivity values for aquifers in the calibrated Regional Model

Aquifer	Layer	Hydraulic Conductivity (m/s)
ORAC Aquifer Complex	1	5.0 x 10^{-5} to 1.0x10^{-4}
Upper Part of Lower Sediments	3	2.5 x 10^{-5}
Lower Part of Lower Sediments	4	5.0 x 10^{-5}
Weathered Bedrock	5	6.7x10^{-6} (assuming a 15 m thickness)

The initial estimates were adjusted during model calibration. Calibrated values are shown in**Table 7**. A more complex procedure for assigning spatially variable hydraulic conductivity values was developed for the Core Model and is described further on in this report

6.5 Calibration of the Regional Model

6.5.1 Calibration Process

The calibration process started with Regional Model runs using initial estimates of hydraulic conductivity, anisotropy, and recharge rates. Simulated water levels were visually compared in VIEWLOG by overlaying contour maps of the interpolated observed data on top of contour maps of simulated values. Maps of residuals were obtained by subtracting simulated potentials from interpolated observed values and then colour-contouring the results. These maps helped to identify areas where simulated water levels were generally too high or too low. Numerous cross-sections were created across the study area to visually compare simulated and observed water levels and vertical gradients.

Model parameters, primarily hydraulic conductivity and recharge, were adjusted in a trial-and-error process to improve the qualitative fits and reduce residuals. Model results were not expected to match the observed data perfectly because the aquifer properties are highly variable and the observed data are sparse for the deeper aquifers and are of variable quality. Qualitative checks and statistical tests were applied to determine whether the calibration met the required "goodness-of-fit" criteria.

6.5.2 Calibration to Static Water Levels and Baseflow

The primary target for the calibration of the Regional Model was matching observed static water levels in the ORAC deposits above the Newmarket Aquitard and in the Lower Sediments. Static water levels were obtained from the MOE well records in order to compare model results against the most comprehensive, areally-extensive data set available.

Two potentiometric surface maps were prepared using the static water level data. **Figure 75** shows a potentiometric surface for wells screened above the Newmarket Aquitard. This surface corresponds to the water table except where the ORM deposits are confined by the Halton/Kettleby Aquitard. **Figure 76** shows the potentiometric surface for the Lower Sediments. Because of the inherent error in the data, model calibration efforts were not directed at matching the observed heads at individual wells. Instead, the focus was on trying to match interpolated heads (which averaged out some of the error), flow patterns, and gradients.

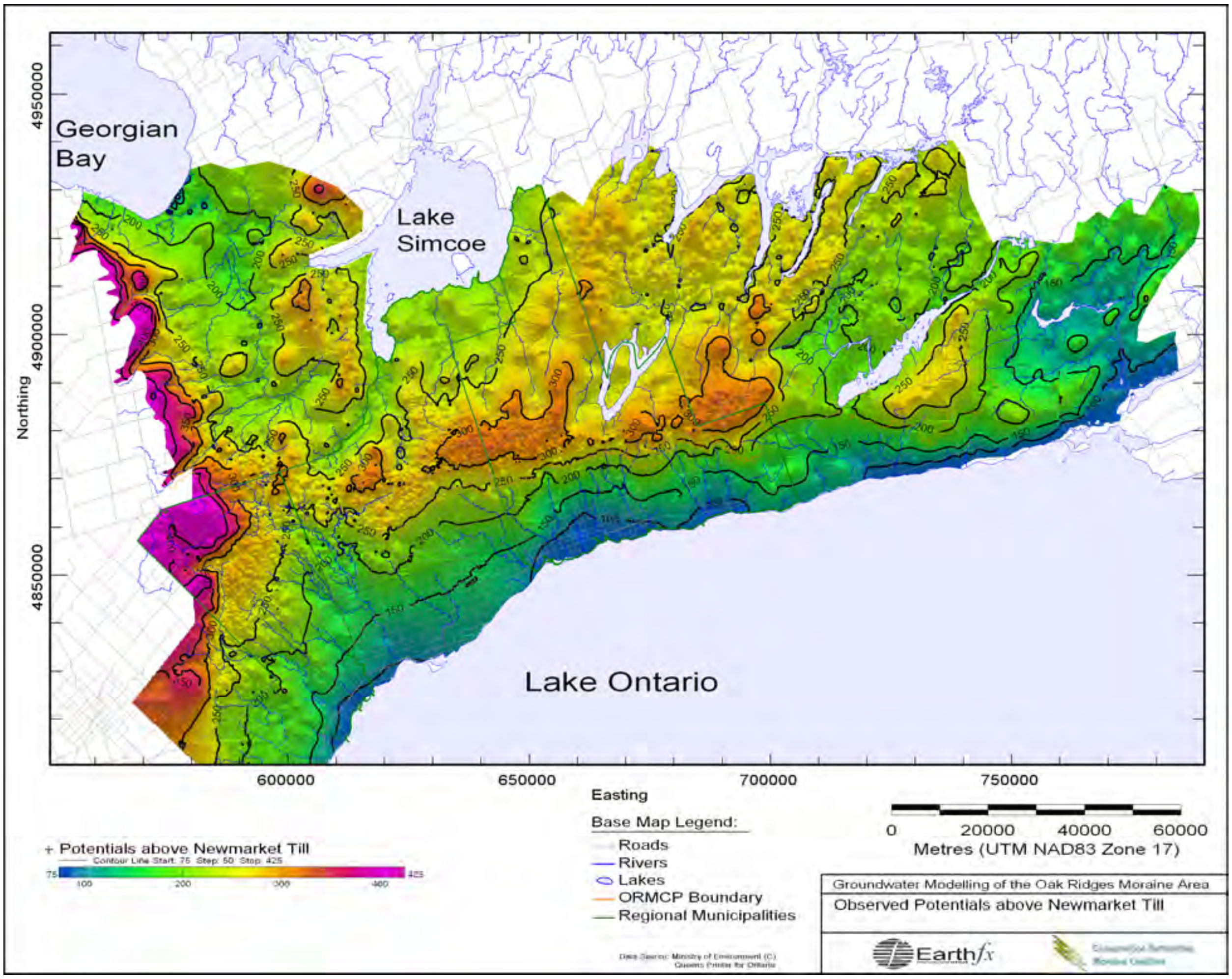

Figure 75: Observed potentials above the Newmarket Aquitard

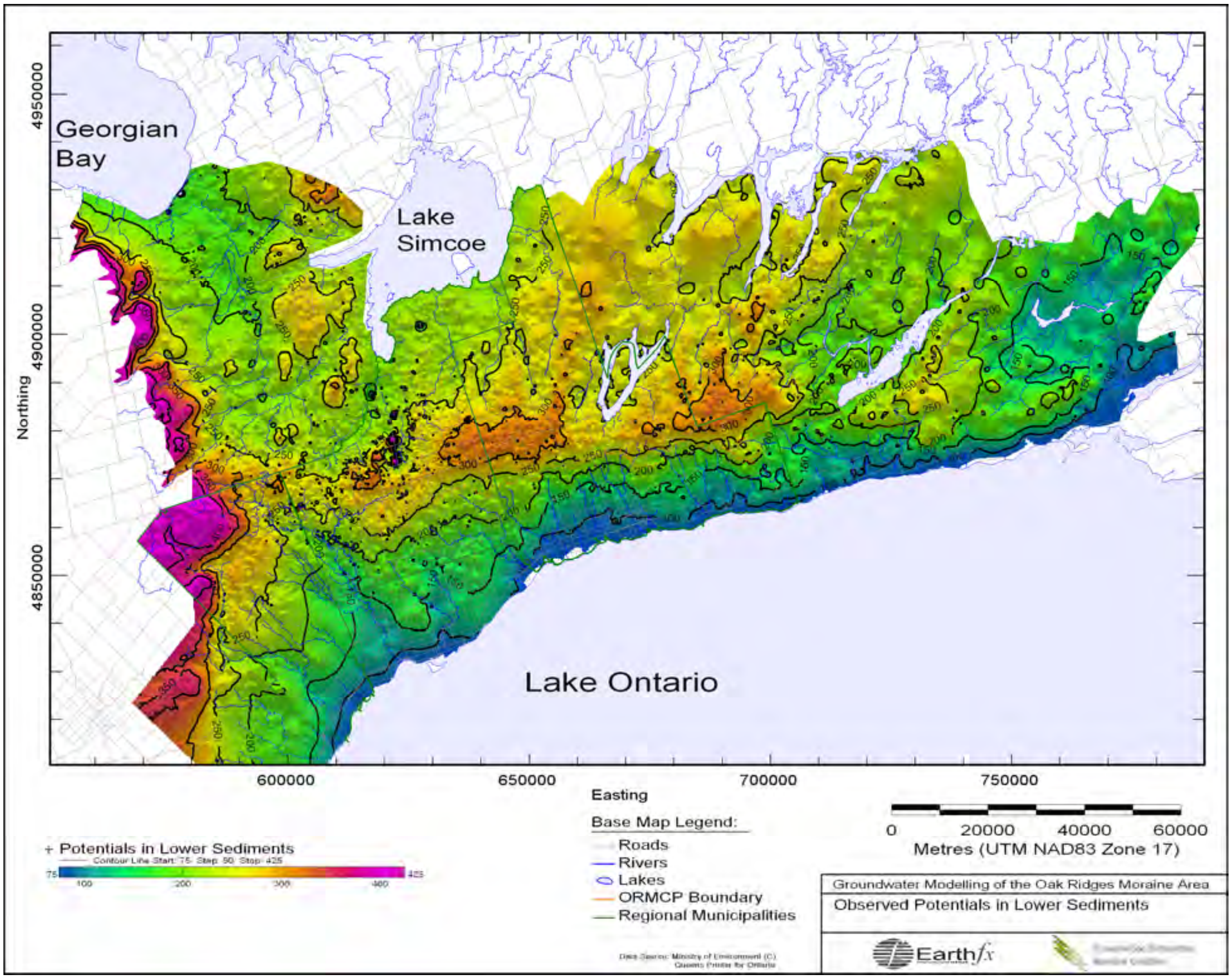

Figure 76: Observed potentials in Lower Sediments.

Matching baseflow in the study area streams was the second calibration target. As discussed earlier, baseflow separation techniques were applied to determine annual average discharge to streams. These target values are shown in **Table 3**. Spot flow measurements were also checked during the calibration process, but the focus was primarily on matching long-term baseflow data as a check on recharge estimates.

6.5.3 Simulated Heads and Baseflow

Simulated heads for the calibrated Regional Model were obtained for each layer. The simulated water table (potentials in the uppermost active layer) and potentials for Layer 3 (upper part of the Lower Sediments) are presented in **Figure 77** and **Figure 78**, respectively.

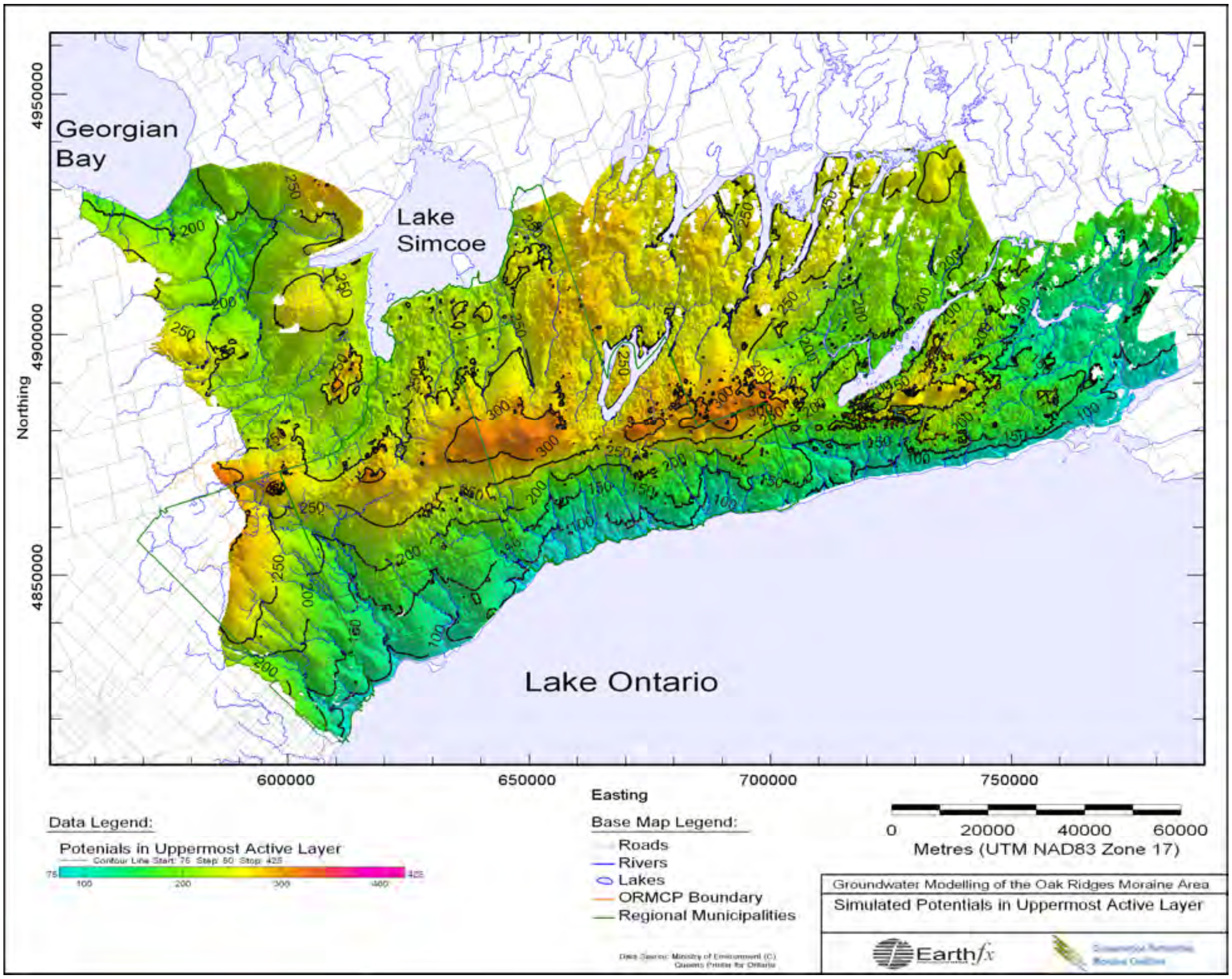

Figure 77: Simulated heads above the Newmarket Aquitard

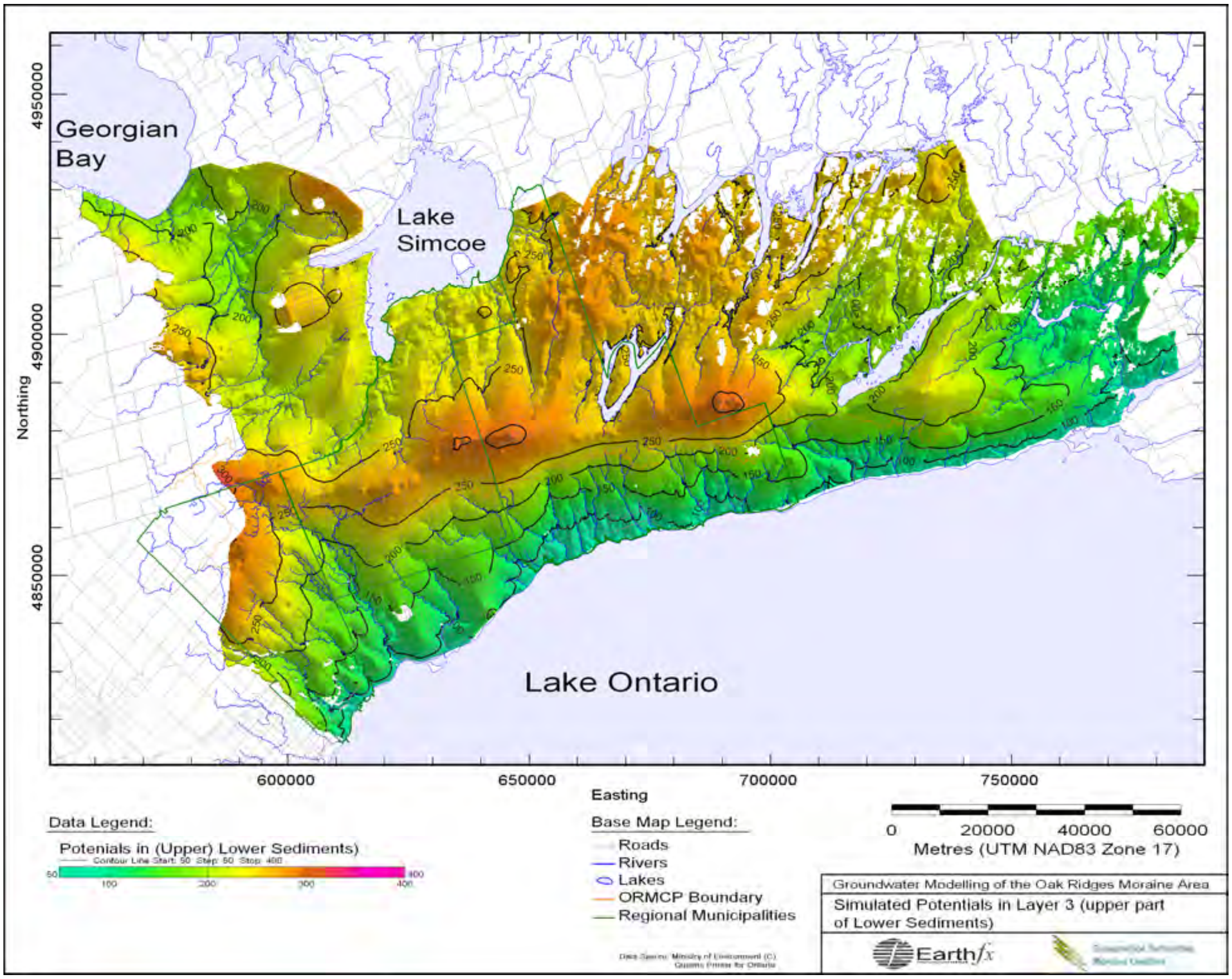

Figure 78: Simulated potentials in Layer 3 (upper portion of Lower Sediments)

Visual comparisons of these figures with the observed potentials show that the model was able to reproduce the observed head distribution and flow patterns. Contours of simulated and observed potentials in the Lower Sediments are overlain for a small portion of the model area south of Lake Scugog in Durham Region (**Figure 79** – purple contours are observed and black contours are simulated) and show the quality of the match that was achieved even though relatively uniform hydraulic properties were used in the model. The figure also shows that the model is able to reproduce the influence of the streams on the potentials.

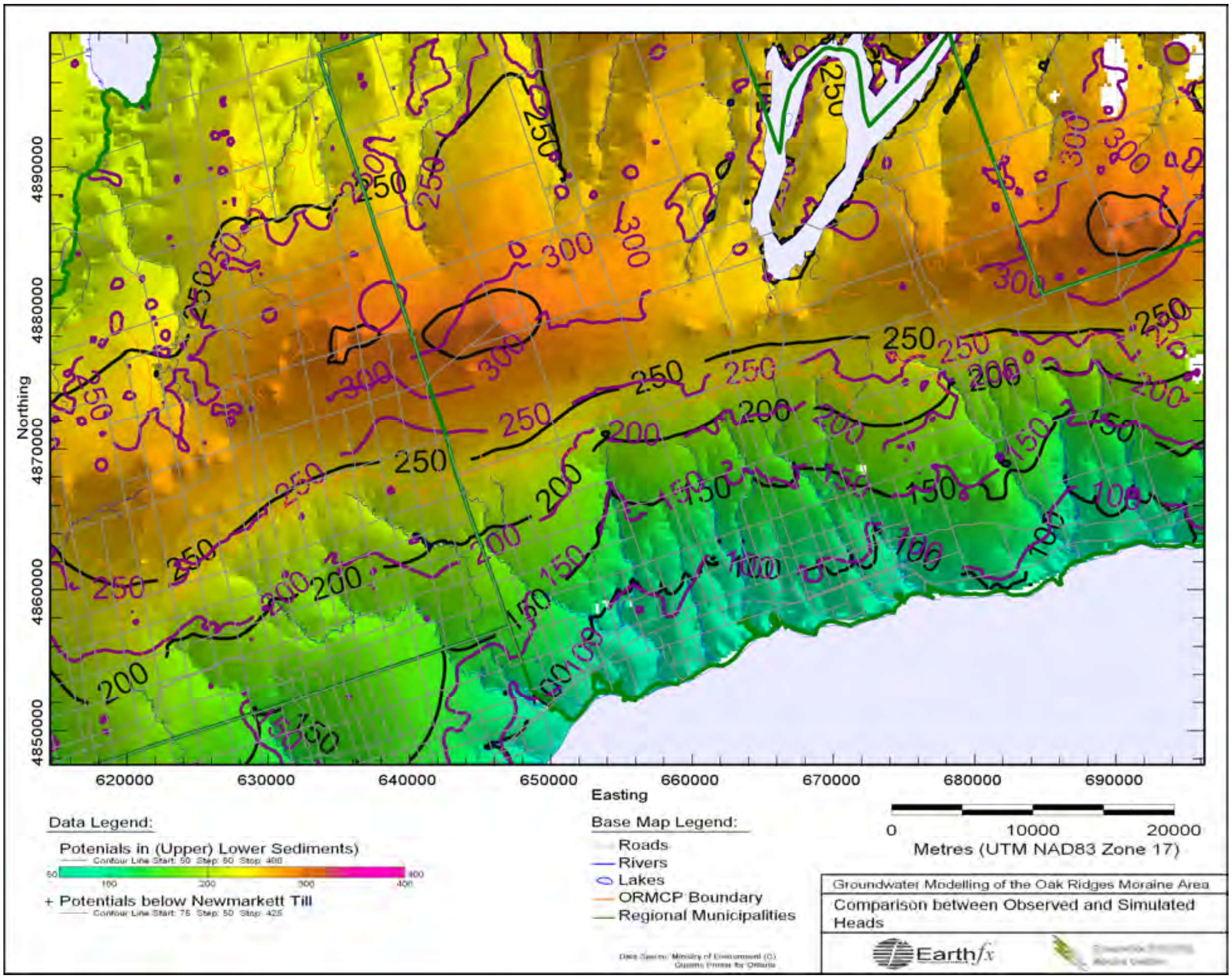

Figure 79: Comparison between observed potentials in Lower Sediment and simulated potentials in upper part of Lower Sediments

6.5.4 Calibration Statistics

Scatterplots of simulated potentials versus observed potentials were produced to determine whether errors were uniformly distributed and to help identify causes of the larger deviations. Scatterplots for the ORAC and Lower Sediments are shown in **Figure 80** and **Figure 81**, respectively. Ideally, all data points should fall on the 45° line shown on the figures. The scatterplots show that most data points fall within bands defined by ±15 m for the ORAC and ±20 m for the Lower Sediments (which includes wells screened in the TAC and SAC). The plots also show that the residuals are somewhat biased and that the model tends to slightly underpredict heads in the ORM deposits and overpredict heads in the Lower Sediments.

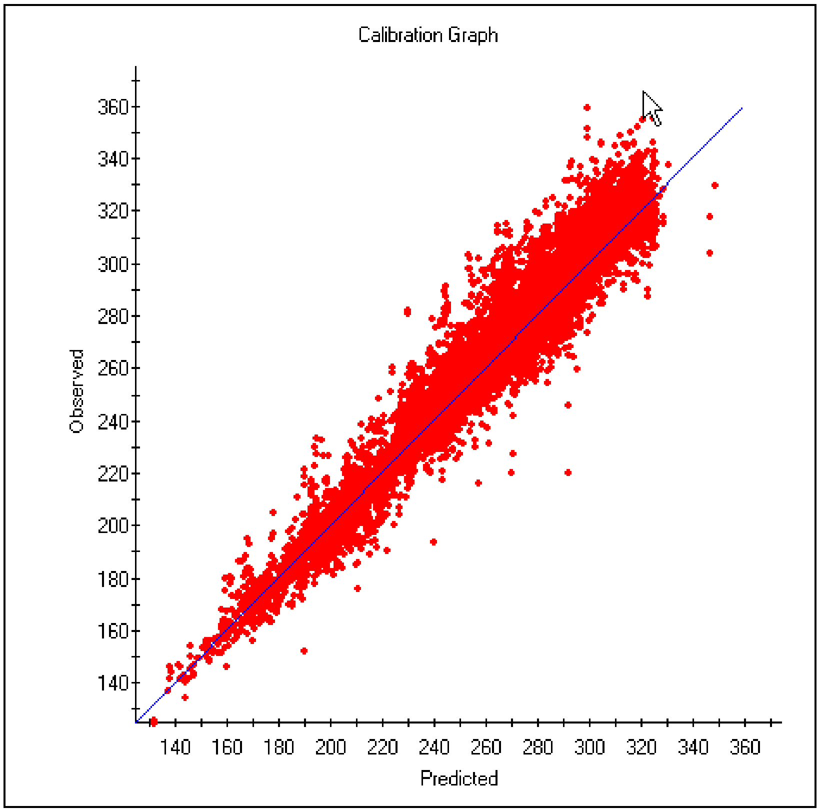

Figure 80: Scatterplot for heads in the ORAC

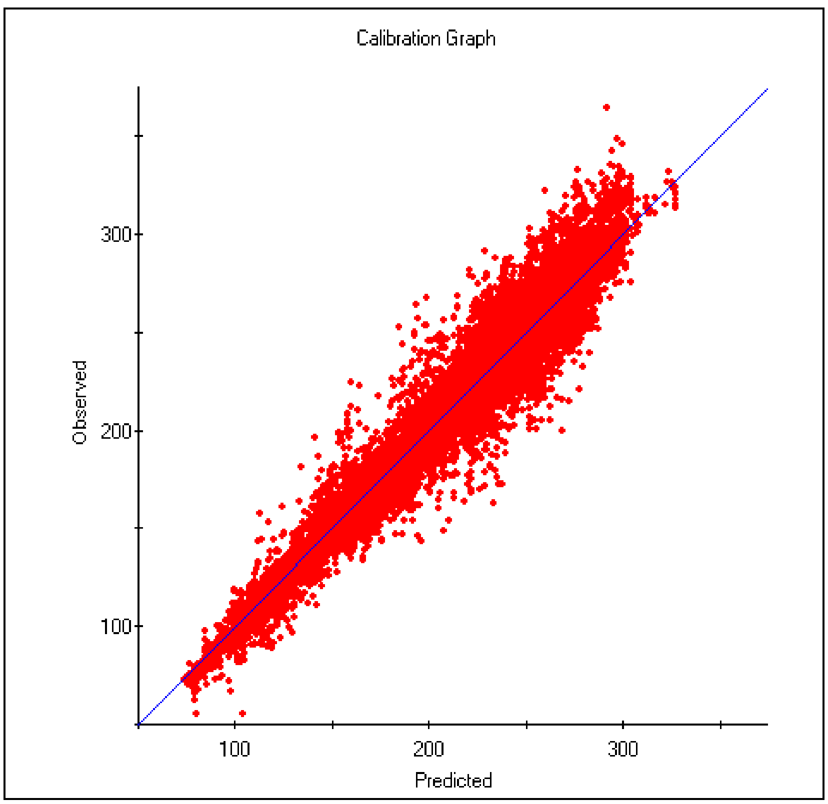

Figure 81: Scatterplot for heads in the (Upper) Lower Sediments

Three calibration statistics were used to assess and demonstrate model accuracy: the mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE). These are given by Anderson and Woessner (1992) as:

$$\text{Mean Error} = \frac{1}{n}\sum_{1}^{n}(h_O - h_S)_i \qquad \text{(Eq. 6.2)}$$

$$\text{Mean Absolute Error} = \frac{1}{n}\sum_{1}^{n}\left|(h_O - h_S)_i\right| \qquad \text{(Eq. 6.3)}$$

$$\text{Root Mean Squared Error} = \sqrt{\frac{1}{n}\sum_{1}^{n}(h_O - h_S)_i^2} \qquad \text{(Eq. 6.4)}$$

where: h_o = Observed hydraulic head;
h_s = Simulated hydraulic head; and,
n = Number of wells.

Calibration statistics for heads in the ORM and upper part of the Lower Sediments (Layer 3) are presented in **Table 8**. In general, a slightly better match was achieved in the ORM aquifer where properties are better understood and more data are available. The sign on the ME values indicates that simulated values are generally higher than the observed values in the ORM and generally lower in the Lower Sediments. The MAE and RMSE provide a good estimate of the average magnitude of the difference between the observed and simulated values. The values for RMSE are 1.7 to 1.5 times greater than the estimate of variance in the observed water level data yielded by the variogram analysis (see Section 5). While additional improvements could be made in the calibration, the residual error would not likely be reduced beyond ±6 m for the ORAC and ±8 m for the Lower Sediments.

Table 8: Calibration statistics for heads

Model Result	Number of Wells	ME (m)	MAE (m)	RMSE (m)
ORAC Heads	13,178	3.85	7.50	10.37
(Upper) Lower Sediment Heads	21,252	-1.16	8.18	11.85

Values for MAE and RMSE are often compared to the overall response of the model (Anderson and Woessner, 1992); in this case, the range in heads over the study area. The total range for the ORM aquifer was close to 270 m (from 90 masl near Lake Ontario to 360 masl below the crest of the moraine) and about 245 m for the Thorncliffe Aquifer Complex (from 70 masl at Lake Ontario to 315 masl below the crest of the moraine). Accordingly, MAE varied from 2.8% to 3.6% and RMSE varied from 3.8% to 4.8% of the range. Spitz and Moreno (1996) state that an error of less than 10% of the range indicates an acceptable calibration. Mass balance error was less than 2.0%.

The simulated discharge to the streams (in L/s) on a cell-by-cell basis is shown in **Figure 82**. Comparisons between calculated baseflows at the Environment Canada gauges and the simulated groundwater discharge to streams are presented in **Table 3** and shown graphically in a scatterplot in **Figure 83**. The match between the observed and simulated values is quite good considering the uncertainty inherent in baseflow separation, the simplifying assumptions made in representing the streams, and the uncertainty in the model input parameters. The match indicates that the rates of recharge used in the model (the primary input in the water balance) are reasonable when compared against the baseflow values (the primary output in the water balance).

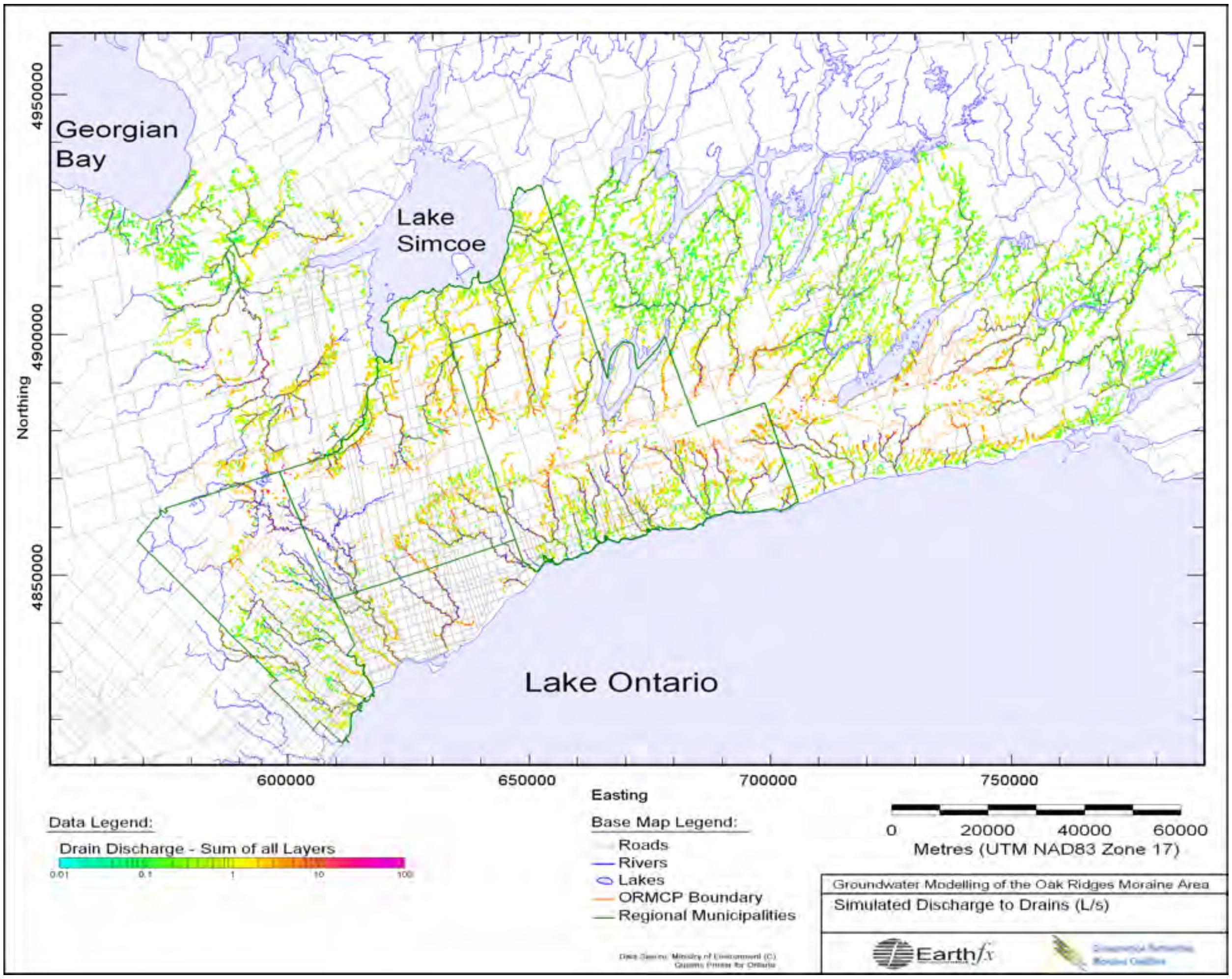

Figure 82: Simulated discharge to streams

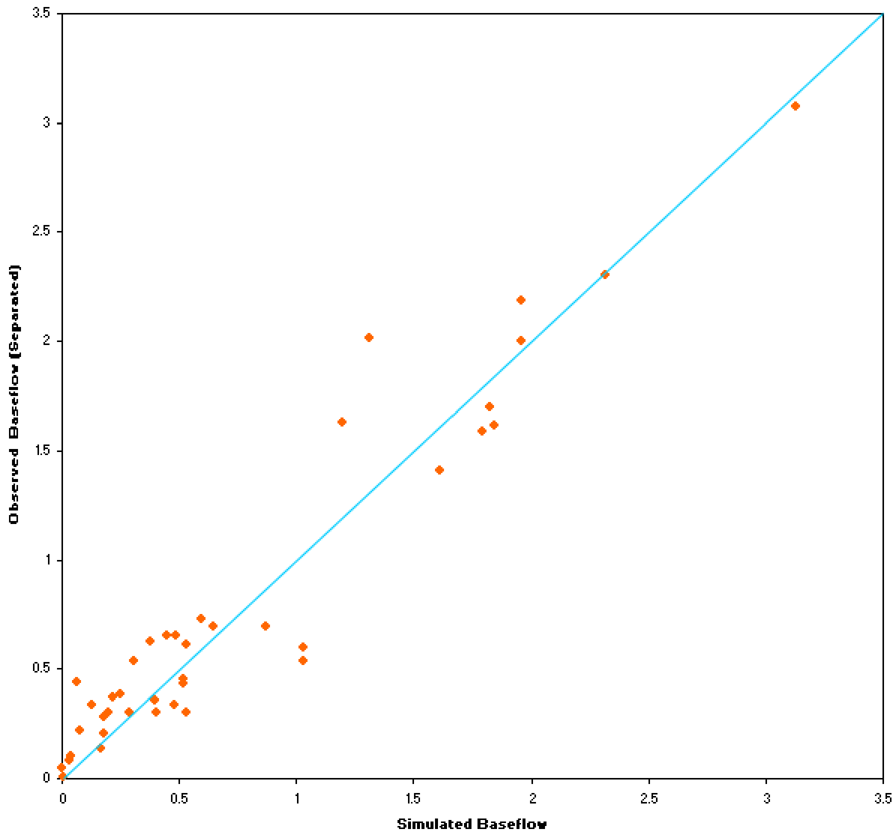

Figure 83: Scatterplot showing simulated versus baseflow in the calibrated Regional Model

6.6 Regional Model Findings

Some general conclusions that can be drawn from the Regional Model results include:

(1) groundwater flow patterns were strongly influenced by streams, and fine discritization was needed to properly represent the stream network;

(2) estimates of recharge and hydraulic conductivity produced reasonable matches to observed heads, gradients, and baseflows;

(3) model results were extremely sensitive to the permeability of the Newmarket Aquitard which controlled aquifer heads both above and below the till layer;

(4) calibrated hydraulic conductivity values did not vary greatly between aquifers and indicated that, in a regional sense, silts and fine sands are primary aquifer components;

(5) aquifer and aquitard properties used in the model agreed well with previous estimates by Gerber (1999) and Mowatt (2001);

(6) hydraulic conductivity of the Newmarket Aquitard is higher than test values from core samples due to the presence of fractures and sand bodies within the Newmarket Till that contribute to a higher effective vertical permeability; and

(7) regional-scale modelling of the ORM area is possible using the available data and available modelling codes (although it had never been tried previously).

6.6.1 Regional Mass Balance

A mass balance for the study area, as computed by the Regional Model, is provided in **Table 9**

Table 9: Simulated mass balance for the Regional Model

Flow Rate	m^3/s	% of Total
Inflows:		
Net Recharge	50.5	94.9
Constant Head Boundaries	2.70	5.1
Outflows:		
Constant Head Boundaries	5.38	9.8
Stream Leakage (from aquifer)	48.6	90.2

Even though reasonable matches to the observed heads and flows were obtained, it was felt that more work was needed to map the bedrock valleys and tunnel channels and to better represent stratigraphy of the Lower Sediments if the model was to be used for predictive and management analysis. Refining of the stratigraphy is detailed in Section 3. Efforts were also made to refine model discritization (i.e. use smaller cell size), better represent the upper sediments (ORAC deposits, Halton/Kettleby Aquitard, and Recent Deposits), and account for local variability of aquifer properties in the development of the Core Model. Further work on the entire ORM area is anticipated to proceed through expansion of the Core Model to the east and west rather than through additional work on the Regional Model.

7 Core Area Groundwater Flow Model

The second phase of the modelling effort involved a more detailed assessment of the central part of the Regional Model study area. The Core Model area (**Figure 3**) was selected because of the number and detail of previous investigations, the availability of high quality well log data, and the ability to combine this work with concurrent model development studies for the Regional Municipality of York (York Region) and for the Toronto and Region Conservation Area (TRCA) watersheds under the York-Peel-Durham-Toronto Groundwater Management Strategy Study (YPDT Study). The objectives and reasons for the development of the refined Core model are presented in Section 3.2.

Constructing the numerical model started with the design of the numerical model grid and preparation of input data files. The sub-regional model was actually developed in a number of stages. A small, test-scale model was developed for the Duffins Creek area to test model performance in an area where a previous model had been developed (see Gerber, 1999). A larger test model was then developed for the East Gwillimbury area, which covered most of York Region north of the regional groundwater divide. The small-scale models were described in informal progress reports and presentations and are not discussed further here. Expansion of the model, refinement of geologic surfaces, and final calibration of the model were completed in December 2003.

Much of the basic modelling approach used in developing the Regional Model was applied in developing the Core Model. This section of the report therefore focuses on where the Core Model development differed.

7.1 Model Grid

The finite-difference grid constructed to represent the Core Model study area was made up of square cells, each 100 m on a side. The grid extends some distance beyond the limits of the study area so only a portion of it is shown on **Figure 84**. Also, the number of lines needed to show all cells in the model grid would render the figure unreadable, so only a coarse grid is shown in which each coarse grid cell is actually composed of 100 (10 x 10) model grid cells (see inset map on **Figure 84**).

Although a larger model grid cell-size would have been adequate for sub-regional flow modelling, the smaller cell size was selected to better represent stream-aquifer interaction and drawdowns around the municipal wells. The model grid has 840 rows, 1056 columns with eight layers, for a total of nearly 7.1 million cells. A local origin for the model grid was selected at UTM coordinates 550665 E and 4810550 N. All digital maps and well data for the study area were referenced using UTM NAD83 (Zone 17) grid coordinates.

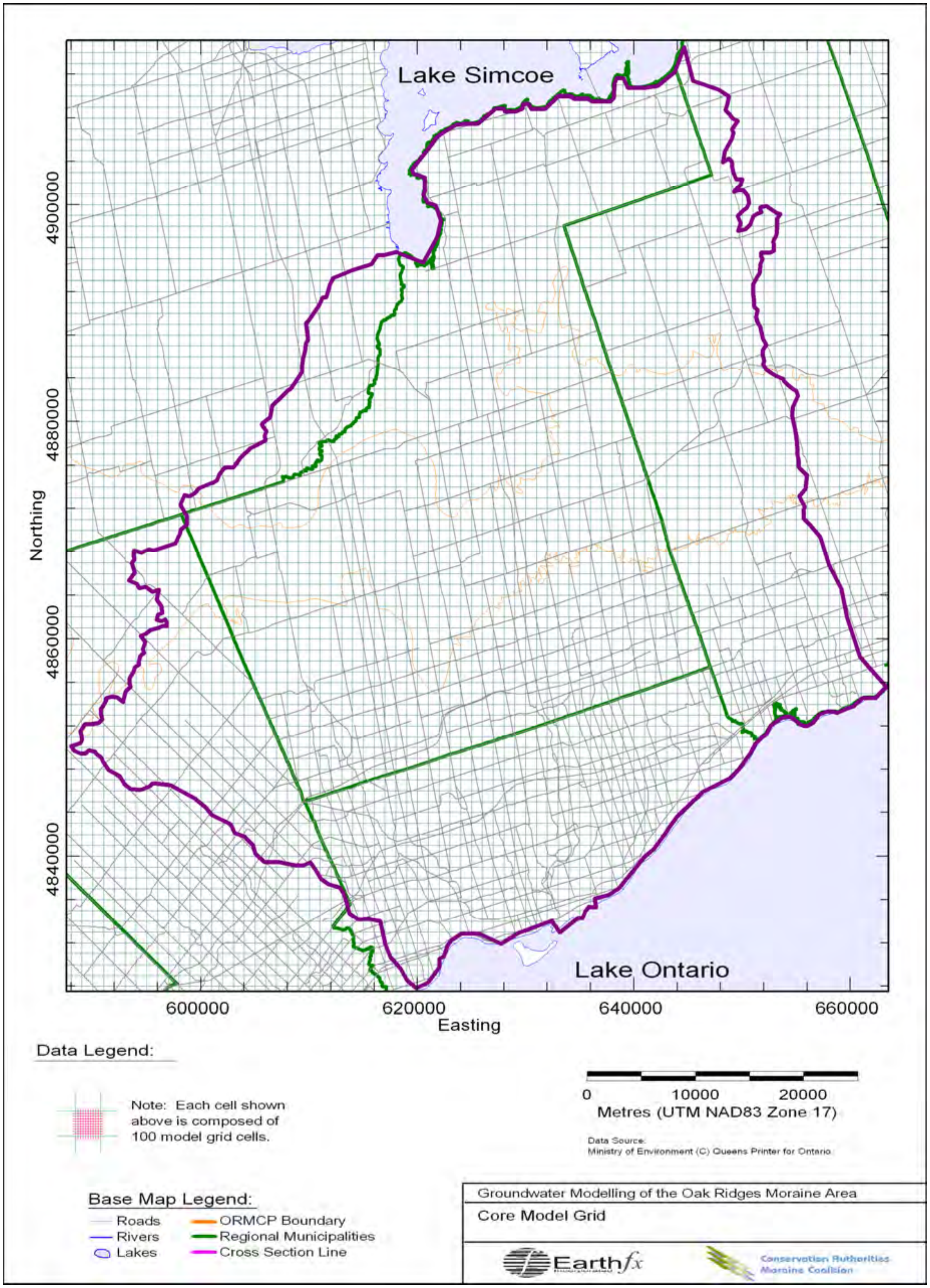

Figure 84: Core Model grid

7.2 Model Layers

Regional hydrostratigraphy was based on geologic layering defined by the Geologic Survey of Canada and revised as described in Section 3. Eight layers were used in the Core Model to represent the following hydrostratigraphic units:

Layer 1: Surficial Deposits and/or weathered Halton/Kettleby Aquitard

Layer 2: Halton/Kettleby Aquitard

Layer 3: Oak Ridges Aquifer Complex and/or weathered Newmarket Aquitard

Layer 4: Newmarket Aquitard

Layer 5: Thorncliffe Aquifer Complex

Layer 6: Sunnybrook Aquitard

Layer 7: Scarborough Aquifer Complex

Layer 8: Weathered Bedrock

A north-south section through the Core Model study area is presented in **Figure 85** to illustrate the extent and relative thickness of the eight layers. The location of the Yonge Street section line is shown on **Figure 69**.

Land surface forms the uppermost model layer surface (i.e. top of Layer 1). Land surface topography was obtained from a 10-m Digital Elevation Model (DEM) prepared by the Ontario Ministry of Natural Resources (MNR). The DEM was re-sampled to the 100-m model grid. A shaded relief map of land surface topography is shown in **Figure 2**.

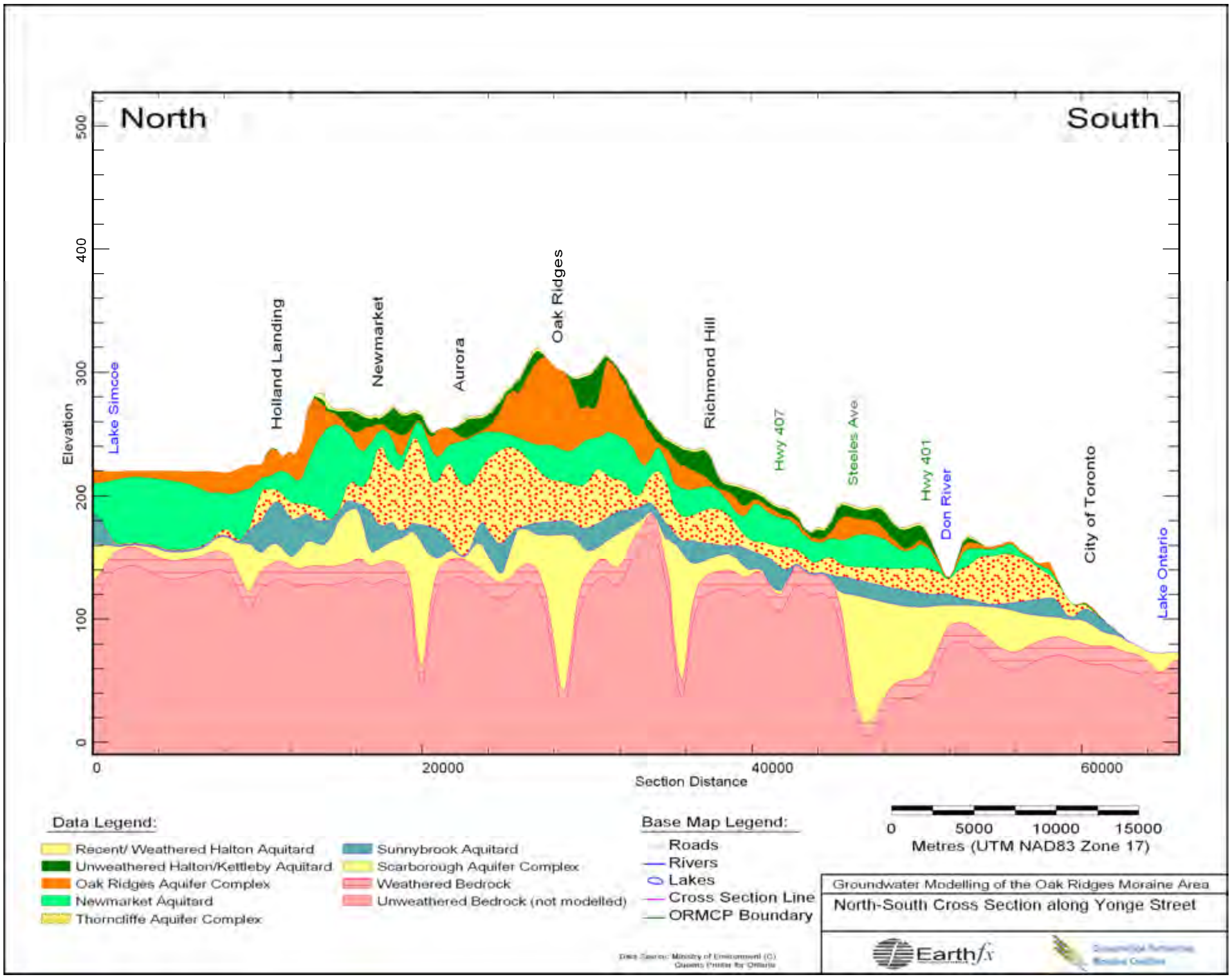

Figure 85: North-South cross section along Yonge Street through the Core Model

The MODFLOW code requires continuity of aquifer layers whereas the hydrostratigraphic model has units that pinch out. Where upper layers pinched out, the layer thickness was set to zero and the cells were designated as "inactive" (i.e. they were no longer considered part of the flow system). Model surfaces for intermediate layers were checked for zero thickness and a complex set of rules, described in Appendix D, was developed to make adjustments to aquifer tops and bottoms to ensure a minimum one-metre thickness everywhere. Aquitard layers were also assigned a minimum 1-m thickness where they pinched out, but hydraulic properties of the underlying aquifer were assigned to the cells in the pinch-out areas. Adjustments were also made to the hydraulic properties of the confining units to account for weathering where they are exposed. The model layer geometry shown in **Figure 85** reflects the minor adjustments made to ensure layer continuity (for comparison, see the hydrostratigraphic cross section in **Figure 47**).

7.3 Model Boundaries

The Core Model area is bounded to the west by the western edges of the Mimico Creek, Humber River and Holland River watersheds and to the east by the eastern edges of the Duffins, Carruthers and Uxbridge Creek watersheds. The model extends southward from Lake

Simcoe to Lake Ontario. Cells outside the model boundaries were marked as being “inactive” and were excluded from model calculations.

MODFLOW can represent three general types of conditions along the physical boundaries of the model, as described in Section 6. All three boundary condition types, constant head; no-flow, and head-dependent discharge boundaries, were employed in the Core Model. Boundary conditions for Layer 8, the active bedrock layer, are shown in **Figure 86**. Boundary conditions for the other layers are nearly identical but varied slightly where some of the upper layers pinch out.

7.3.1 Constant Head Boundaries

Cells bordering Lake Ontario and Lake Simcoe were treated as constant head boundaries in all model layers. The water elevations at the constant head cells along Lake Ontario were set at 75.2 masl and 219.0 masl at Lake Simcoe. A constant head boundary was also used where the model boundary crosses the buried bedrock valley at Caledon (**Figure 86**). This constant head boundary condition was applied to cells in the Thorncliffe Aquifer Complex, Scarborough Aquifer Complex, and the weathered bedrock. An elevation of 280 masl was assigned to these cells based on observed water levels. Specifying the head at the boundary allowed the model to determine the rate of underflow into or out of the model area. Post-simulation mass balances were analyzed to ensure that the simulated flow rates across the boundary remained within reasonable ranges.

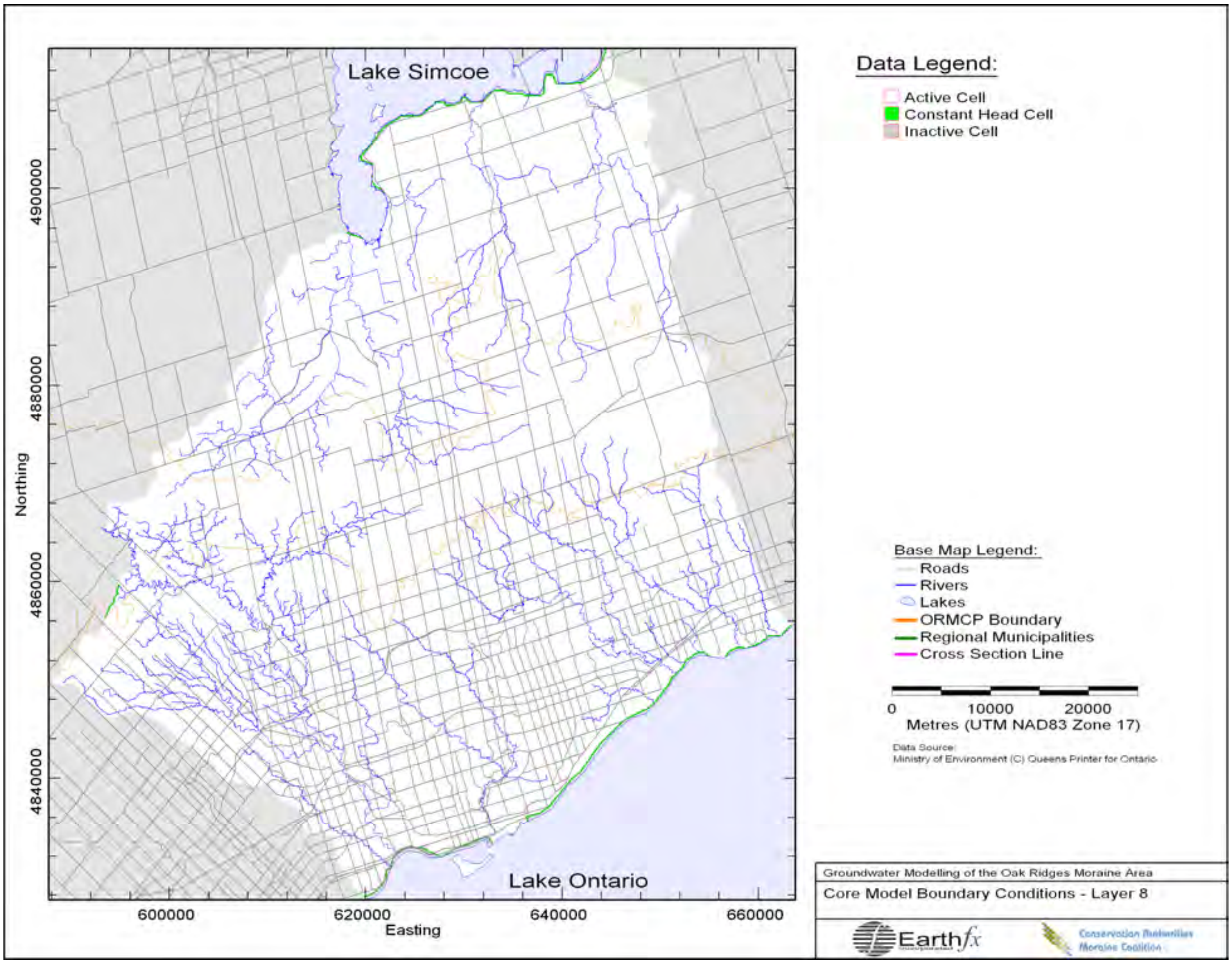

Figure 86: Model boundary conditions for Layer 8 (weathered bedrock)

7.3.2 No-Flow Boundaries

A no-flow boundary condition was applied along the eastern boundary of the model to represent the eastern edges of the Duffins Creek, Carruthers Creek and Uxbridge Creek watersheds. A no-flow boundary condition was also imposed along the west side to represent the western edges of Mimico Creek, the upper Humber River, and the Holland River watersheds. The western part of the upper Humber River watershed was not represented in this version of the model because the geology is still being refined in the area near the Niagara Escarpment. A combination of inter-stream divides (no flow boundaries) and streamlines below major tributaries (also no flow boundaries) were used to represent the boundary as best as possible in the area where the model boundary cut off headwater tributaries of the upper Humber River.

A no-flow boundary condition was applied at the base of the lowest model layer. This boundary condition assumes that the bedrock below a 15-metre thick weathered zone was much less permeable than the weathered zone and did not contribute significantly to the flow system.

As noted earlier, geologic units are not continuous everywhere in the model area. Where upper layers were missing, the layer thickness was set to zero and the cells were designated as “inactive”. No flow can occur to or from inactive cells. However, recharge to an inactive cell was allowed to pass down to the uppermost active cell.

Cells in the model can go "dry" during a simulation if the water table drops below the base of an active layer. The number of dry cells and their locations varied in each model simulation in response to changes in model input data. The MODFLOW "re-wetting" option (McDonald et al., 1991) was used to allow a dry cell to reactivate. Re-wetting parameters were modified during the course of the calibration to improve model stability and to speed model convergence (see Appendix D).

7.3.3 Groundwater-Surface Water Interaction – Head-Dependent Boundaries

MODFLOW uses several types of head-dependent discharge boundaries to simulate groundwater/surface water interaction. Two important boundary types are referred to in MODFLOW terminology as "rivers" and "drains". MODFLOW drains were described in Section 6 and were used in the Core Model to simulate discharge to the headwater tributaries of the streams (Strahler Class 1 and 2 and all stream reaches within Layer 1). Drain conductances and drain elevations were specified for each drain segment (i.e. the part of a stream reach contained within a model cell).

MODFLOW rivers were used to simulate discharge to the lower reaches of major streams (Strahler Class 3 and above). The key assumption regarding MODFLOW rivers is that leakage can occur in either direction when the aquifer head is above the bottom elevation of the streambed (**Figure 87**). When aquifer heads drop below the base of the streambed, the river is assumed to be perched and water leaks out of the river at a constant rate based on the difference between the river stage and the elevation of the streambed bottom. A MODFLOW parameter, called the "river conductance", groups streambed properties and geometry terms in Equation 6.1. River conductance, river stage, and streambed bottom elevation values were assigned to each river segment.

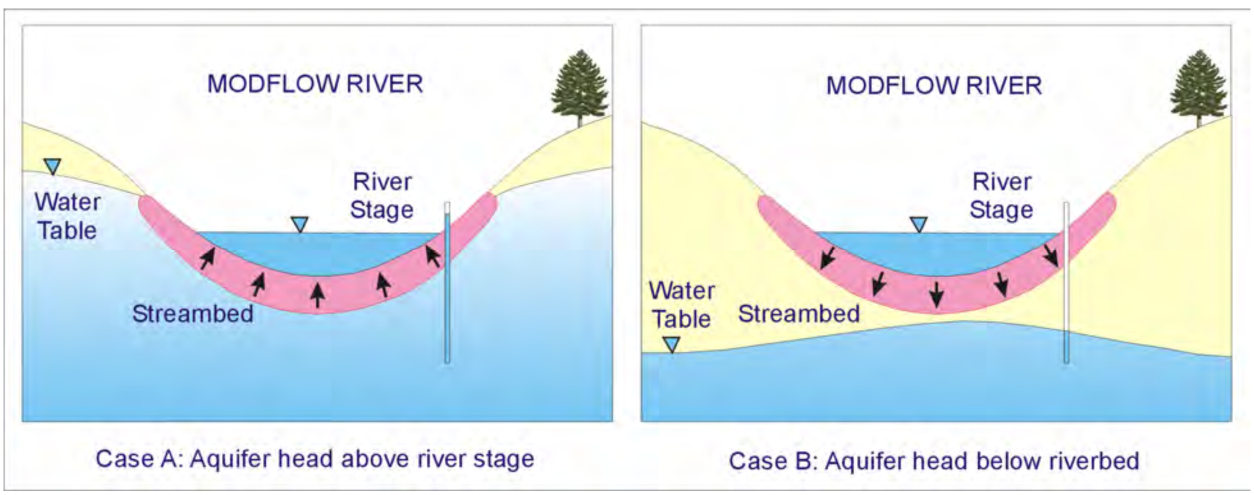

Figure 87: Cross section showing leakage between river and aquifer

As in the Regional Model, some simplification was necessary to automate the process of assigning stream properties. Stream reaches were first assigned a Strahler classification number and then each stream reach was assigned an average width and bed thickness (B') based on the Strahler number. Segments were assigned a streambed hydraulic conductivity (K') value related to the aquifer layer it penetrated. Stream segments were split where they crossed from one aquifer layer to another. For example, if a stream reach started in an area where Layer 1 was present and then crossed into an area where Layer 3 outcropped, the stream reach was split at the transition point and the lower part of the reach was assigned to Layer 3. Drain and river conductance values were adjusted slightly during model calibration. Streambed conductance (K'/B') was in the range of silt to silty-fine sand, as shown in **Table 10**.

Table 10: River and drain properties used in the Core Model

Strahler Code	Aquifer Layer	MODFLOW Package	Streambed Conductance (s^{-1})	Streambed Thickness (m)	Stream Width (m)	Surface Water Elevation (masl)
1	1	DRAIN	5×10^{-06}	1	1	DEM - 0.5 m
1	3	DRAIN	5×10^{-06}	1	1	DEM - 0.5 m
1	5	DRAIN	5×10^{-06}	1	1	DEM - 0.5 m
1	7	DRAIN	5×10^{-06}	1	1	DEM - 0.5 m
2	1	DRAIN	5×10^{-06}	1	2	DEM - 0.5 m
2	3	DRAIN	5×10^{-06}	1	2	DEM - 0.5 m
2	5	DRAIN	5×10^{-06}	1	2	DEM - 0.5 m
2	7	DRAIN	5×10^{-06}	1	2	DEM - 0.5 m
3	1	DRAIN	5×10^{-06}	1	4	DEM - 0.5 m
3	3	RIVER	5×10^{-06}	1	4	DEM - 0.5 m
3	5	RIVER	5×10^{-06}	1	4	DEM - 0.5 m
3	7	RIVER	5×10^{-06}	1	4	DEM - 0.5 m
3	8	RIVER	5×10^{-07}	1	4	DEM - 0.5 m
4	1	DRAIN	5×10^{-06}	1	6	DEM - 0.5 m
4	3	RIVER	5×10^{-06}	1	6	DEM - 0.5 m
4	5	RIVER	5×10^{-06}	1	6	DEM - 0.5 m
4	7	RIVER	5×10^{-06}	1	6	DEM - 0.5 m
5	1	DRAIN	5×10^{-06}	1	8	DEM - 0.5 m
5	3	RIVER	5×10^{-06}	1	8	DEM - 0.5 m
5	5	RIVER	5×10^{-06}	1	8	DEM - 0.5 m
5	7	RIVER	5×10^{-06}	1	8	DEM - 0.5 m
6	1	DRAIN	5×10^{-06}	2	15	DEM - 0.5 m
6	3	RIVER	5×10^{-07}	2	15	DEM - 0.5 m
6	5	RIVER	5×10^{-07}	2	15	DEM - 0.5 m
6	7	RIVER	5×10^{-06}	2	15	DEM - 0.5 m
6	8	RIVER	5×10^{-07}	2	15	DEM - 0.5 m
7	3	RIVER	5×10^{-06}	4	30	DEM - 0.5 m
7	5	RIVER	5×10^{-06}	4	30	DEM - 0.5 m
7	7	RIVER	5×10^{-06}	4	30	DEM - 0.5 m
7	8	RIVER	5×10^{-07}	4	30	DEM - 0.5 m

Line segments representing all streams on the digital maps supplied by MNR were imported into VIEWLOG. The length of each drain and river segment within a cell was obtained by "intersecting" the model grid with the line segments representing the streams. Initially, controlling drain and river elevations were estimated from the 100-m DEM. Interpolation errors, caused by using the elevation at the centre of the cell to control drains that crossed through edges of the cells, introduced mass-balance errors and led to model instability. To resolve this issue, the 10-m DEM was used in estimating controlling drain and river elevations. This eliminated much of the mass balance and stability problems. VIEWLOG calculated the conductance values and, after processing each drain and river segment, created the two input data files for MODFLOW. A total of 51,440 drain segments and 12,739 river segments were used in the Core Model.

7.3.4 Groundwater Recharge

Average precipitation, measured at 48 stations in the study area with periods of record greater than eight years during 1980 to 2002, ranged between 734 mm/a and 946 mm/a (Environment Canada, 2002). **Figure 88** shows station locations and a colour-scale plot of the observed values interpolated to the model grid. Higher values generally occur in the eastern and northern part of the study area. Highest values occurred on the east side of Cooks Bay and may reflect local influence of lake-effect rain and snow from Lake Simcoe. Lowest values were observed in the Toronto area and may be affected by microclimates in the urban area.

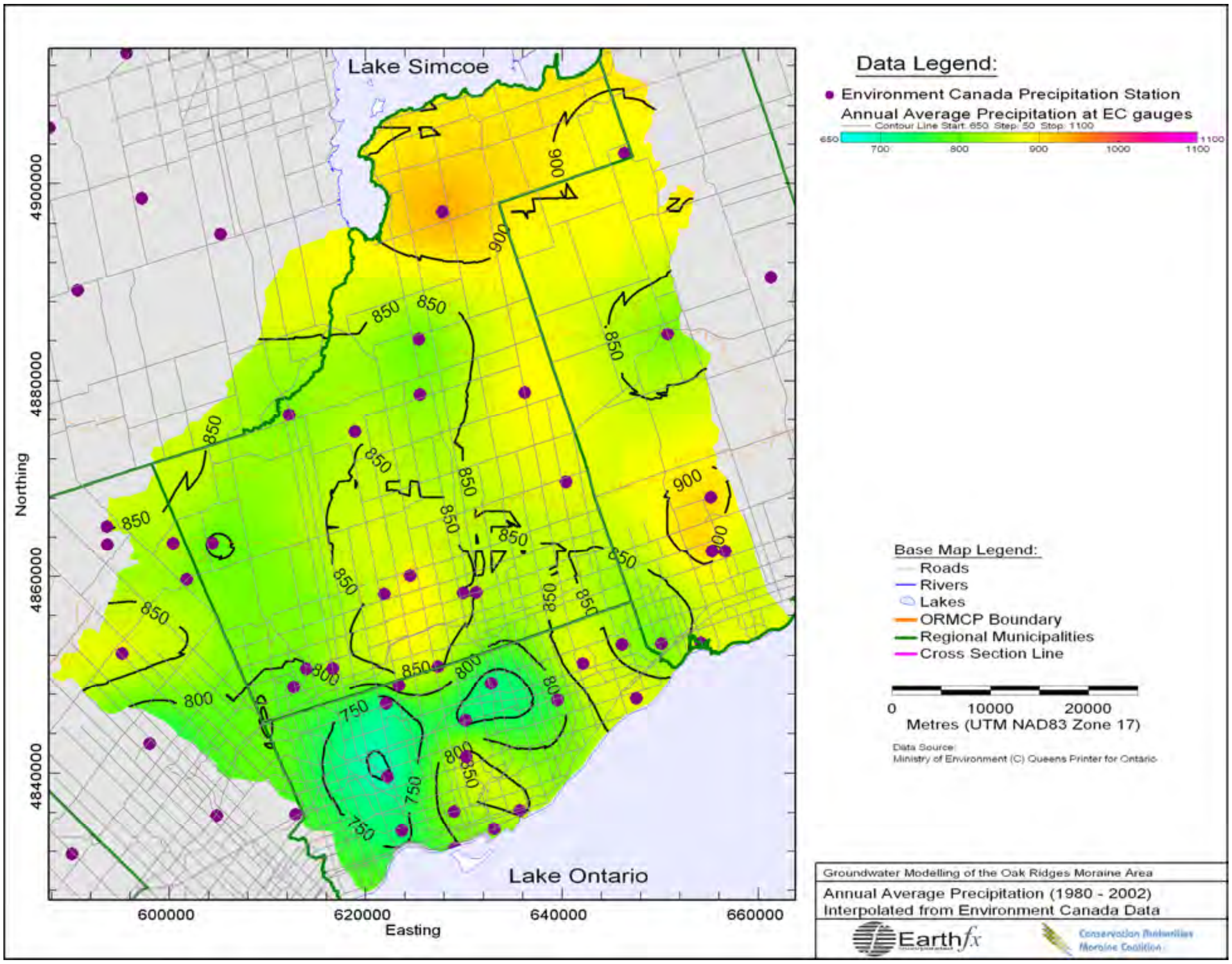

Figure 88: Annual average precipitation 1980-2002

Applying the Thornthwaite water balance equation (Thornthwaite and Mather, 1955), the annual potential evapotranspiration (PET) was estimated to vary between 575 to 603 mm/a (Environment Canada, 2002), with a value of 580 mm/a covering most of the area. The average water surplus (i.e. precipitation minus actual ET) varied between 193 mm/a in the Toronto area to 290 mm/a in the East Gwillimbury area. Part of the water surplus ends up as surface runoff to area streams while the balance infiltrates through the soil profile and may eventually recharge the groundwater system. The Thornthwaite method is a very simple method of calculating PET and water surplus and it does not account for local variations in precipitation, snowmelt, soil type, land surface topography, and land use which can affect actual ET, runoff and recharge rates. This likely accounts for the discrepency between the recharge rates used to calibrate the model, which are sometimes greater than the estimated water surplus.

Data on land use, climate, and soil properties were analyzed to provide initial estimates of the spatial distribution of groundwater recharge. The initial estimates of annual average net recharge were supplied as input to the MODFLOW model and adjusted during model calibration. Calibrated values are listed in **Table 11**. Spatial distribution of recharge is shown in **Figure 89**. As can be seen, the primary influence on the recharge distribution was surficial geology. Areas with hummocky topography were assigned higher recharge rates since the runoff that would be generated from these soils is focused into the bottoms of depressions where it can readily infiltrate through the surficial soils. Tills in the northern part of the study area were assigned slightly higher recharge rates due to the flatter topography. Recharge rates in urban areas were reduced compared to those in rural areas to account for the higher runoff generated by roads, rooftops, and other impervious surfaces. More complex recharge models are planned for the next phase of model development to refine these estimated recharge rates.

Table 11: Annual average recharge rates used in the calibrated Core Model

Surficial Material	**Recharge (mm/a)**
Glacial Lake Sands	180
Glacial Lake Silts and Clays	90
Other Recent Deposits	160
Halton Till – Hummocky Topography	360
Halton Till – North of Moraine	120
Halton Till – South of Moraine	90
ORM Deposits – Hummocky Topography	420
ORM Deposits – Non-Hummocky Topography	320
Newmarket Till	30
Lower Sediments/Weathered Bedrock	30
Urban Areas – recharge value factor	60%

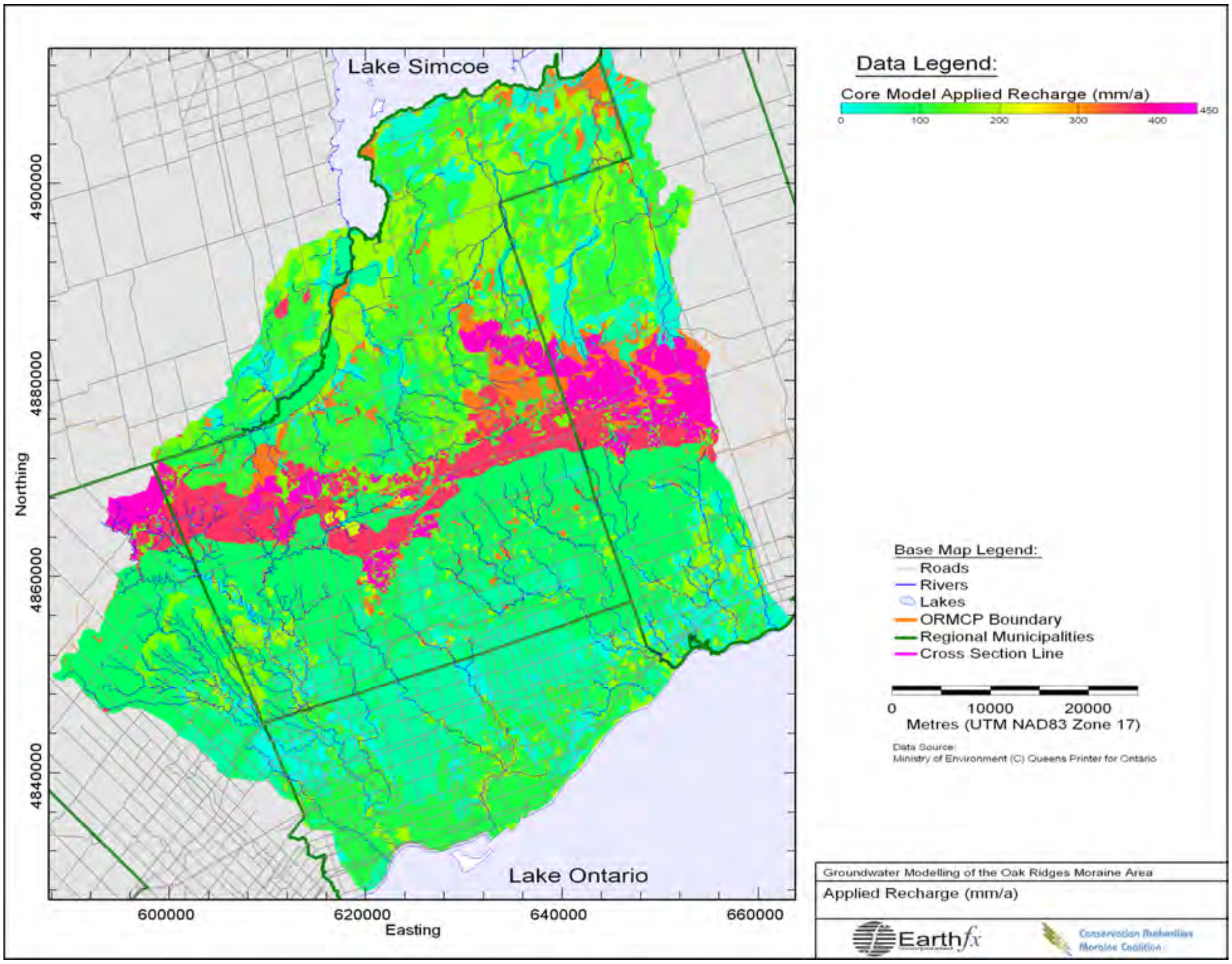

Figure 89: Distribution of applied recharge in the Core Model

7.3.5 Groundwater Extraction

Groundwater is extracted from the aquifers in the study area for municipal water supply, agricultural use, industrial use, golf course irrigation, and private (domestic) water supply. Rates of use over 50,000 litres of water per day from a surface or groundwater source are regulated by the Ministry of Environment through Permits to Take Water (PTTW). Actual water use is generally less than the permitted water takings.

7.3.5.1 Municipal Wells

York Region currently operates 37 municipal wells to supply Newmarket, Aurora, Holland Landing, Sharon, and Queensville in the Yonge Street area and the towns of Ansnorveldt, Ballantrae, King City, Kleinberg, Mt. Albert, Nobleton, Stouffville, and Schomberg. For each well or wellfield the PTTW specifies limits on the average and peak pumping rates. In addition, the Yonge Street wells have a cumulative average daily limit of 42,000 cubic metres per day (m^3/d) Some of the wells are considered standby wells (for example, Sharon-Queensville Well 2 generally operates only when Well 1 is off-line). Municipal wells operated by the City of Bradford (Simcoe County) and the Region of Durham (Uxbridge and Uxville) and Peel (Palgrave and Bolton) were also simulated in the Core Model. A list of municipal wells and their average pumping from 1990 to 2002, along with permitted rates are provided in **Table 12**. Well locations are shown in **Figure 90**. Some of the wells, such as the Oak Ridges Wells 1-3, Newmarket Wells 9 and 11, and Bolton 3-6a are currently inactive.

Wells were assigned to different aquifers based on their screen settings. In the calibration, York Region municipal wells were pumped at their average reported rates. Other wells, such as Uxbridge and Bradford, did not have pumping data in the database and were pumped at their permitted rates.

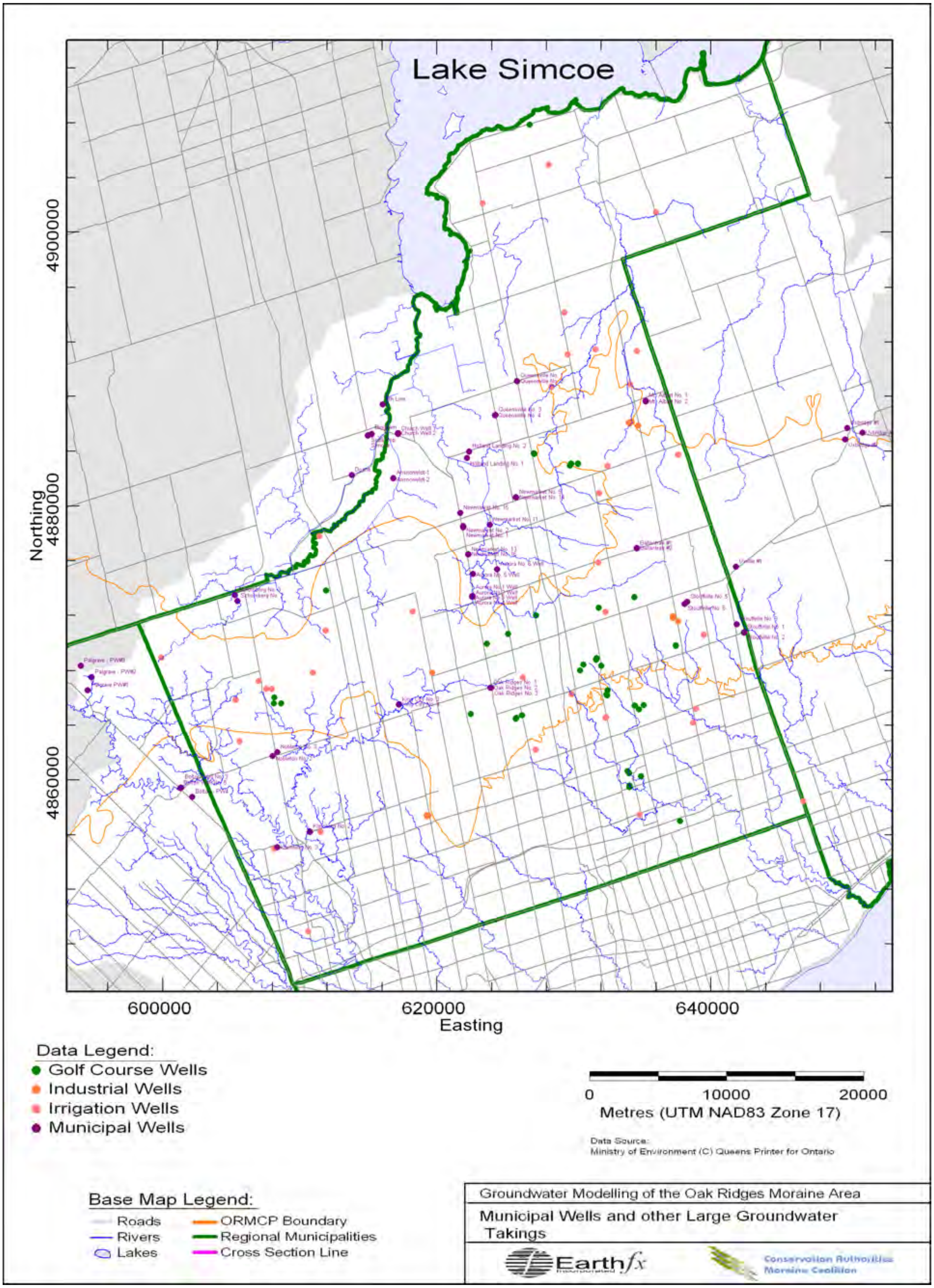

Figure 90: Location of municipal wells and other large groundwater takings

Table 12: Municipal water takings

Well Name	Region	Aquifer Layer Assignment	Simulated Average Pumping (m^3/d)	Simulated Maximum Permitted Pumping (m^3/d))
Ansnorveldt-1	York	SAC	22.46	144.29
Ansnorveldt-2	York	SAC	42.34	184.03
Aurora-1	York – YSA	TAC	171.07	3272.83
Aurora-2	York – YSA	TAC	2316.38	5889.89
Aurora-3	York – YSA	TAC	2870.21	5238.43
Aurora-4	York – YSA	TAC	4698.43	7855.49
Aurora-5	York – YSA	SAC	2516.83	5889.89
Aurora-6	York – YSA	TAC	1391.90	3456.00
Ballantrae #1	York	TAC	84.67	2190.24
Ballantrae #2	York	TAC	469.15	2190.24
Holland Landing-1	York – YSA	TAC	563.33	2289.60
Holland Landing-2	York – YSA	SAC	1886.98	3600.29
King City 3	York	TAC	949.54	1963.87
King City 4	York	TAC	960.77	2618.78
Kleinberg 2	York	TAC	98.50	237.60
Kleinberg 3	York	SAC	761.18	3283.20
Mt. Albert-1	York	TAC	532.22	3264.19
Mt. Albert-2	York	TAC	368.93	3264.19
Newmarket-1	York – YSA	TAC	1016.06	2291.39
Newmarket-2	York – YSA	TAC	2649.89	4581.79
Newmarket-9	York – YSA	ORAC	67.39	0.00
Newmarket-11	York – YSA	SAC	490.75	0.00
Newmarket-13	York – YSA	SAC	3486.24	5890.75
Newmarket-14	York – YSA	ORAC	247.97	0.00
Newmarket-15	York – YSA	SAC	1775.52	3272.83
Newmarket-16	York – YSA	SAC	3432.67	5631.55
Nobleton 2	York	SAC	163.30	0.00
Nobleton 3	York	SAC	786.24	1963.87
Oak Ridges 1	York	ORAC	196.13	0.00
Oak Ridges 2	York	ORAC	1005.70	0.00
Oak Ridges 3	York	ORAC	1361.66	0.00
Sharon-Queensville-1	York – YSA	TAC	1969.92	6544.80
Sharon-Queensville-2	York – YSA	TAC	1701.22	0.00
Sharon-Queensville-3	York – YSA	SAC	3203.71	6544.80
Sharon-Queensville-4	York – YSA	SAC	2970.43	0.00
Schomberg-2	York	SAC	33.70	1636.42
Schomberg-3	York	SAC	391.39	2289.60
Stouffville #1	York	TAC	415.58	1657.15
Stouffville #2	York	TAC	495.94	1657.15
Stouffville #3	York	ORAC	1666.66	1657.15
Stouffville #5	York	ORAC	1643.33	1526.69
Stouffville #6	York	ORAC	1351.30	2073.60
Church Well #1	Simcoe - Bradford	SAC	1641.60	1637.28
Church Well #2	Simcoe – Bradford	SAC	4320.00	4911.84
Soda Pop	Simcoe – Bradford	SAC	786.24	786.24
8th Line	Simcoe – Bradford	SAC	864.00	1637.28

Well Name	Region	Aquifer Layer Assignment	Simulated Average Pumping (m^3/d)	Simulated Maximum Permitted Pumping (m^3/d))
Bingham	Simcoe – Bradford	TAC	587.52	589.25
Simcoe	Simcoe – Bradford	TAC	864.00	1046.30
Doane	Simcoe – Bradford	TAC	2592.00	2617.92
Uxbridge #1	Durham	ORAC	0.00	750.82
Uxbridge #5	Durham	TAC	900.29	2251.58
Uxbridge #6	Durham	TAC	1481.76	3002.40
Uxville-1	Durham	ORAC	9.50	1900.80
Bolton PW3	Durham	SAC	805.25	805.25
Bolton PW4	Peel	SAC	1144.80	1144.80
Bolton PW5	Peel	SAC	3054.24	3054.24
Palgrave 1	Peel	TAC	142.56	142.56
Palgrave 2	Peel	TAC	192.67	192.67
Total YSA Pumping			**41,900**	**72,250**
Total York Pumping			**100,457**	**199,607**
Total Simulated Pumping			**119,843**	**226,078**

7.3.5.2 Other Water Takings

Golder Associates Limited (GAL) and Marshall Macklin Monaghan (MMM) conducted a review of non-municipal water use in York Region (GAL, in review). Locations of wells, owners' names, and estimated water use are provided in their report. Wells extracting more than 17.3 m^3/d (12 L/min) were represented in the current version of the model and are shown in **Figure 90**. This ensured that all major PTTW holders, including those with permits for less than the required minimum (50m^3/d) were considered. Total pumping by category for the 90 larger water takings simulated in the model is shown in **Table 13**. The commercial/industrial category includes several wells used in aquaculture (trout ponds). Crop irrigation was considered separately from golf course irrigation in the Golder/MMM study. In their report, Golder spent considerable effort to ensure that the reported takings were representative of the actual water used. For example, where possible water takers were surveyed and where no contact could be made, reasonable assumptions were made. For example, golf course takings were considered to only occur over the summer months.

Table 13: Large non-municipal water takings in York Region

Water Use	Number of wells	Total Pumping (L/min)
Commercial/Industrial	12	10,616
Irrigation	39	1748
Golf Course	39	5689

No large water takings within the City of Toronto were incorporated into the model although there are likely several groundwater takings within the city. These will be incorporated following work to confirm these takings being undertaken by the TRCA.

7.4 Model Parameter Values

7.4.1 Aquitard Properties

As noted earlier, there is only limited information on the hydraulic properties of the confining units (Halton/Kettleby Aquitard, Newmarket Aquitard, and Sunnybrook Aquitard) and insufficient information to systematically vary the properties. Uniform properties were therefore assigned to the confining units based on the available field data, the results of previous modeling studies, and the results of the Regional Model calibration. The initial estimates used in the Core Model were varied during the model calibration process. Calibrated horizontal and vertical hydraulic conductivity values are presented in **Table 14**.

Table 14: Hydraulic conductivity values for aquitards (calibrated model)

Layer	Primary Model Layer	Horizontal Hydraulic Conductivity (m/s)	Vertical Hydraulic Conductivity (m/s)
Halton/Kettleby Aquitard	2	5.0×10^{-7}	1.5×10^{-7}
Weathered Halton/Kettleby Aquitard	1	5.0×10^{-6}	5.0×10^{-6}
Newmarket Aquitard	4	5.0×10^{-8}	1.0×10^{-8}
Newmarket Aquitard under ORM	4	5.0×10^{-8}	1.25×10^{-9}
Weathered Newmarket Aquitard	3	5.0×10^{-6}	5.0×10^{-6}
Tunnel Channel Silts	4	5.0×10^{-7}	1.0×10^{-7}
Sunnybrook Aquitard	6	5.0×10^{-8}	5.0×10^{-9}

Hydraulic conductivity of Layer 4 was adjusted in the tunnel channel areas (**Figure 91**). The Newmarket Aquitard was assumed to be missing in these areas but a degree of confinement of the lower units was still afforded by silt layers deposited in the tunnel channels. The higher vertical permeability of the silts (as compared to the Newmarket Till) allowed for a greater exchange of water between the Thorncliffe Aquifer Complex and the overlying units. The areas of high hydraulic conductivity in Peel Region and in Toronto (**Figure 91**) represent areas where the Newmark Till was thinner than 1 m. The average hydraulic conductivity of the underlying TAC was assigned to Layer 4 in these areas.

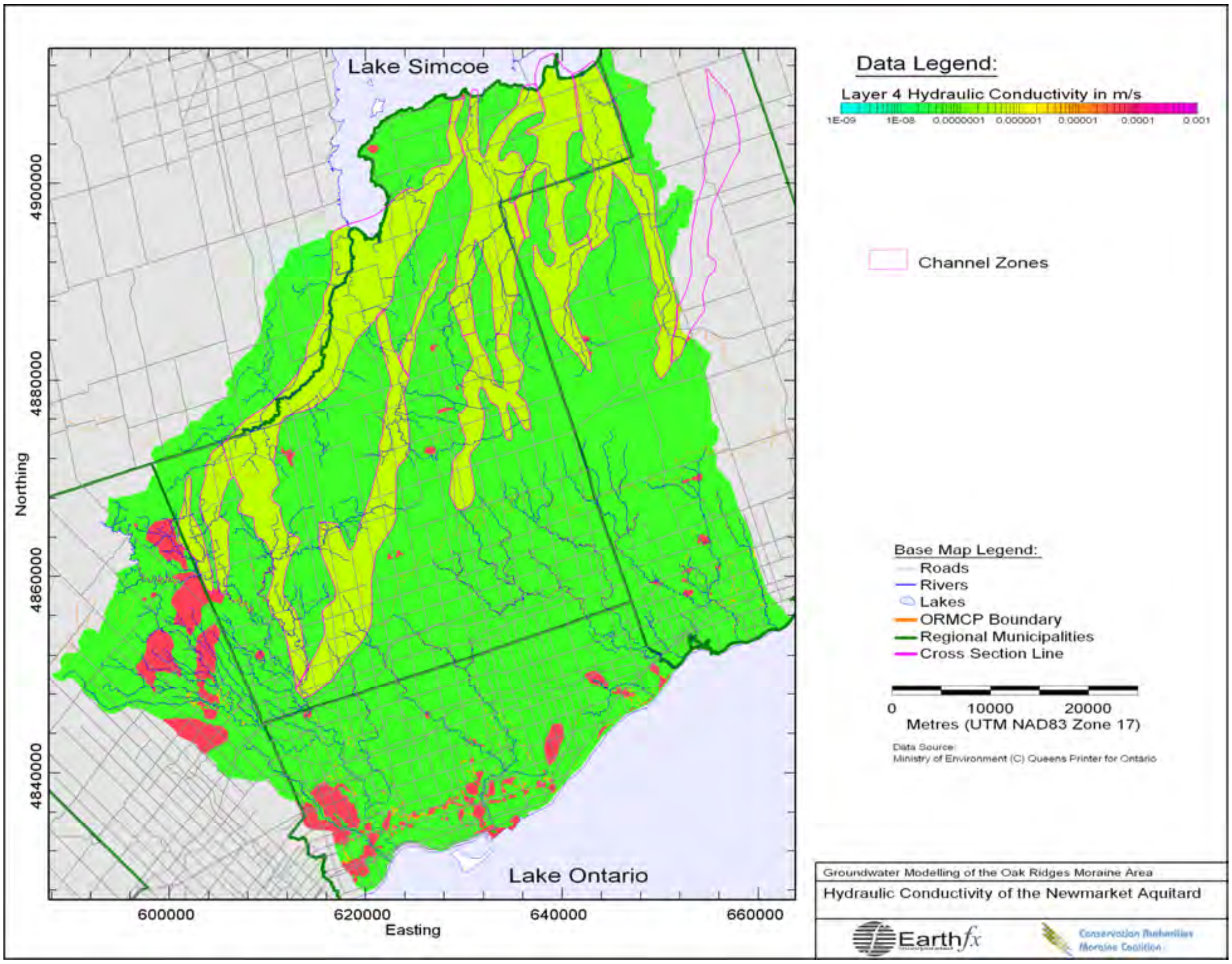

Figure 91: Hydraulic conductivity of the Newmarket Aquitard

As was the case with the Regional Model, the Core Model results also tended to be extremely sensitive to the vertical hydraulic conductivity of the Newmarket Aquitard and Sunnybrook Aquitard. A slight decrease in permeability below the calibrated value caused heads to increase sharply in the upper units and also resulted in insufficient flux to maintain heads in the lower aquifers. Model stability also degraded at these low hydraulic conductivity values. Conversely, a slight increase in vertical permeability caused the head difference between the two bounding aquifers to decrease to near zero and the model was unable to match the observed head differences between aquifer layers.

7.4.2 Aquifer Properties

Estimates of hydraulic conductivity for the aquifer layers in the Core Model were derived from the available well data. Several different methods were tested in the process of developing the model. These included estimating properties from (1) aquifer performance tests in the study area, (2) from specific capacity data and (3) from lithologic descriptions in the MOE database.

Of the three methods, the aquifer performance test data were presumed to have the greatest reliability. However, there are only a limited number of tests and the tests do not provide sufficient insight on the distribution of hydraulic conductivity on a regional scale. These transmissivity values were therefore used only to adjust aquifer properties in the vicinity of the municipal wellfields.

The MOE water well records include results of specific capacity tests conducted at the time of well installation. Specific capacity data were analyzed using a method described in Appendix D. Analysis of specific capacity offered greater spatial coverage than the aquifer test data. However, it was recognized that (1) the short duration tests provide only a local measurement of hydraulic conductivity in the vicinity of the well screen, (2) the results are biased upward since drillers typically set the well screen in the most productive zone they encounter, (3) the method is affected by the screen and gravel pack properties when testing highly permeable formations, and (4) the method makes a number of simplifying assumptions that may introduce errors. Nevertheless, maps produced using this method were surprisingly consistent and helped delineate areas of higher and lower permeability.

A method used by Martin and Frind (1998) to estimate hydraulic conductivities from lithologic logs in the Waterloo Moraine was modified and applied to this study. Equivalent horizontal hydraulic conductivities for each aquifer layer were estimated from the lithologic descriptions in the MOE well records through a series of steps described in Appendix D. The log (base 10) of the hydraulic conductivity estimates were interpolated to the model grid. Again, it was found that the results appeared to be much more continuous than first expected given the high variability of the data. The data appeared to spatially correlate reasonably well with the specific capacity data.

Several limitations to the method of using lithologic descriptions were recognized. For example, a “clay-sand” combination might refer to zones where alternate layers of sand and clay were encountered or, possibly, a zone of sandy clay. Russell and others (1998) noted that many drillers tend to report silts as clay. In addition, descriptors such as “fine sand” or “coarse gravel”, can provide useful information regarding the hydraulic conductivity of the material but these more detailed descriptors occur rarely within the database (i.e. most drillers simply report “sand” or ”gravel”).

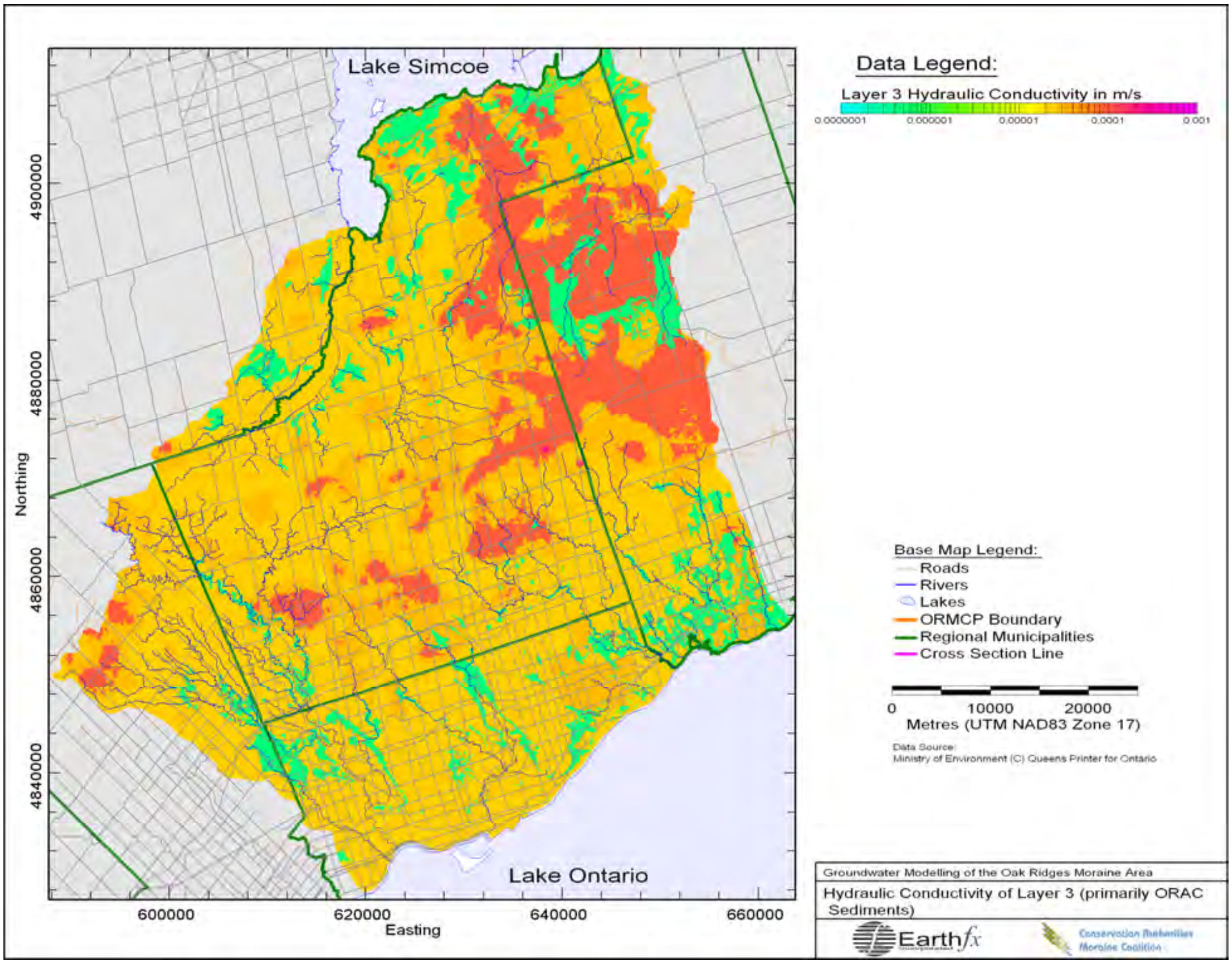

Figure 92: Hydraulic conductivity of Layer 3 (Primarily ORAC)

The lithologic material method (with corrections based on aquifer performance tests) was applied since it had the best spatial distribution and was felt to be more reliable than the specific capacity method. During model calibration, it was found that using the extreme high hydraulic conductivity values and extreme low values predicted by the method yielded heads that did not match observed data. Better results were obtained after the raw results were smoothed and the lowest values were adjusted upward and the highest values adjusted downward and when uniform values for anisotropy ratios (K_v/K_h) were used. A map of the final distribution of horizontal hydraulic conductivity in Layers 3, 5, and 7 are shown in Figure 92, Figure 93 and Figure 94, respectively.

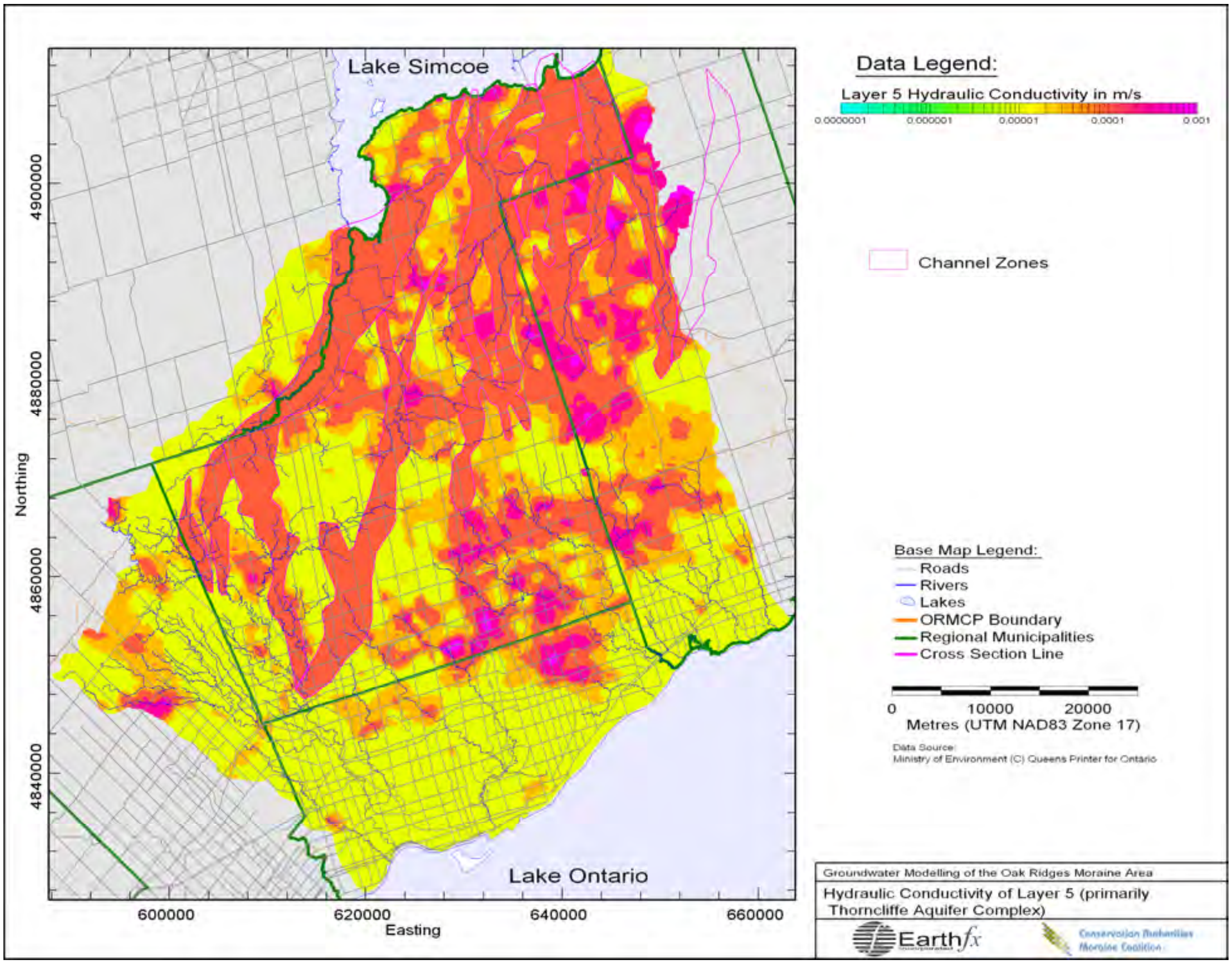

Figure 93: Hydraulic conductivity of Layer 5 (Primarily TAC)

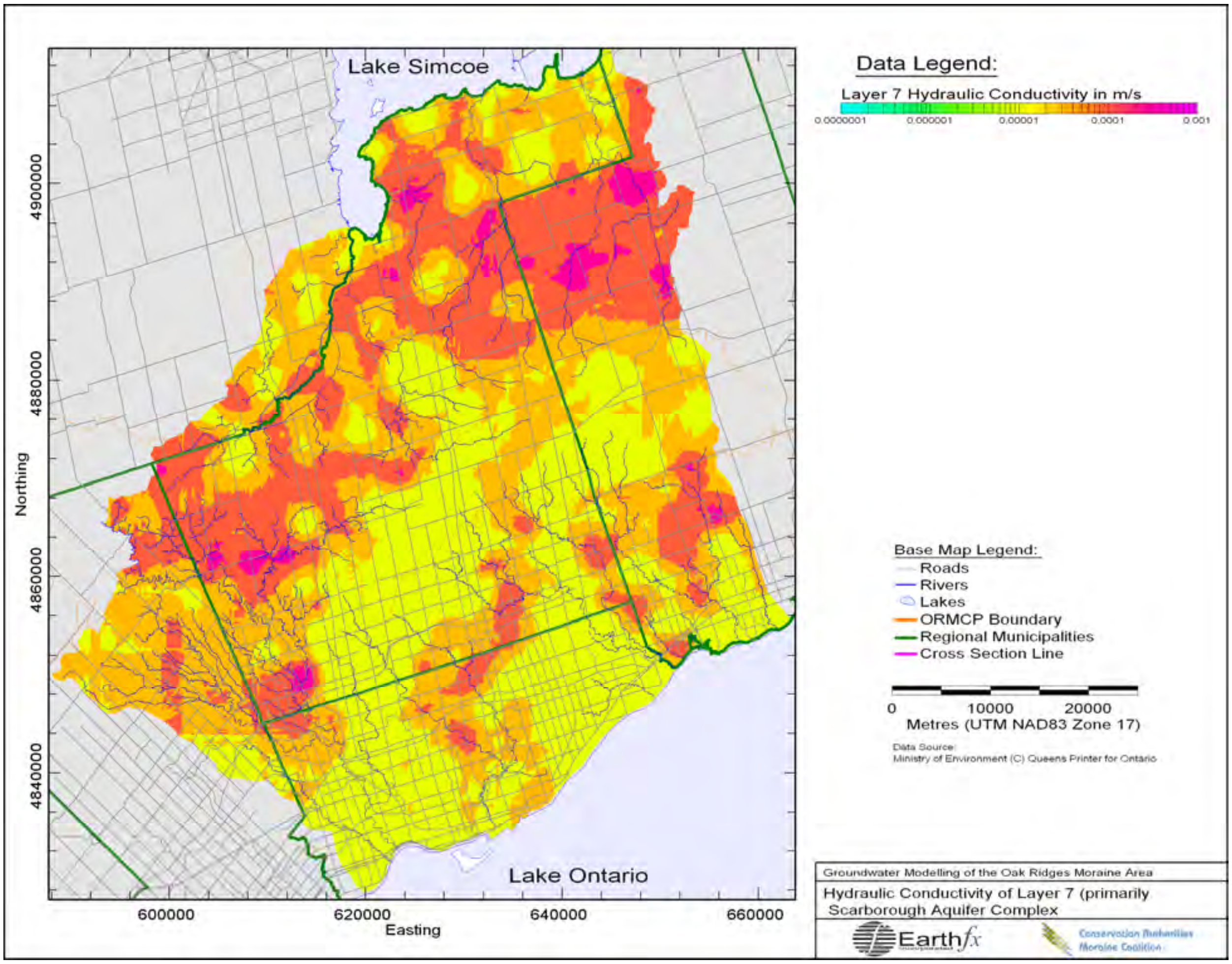

Figure 94: Hydraulic conductivity of Layer 7 (Primarily SAC)

7.4.3 Vertical Conductance

MODFLOW uses a "vertical conductance" term to control the exchange of water between model layers. The general formulation for calculating vertical conductance is given by McDonald and Harbaugh (1988) as:

$$VC_{UL} = \frac{2}{\dfrac{\Delta Z_U}{K_{zU}} + \dfrac{\Delta Z_L}{K_{zL}}} \qquad \text{(Eq. 7.1)}$$

where: VC_{UL} = vertical conductance between an upper and lower layer;
ΔZ_U = thickness of the upper layer
K_{zU} = vertical hydraulic conductivity the upper layer
ΔZ_L = thickness of the lower layer
K_{zL} = vertical hydraulic conductivity the lower layer

The vertical hydraulic conductivity of an aquifer layer, K_z, can be computed from the horizontal hydraulic conductivity as:

$$K_z = \alpha K_h \qquad \text{(Eq. 7.2)}$$

where α is the anisotropy factor (i.e. the ratio of vertical to horizontal hydraulic conductivity.

VIEWLOG was used to calculate a unique vertical conductance (VC) value for each cell in the active model grid (except for Layer 8 which does not need a VC term). Values were calculated based on the assigned hydraulic conductivity, anisotropy factor, and layer thickness. Calibrated values for the anisotropy factor (ratio of the vertical hydraulic conductivity to horizontal hydraulic conductivity) varied for each material as shown in **Table 15**.

Table 15: Anisotropy factors

Surficial Material	Anisotropy Value
Recent Deposits	1.0
Halton/Kettleby Aquitard	0.3
Weathered Halton/Kettleby Aquitard	1.0
ORAC Deposits	0.5
Newmarket Aquitard	0.2
Weathered Newmarket Aquitard	1.0
Newmarket Aquitard under the ORM	0.03
Tunnel Channel Silts	0.2
Tunnel Channel Fill (Layer 5)	1.0
Thorncliffe Aquifer Complex	0.5
Sunnybrook Aquitard	0.1
Scarborough Aquifer Complex	1.0
Weathered Bedrock	1.0

7.5 Calibration of the Core Model

7.5.1 Calibration to Static Water Levels and Baseflow

The calibration process is discussed in Appendix D. The primary target for model calibration was matching observed static water levels in the ORAC, Thorncliffe Aquifer Complex, and Scarborough Aquifer Complex. Static water levels from the MOE well records represent the most comprehensive, areally-extensive data set available. These data and the uncertainty associated with the measurements are discussed in Section 5. Over 17,200 records were used in the calibration. Daily water levels are also available for the observation well networks maintained by York Region, the Conservation Authorities, and the MOE but the number of wells and areal coverage of the data are limited. This data set was checked in the calibration process and will be used more extensively in calibrating a transient version of the model.

Potentiometric surface and water-table maps were prepared from the static water level data. Data were visually screened for obvious outliers prior to the interpolation of data to the model grid. **Figure 56** shows a potentiometric surface map for the ORAC, **Figure 60** shows a potentiometric surface map for the Thorncliffe Aquifer Complex, and **Figure 63** shows a potentiometric surface map for the Scarborough Aquifer Complex. An analysis of variance (Section 5) indicated that the systematic error in the data was likely around ±6 m for the ORAC, ±10 m for the Thorncliffe Aquifer Complex, and ±12 m for the Scarborough Aquifer Complex. Trying to match heads to a greater accuracy than these values may not be justified; therefore focus was placed on trying to match interpolated heads (which averaged out some of the error), flow patterns, and gradients rather than on matching absolute head measurements at each well.

Matching baseflow in the study area streams was a second calibration target. As discussed in Section 5, a baseflow separation technique was applied to the long-term streamflow data at all Environment Canada HYDAT gauges with sufficient record. **Table 3** lists estimated baseflow values used as calibration targets.

7.5.2 Simulated Heads and Baseflow

Figure 95 shows the simulated heads in the ORAC. Grey areas within the model boundaries represent areas where either the ORAC was absent or where the simulated ORAC heads dropped below the base of the aquifer. The simulated heads in the ORAC demonstrate a number of features that characterize the overall flow system:

1. there are two separate groundwater mounds that can be attributed to high recharge rates where the ORM has hummocky topography and is not covered by Halton Till;
2. heads south and north of the ORM are strongly influenced by the surface water system. Bending of contours around the streams indicates areas where groundwater discharges to the streams;
3. gradients are steeper on the south side of the moraine as flows must decrease from a maximum of 350 masl to 70 masl, while north of the ORM, heads decrease from 350 to 210 masl. Gradients are also flatter in the north because of the presence of many tunnel channels that have eroded the Newmarket Till providing better hydraulic connection with the Thorncliffe Aquifer Complex;
4. stream divides are followed fairly closely within the ORAC and cross-watershed flow occurs only in a limited number of areas.

Figure 96 shows the same simulated heads but with contours of the interpolated observed head overlain on the map. Although the figure is harder to read, it does show high correlation of the observed and simulated values over most of the study area.

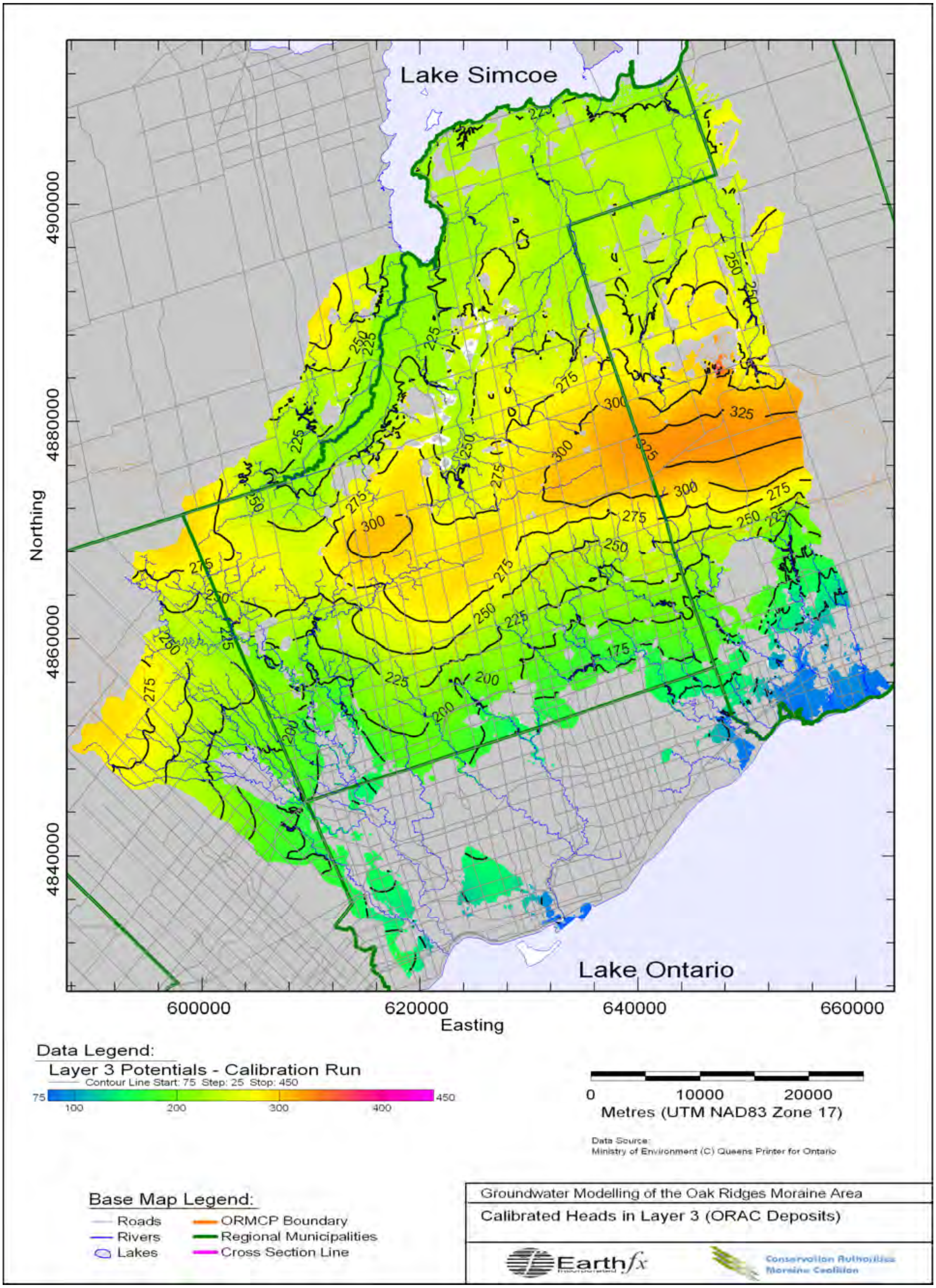

Figure 95: Calibrated heads in the ORAC.

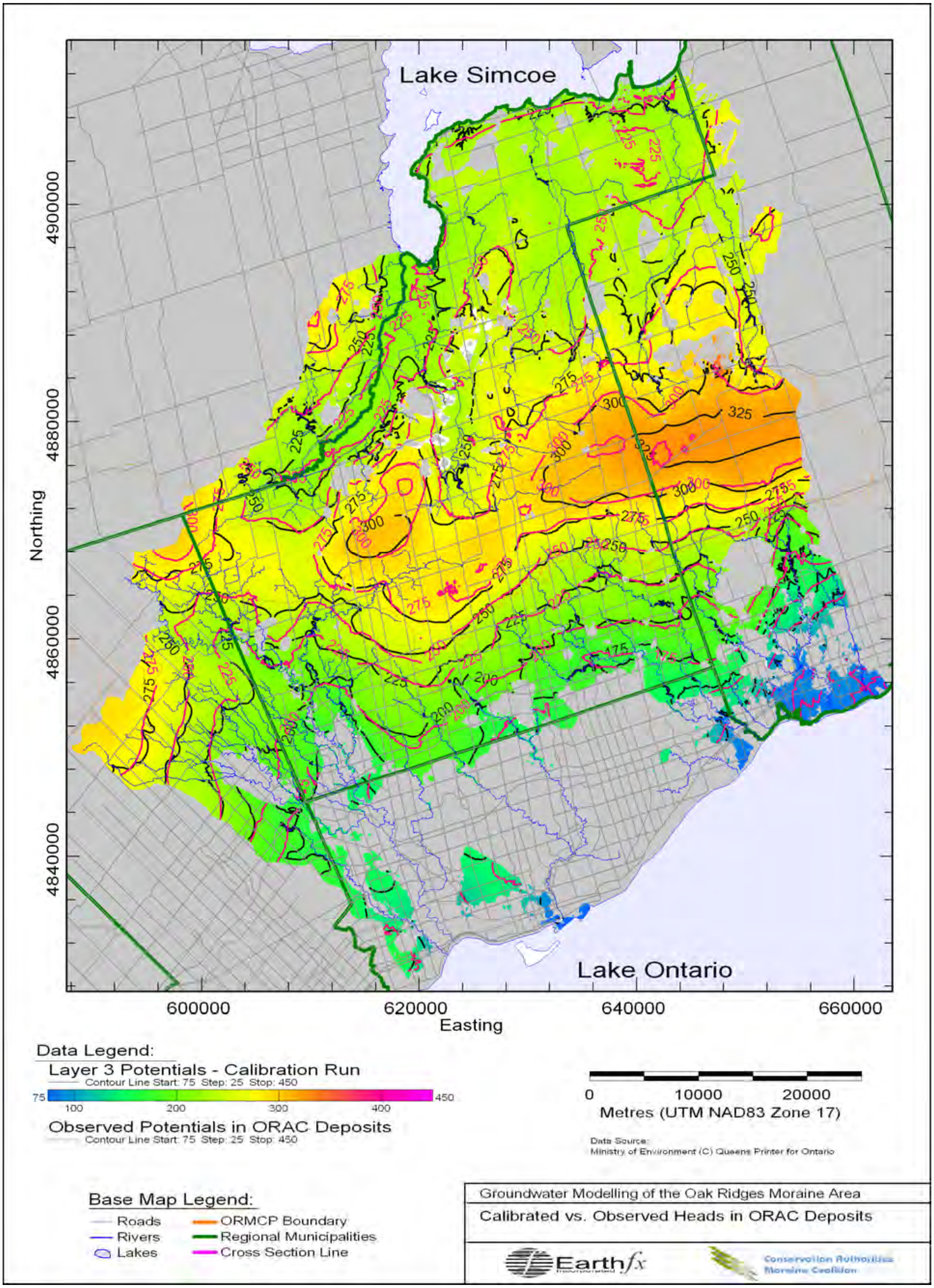

Figure 96: Calibrated versus observed heads in the ORAC

Figure 97 shows the simulated heads in the Thorncliffe Aquifer Complex. Heads beneath the moraine are significantly lower than in the ORAC (reaching a high of over 310 masl as compared to 330 m in the ORAC). Heads tend to be closer to the ORAC (or equivalent) values closer to Lake Simcoe and Lake Ontario. The groundwater mounds and regional groundwater divide in the TAC generally lie below the mounds and regional divide in the ORAC. Surface water divides are also reflected in the heads within the Thorncliffe Aquifer Complex. Cross watershed flows occur in the south where some of the smaller watersheds, such as Highland Creek and Petticoat Creek, intercept south flowing water from the larger watersheds with headwaters on the ORM and in the north where the Maskinonge River and other small streams intercept north-flowing groundwater from the Black River watershed. Other general features noted regarding the ORAC also apply to the TAC.

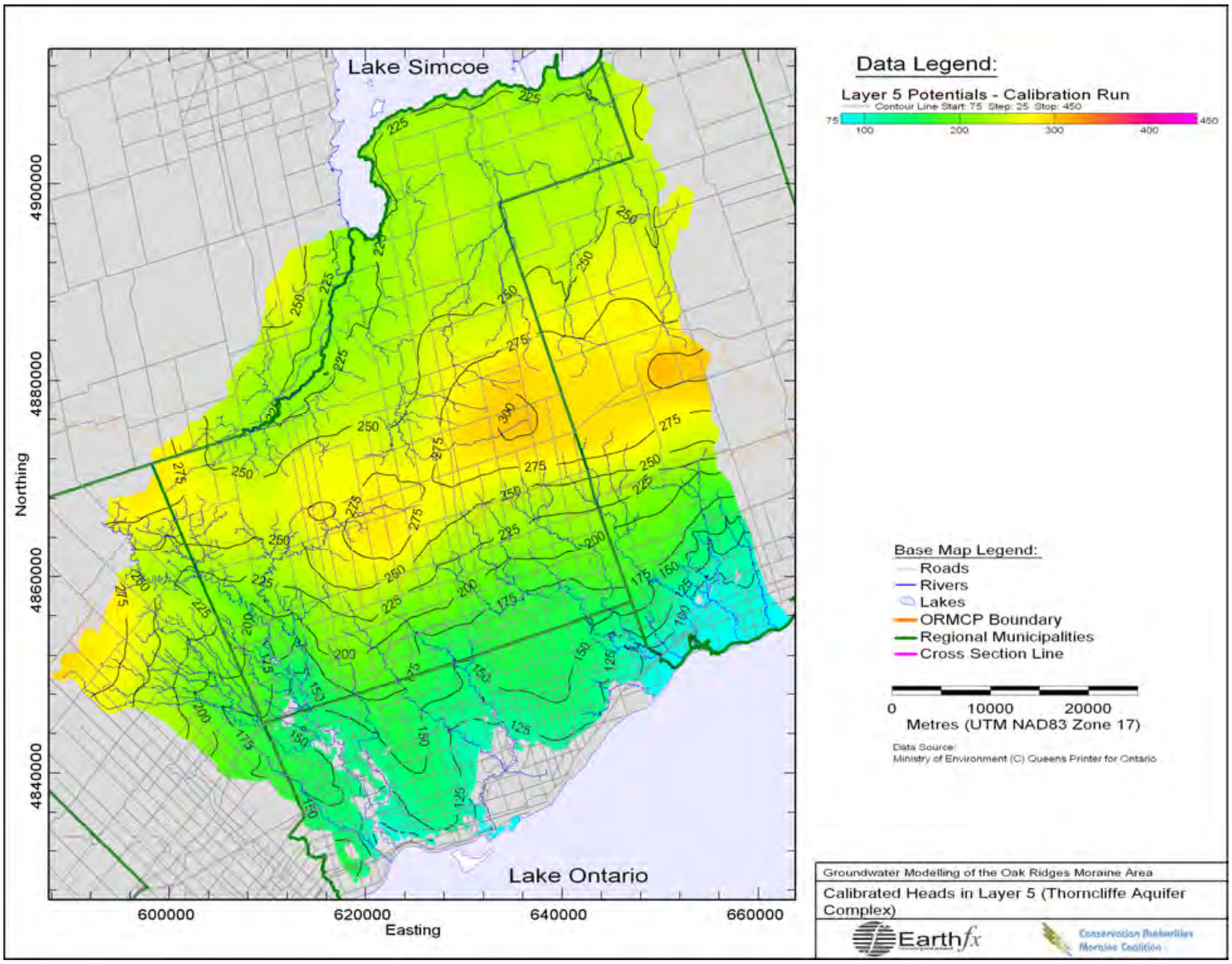

Figure 97: Calibrated heads in the Thorncliffe Aquifer Complex

Figure 98 shows the simulated heads in the Scarborough Aquifer Complex. Heads beneath the ORM are lower than in the Thorncliffe Aquifer Complex (reaching only about 300 masl). Flow patterns are altered by the presence of bedrock valleys where the Scarborough deposits tend to be thicker and more permeable (e.g. in the bedrock valleys underlying the present-day Don and Humber Rivers).

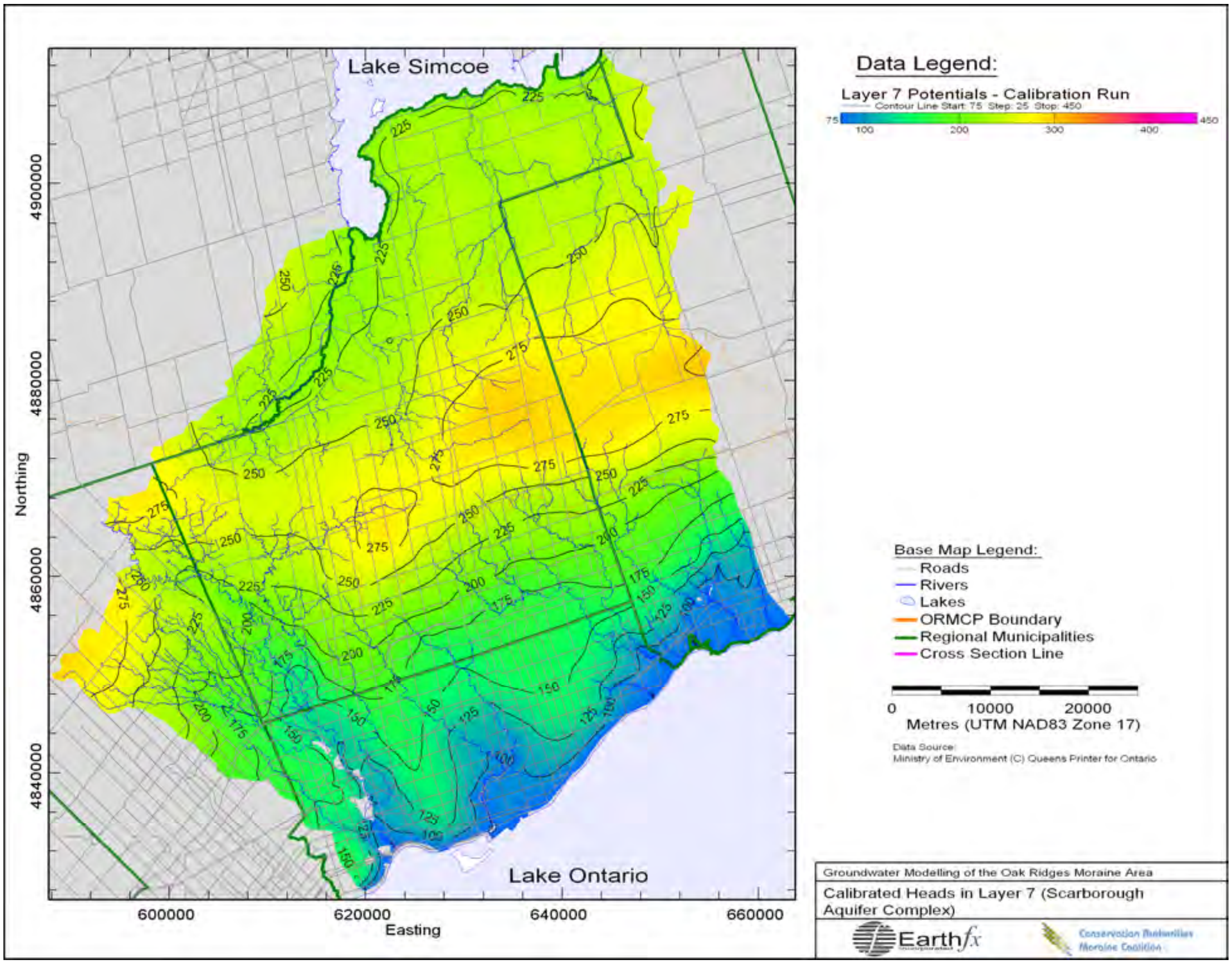

Figure 98: Calibrated heads in the Scarborough Aquifer Complex

7.5.3 Sub-Regional Mass Balance

A mass balance for the study area, as computed by the Core Model, is provided in **Table 16**

Flow Rates	m^3/s	% of Total
Inflows:		
Net Recharge	15.81	95.6
Constant Head Boundaries	0.06	0.4
Stream Leakage (to aquifer)	0.66	4.0
Outflows:		
Wells	1.02	6.1
Constant Head Boundaries	0.73	4.4
Stream Leakage (from aquifer)	14.94	89.5

Table 16: Simulated mass balance for the Core Model area

The table shows that almost all inflow is derived from recharge. Discharge to streams is the primary avenue of outflow from the model, with pumping (under average conditions) and underflow to Lake Simcoe and Lake Ontario a minor component of the overall water budget. Model mass balance errors were less than 1%.

Table 17 provides a breakdown of the simulated stream discharge by watershed. A small part of the flow is lost to minor streams that discharge directly to Lake Ontario or Lake Simcoe.

Table 17: Simulated groundwater discharge to streams by watershed

Watershed	Simulated Baseflow (m^3/s)	Area (km^2)	Equivalent Flow per Unit Area	% of Total Baseflow
Mimico Creek	0.17	76.2	70.4	1.2
Humber River	3.11	902.8		22.1
Don River	1.06	371.1		7.5
Highland Creek	0.15	97.6		1.1
Rouge River	1.39	327.6		9.9
Petticoat Creek	0.02	24.4		0.1
Duffins Creek	1.59	286.8		11.3
Carruthers Creek	0.15	38.6		1.1
Holland River	2.42	592.7	128.8	17.2
Maskinonge River	0.14	63.0		1.0
Amber Creek	0.02	6.6		0.1
Black River	1.71	319.2		12.2
Pefferlaw Brook	2.12	420.3		15.1
Total Simulated Baseflow	**14.05**	**3526.9**		

7.5.4 Calibration Statistics

Once a good qualitative match to the observed heads was obtained, it became difficult to visually evaluate the incremental improvements obtained by small changes in parameter values. Statistical measures of the “goodness-of-fit” were then used as a quantitative guide to improving the calibration.

Three calibration statistics were used to assess and demonstrate model accuracy; the mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE), as described in Section 6. Calibration statistics for heads in the three aquifers and baseflow values are presented in **Table 18**. The mean error should be close to zero if the residuals are randomly distributed. As expected, a better match was achieved for the ORAC where properties are better understood and more data are available. The negative sign on all the ME values indicated that simulated values are generally higher than the observed values. The MAE and RMSE provide a good estimate of the average magnitude of the difference between the observed and simulated values. The values are all close in value to the estimate of variance in the static water level data yielded by the variogram analysis (see Section 5).

Table 18: Calibration statistics for heads and baseflow

Model Result	Number of Wells (n)	ME (m)	MAE (m)	RMSE (m)
ORAC Heads	9,939	-0.41	7.13	9.50
Thorncliffe Aquifer Complex Heads	5,657	-2.31	8.09	11.1
Scarborough Aquifer Complex Heads	1,615	-5.5	8.74	13.62
Model Result	**Number of Gauges (n)**	**ME (m^3/s)**	**MAE (m^3/s)**	**RMSE (m^3/s)**
Baseflow	106	0.070	0.173	0.231

As discussed in Section 6, values for MAE and RMSE can be compared to the overall range in heads over the study area. The total range for the ORAC was close to 280 m (from 70 masl at the Lake Ontario Shore to 350 masl on the ORM) and about 250 m for the Thorncliffe Aquifer Complex and Scarborough Aquifer Complex. Accordingly, MAE ranged from 2.5% to 3.5% and RMSE ranged from 3.4% to 5.4% of the range which is smaller than 10% of the range, indicating an acceptable calibration.

Scatterplots of simulated versus observed heads were also drawn to determine whether errors were uniformly distributed and to help identify causes of the larger deviations. The scatterplots are shown in **Figure 99** through **Figure 101**. Ideally, all data points should fall on the 45° line shown on the figures. The scatterplots show that most data points fall well within bands defined by 5% of the total range of heads. The plots also show that the residuals in the TAC and SAC are somewhat biased and that the model tends to slightly overpredict heads in these units. Further refinement of the calibration to remove this bias is planned.

The scatterplots generated by VIEWLOG are directly linked to the well data making it easy to locate outliers on the base map by clicking on the data point in the graph. Some obvious outliers (where the observed data are incorrect) have been eliminated from the plots. In other cases, such as the cluster of data points in the box on **Figure 100**, the observed data are correct but some local phenomenon that affects the heads in the area is not well represented in the model. The wells shown in the small highlight box are all in the Claremont area. Gerber (personal communication, 2004) indicated that he had a similar problem matching observations in the Claremont area with his Duffins Creek model. Further investigation of the hydrogeology in the area and local refinement of the model may help resolve these differences.

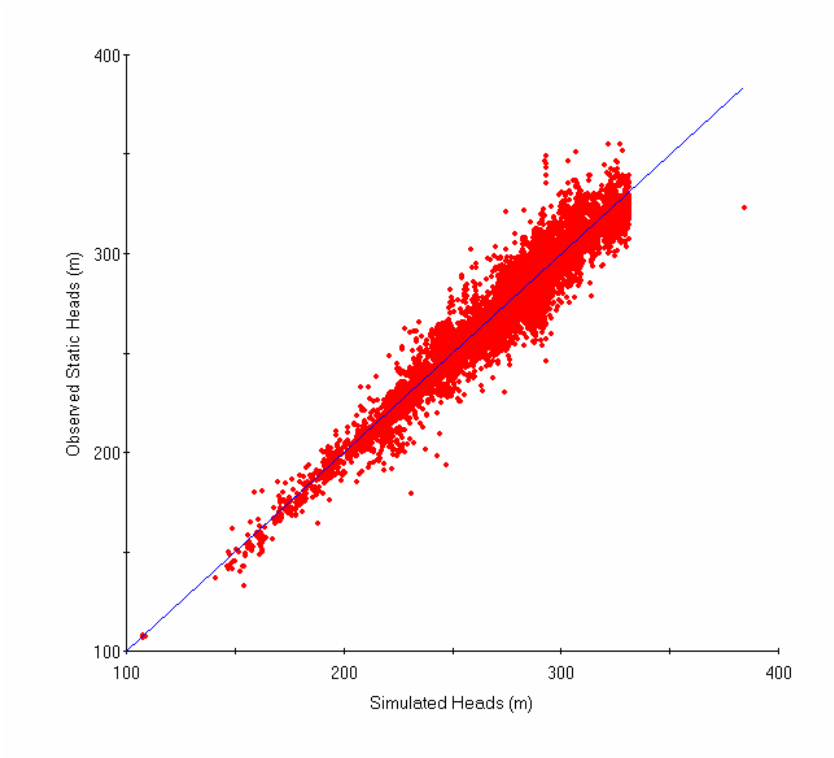

Figure 99: Scatterplot for heads in the ORAC

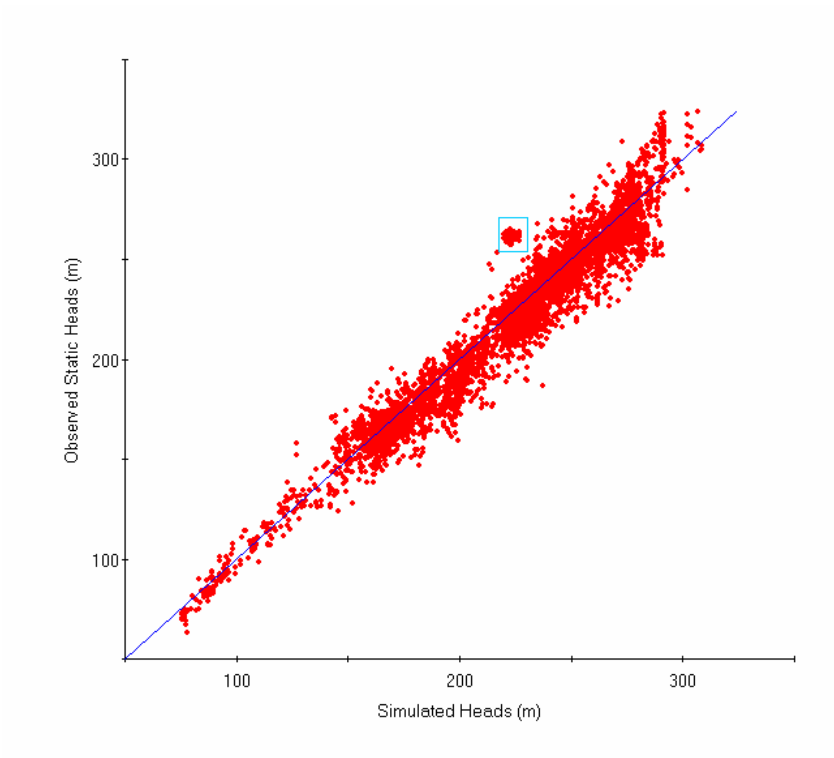

Figure 100: Scatterplot for heads in Thorncliffe Aquifer Complex

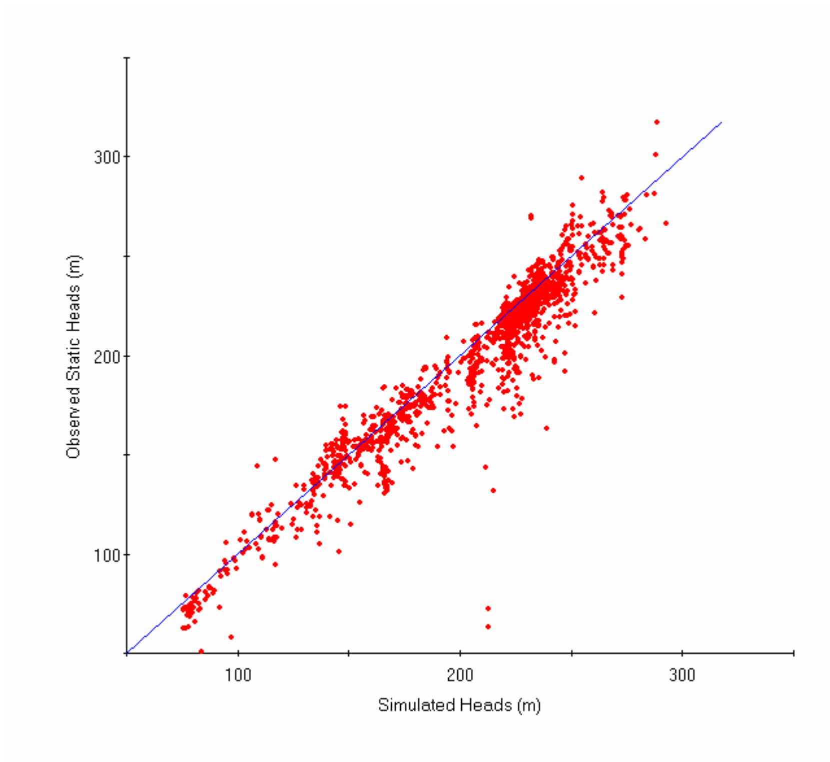

Figure 101: Scatterplot for heads in the Scarborough Aquifer Complex

Simulated values of average groundwater discharge to streams, as computed with the Core Model, were compared against estimated baseflow values determined by hydrograph separation. Simulated and estimated values are presented in **Table 3**. As noted earlier, the HYDAT gauge network does not afford complete coverage of the study area and some key streams north of the ORM are not monitored. Also, a few gauges in the urban areas are influenced by sewage treatment plant discharge and many would be affected by discharge of groundwater leaking into storm sewers. These components of flow could not be distinguished from baseflow in the baseflow separation technique. Simulated baseflow values were also compared against spot flow measurements collected as part of the YPDT studies and by the GSC, TRCA, and LSRCA.

A scatterplot for baseflow values from the HYDAT stations is presented in **Figure 102**. The largest departure is for the Don River gauge at Todmorden, which may be affected by urbanization more than the other catchments. The model also underpredicts flow at the Humber River gauges because part of the upper Humber River was not included in the model. The other data points seem to be evenly scattered about the 45° line. The total range of observed baseflows is from 0.01 m^3/s at Katabokokonk Creek above Locust Hill (a tributary of the Rouge River) to 3.08 m^3/s at the Humber River gauge at Weston. The MAE was 5.6% and RMSE was to 7.5% of this range. Although the percent error fits within the criteria for a good calibration, further work is planned to improve the calibration within the urban areas and to expand the model to cover the entire Humber River watershed.

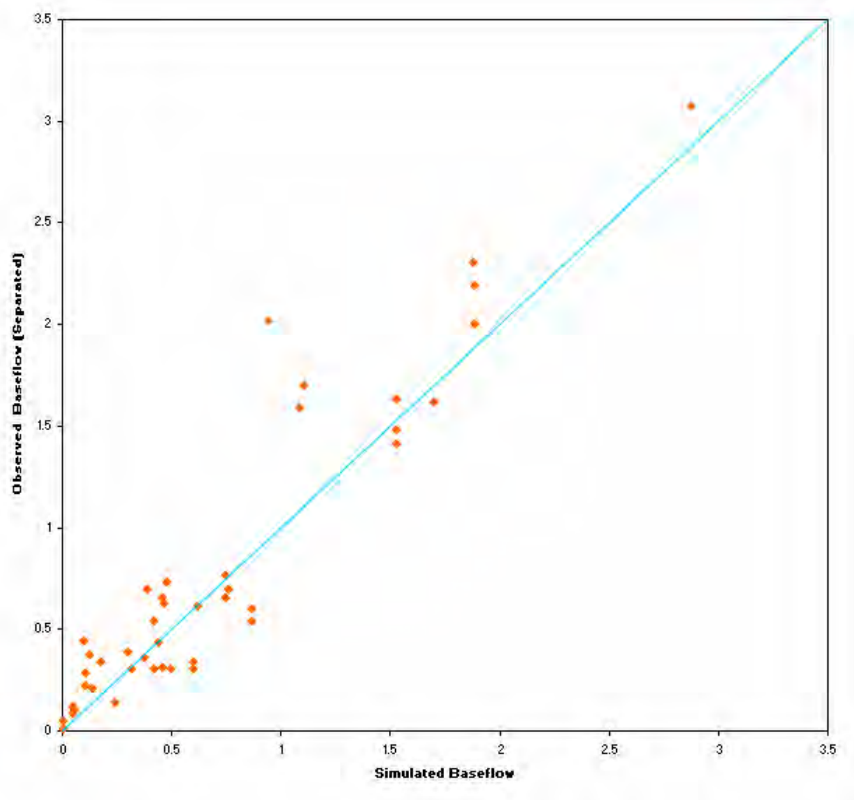

Figure 102: Scatterplot for baseflows

7.6 Model Sensitivity and Uncertainty Analysis

A series of calibration sensitivity analyses, as defined in Anderson and Woessner (1992), were carried out to evaluate the effects of parameter uncertainty and variability on model results. While the calibration process itself provided insight about the range of model sensitivity, sensitivity analyses were also conducted after the calibration was finished as a means of demonstrating that the calibration was unique and that the calibration was done correctly. Methods used in conducting the sensitivity analyses are discussed in Appendix D. Results of tests on the most important parameters are discussed below.

7.6.1 Sensitivity to Aquifer Hydraulic Conductivity

Figure 103 shows the results of multiple model simulations in which the calibrated hydraulic conductivity values for Layer 3 were multiplied by scale factors ranging from 0.1 to 10.0 while all other model parameters were held constant. The graph shows plots of MAE and RMSE for simulated versus observed heads in Layer 3. Heads in Layer 5 were not affected greatly by the changes over the range tested and are not shown for this sensitivity analysis.

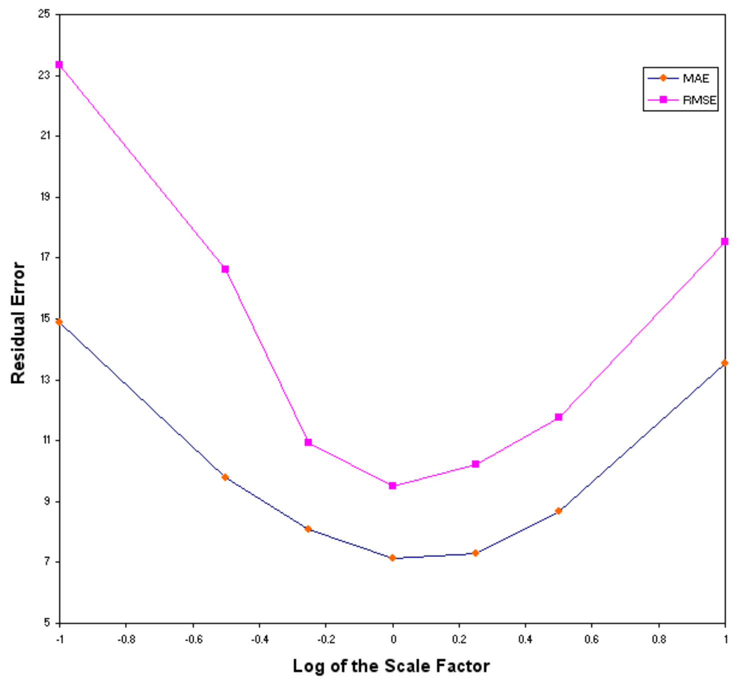

Figure 103: Sensitivity of ORAC heads to hydraulic conductivity of the ORAC

Both lines on the graph exhibit the classic "U" shape indicating that the model is sensitive to the hydraulic conductivity values within the range tested. The calibrated value is at the minimum error indicating that the calibrated value was properly selected. It should be recognized that these are model-wide statistics and it is still likely that local refinement of values could further improve the calibration.

Figure 104 shows the results of model simulations in which the calibrated hydraulic conductivity values for Layer 5 were multiplied by scale factors ranging from 0.1 to 5.6 while all other model parameters were held constant. The model became unstable when the scale factor was increased to 10.0 and results were not obtained for this case. The observation that the model became unstable in this and other simulations does not imply that the physical system would become unstable under these conditions. Rather, it indicates that the groundwater levels would depart substantially from the initial conditions supplied. Methods to overcome numerical instability are discussed in Appendix D. These time-consuming methods were not applied for the sensitivity analysis since a trend was usually established by model results for changes in the stable range.

The graphs showing calibration statistics for simulated heads in Layer 5 indicated that the model is not overly sensitive to the conductance values except at the ends of the range tested. The calibrated value was at the minimum error value.

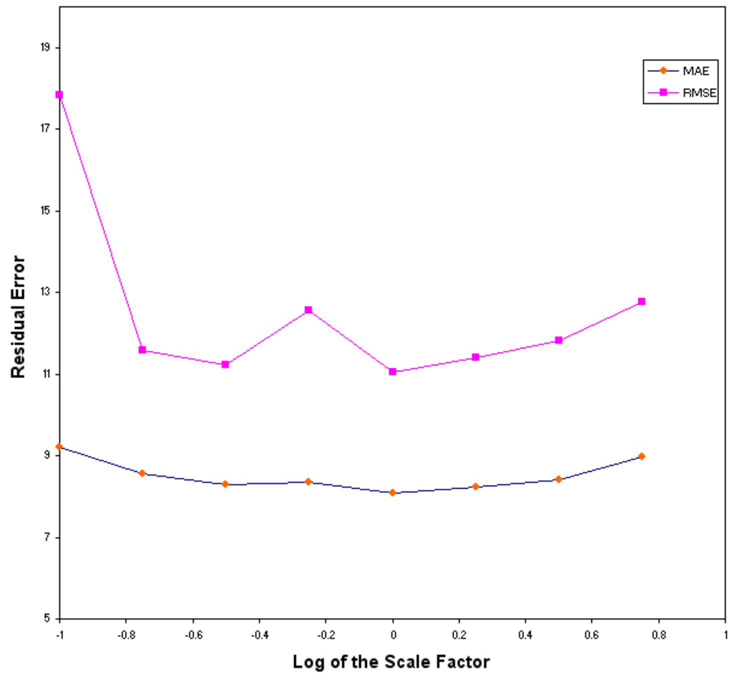

Figure 104: Sensitivity of Thorncliffe Aquifer Complex heads to hydraulic conductivity of the TAC

Figure 105 shows the results of model simulations in which the calibrated hydraulic conductivity values for Layer 7 were multiplied by scale factors ranging from 0.1 to 3.2 while all other model parameters were held constant. The model became unstable when the scale factor was increased to 10.0. The graphs showing calibration statistics for simulated heads in Layer 7 indicated that the model is not overly sensitive to the hydraulic conductivity values except at the upper end of the range tested. A slight improvement in the calibration for Layer 7 would be achieved by scaling the hydraulic conductivity values by 0.3 but further work would be needed to determine whether this improvement would be offset by increased error in other layers.

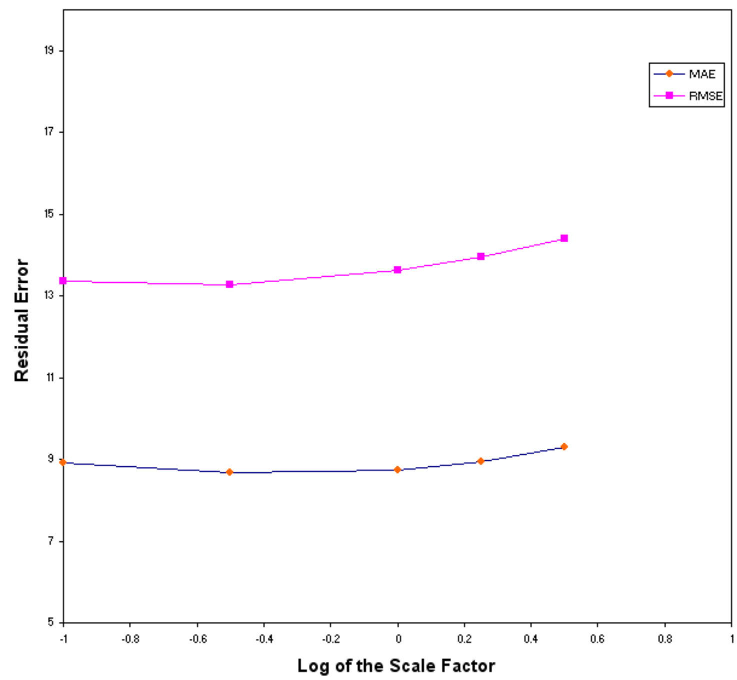

Figure 105: Sensitivity of Scarborough Aquifer Complex heads to hydraulic conductivity of the SAC

7.6.2 Sensitivity to Aquitard Hydraulic Conductivity

Multiple simulations were conducted to determine the sensitivity of the model to the vertical hydraulic conductivity of the Newmarket Aquitard. Calibrated vertical conductance values between model Layers 3 and 4 and between Layers 4 and 5 were multiplied by scale factors ranging from 0.1 to 10.0 while all other model parameters were held constant. **Figure 106** shows calibration statistics for heads in Layer 3 (ORAC) while **Figure 107** shows calibration statistics for heads in Layer 5 (TAC). The graphs show that slightly better results would have been achieved for Layer 3 (**Figure 106**) by using a lower vertical hydraulic conductance but at the cost of increasing the error in Layer 5 (**Figure 107**). Similarly, slightly better results would have been achieved for Layer 5 (**Figure 107**) by using a higher vertical hydraulic conductivity but at the cost of increasing the error in Layer 3 (**Figure 106**). The calibrated value achieved the best balance between the two options.

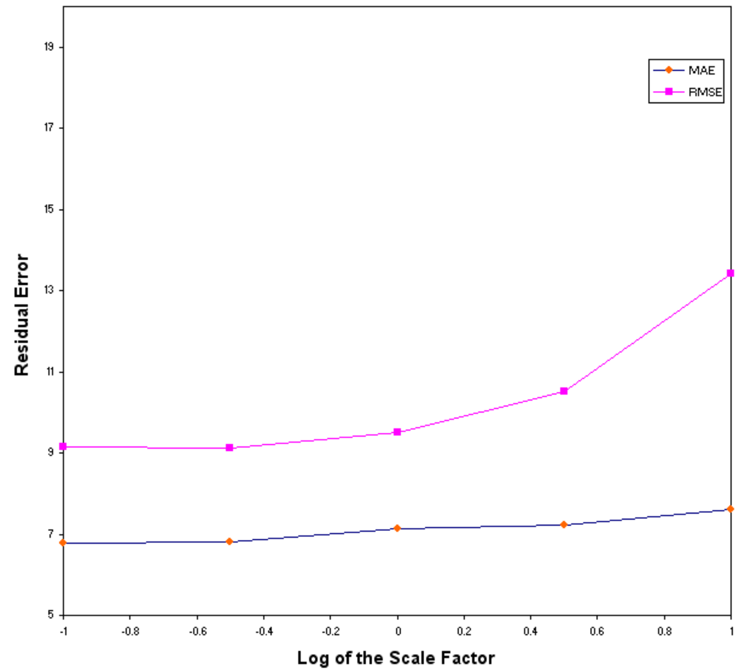

Figure 106: Sensitivity of ORAC heads to hydraulic conductivity of the Newmarket Aquitard

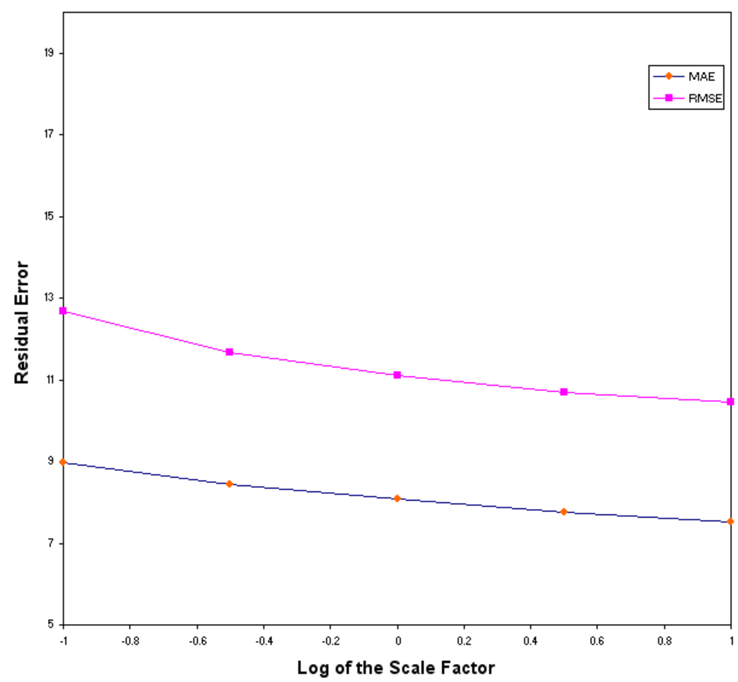

Figure 107: Sensitivity of Thorncliffe Aquifer Complex heads to hydraulic conductivity of the Newmarket Aquitard

Simulations were conducted to determine the sensitivity of the model to the vertical hydraulic conductivity of the Sunnybrook Aquitard. Calibrated vertical conductance values between model Layers 5 and 6 and between Layers 6 and 7 were multiplied by scale factors ranging from 0.1 to 3.1 while all other model parameters were held constant. The model became unstable when the scale factor was increased to higher values. **Figure 108** shows calibration statistics for heads in Layer 5 (TAC) while **Figure 109** shows calibration statistics for heads Layer 7 (SAC). The graphs indicate that the model is relatively insensitive to the vertical hydraulic conductivity values at the lower end of the range tested but highly sensitive at the upper end of the range tested. The graphs show that slightly better results would have been achieved by scaling the vertical hydraulic conductivity by a factor of 3 but at the cost of approaching a limit of model stability.

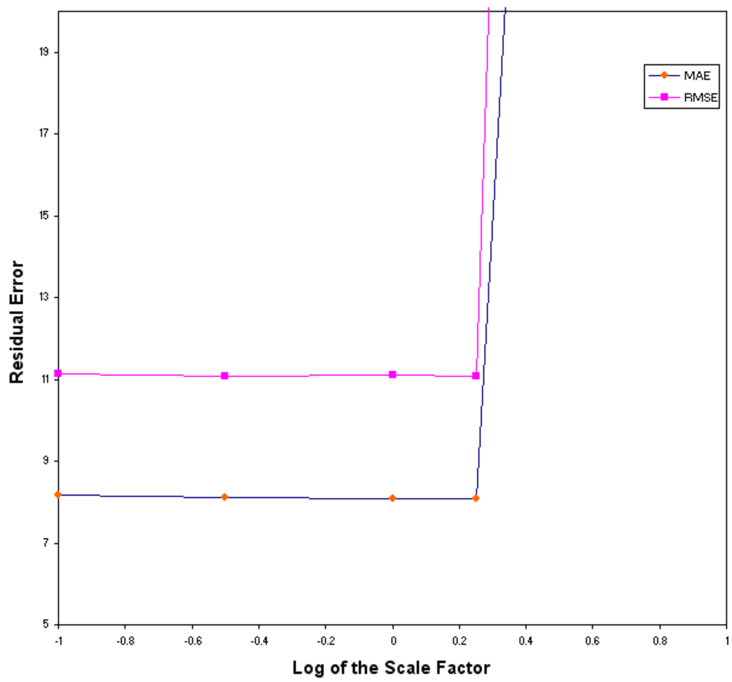

Figure 108: Sensitivity of Thorncliffe Aquifer Complex heads to hydraulic conductivity of the Sunnybrook Aquitard

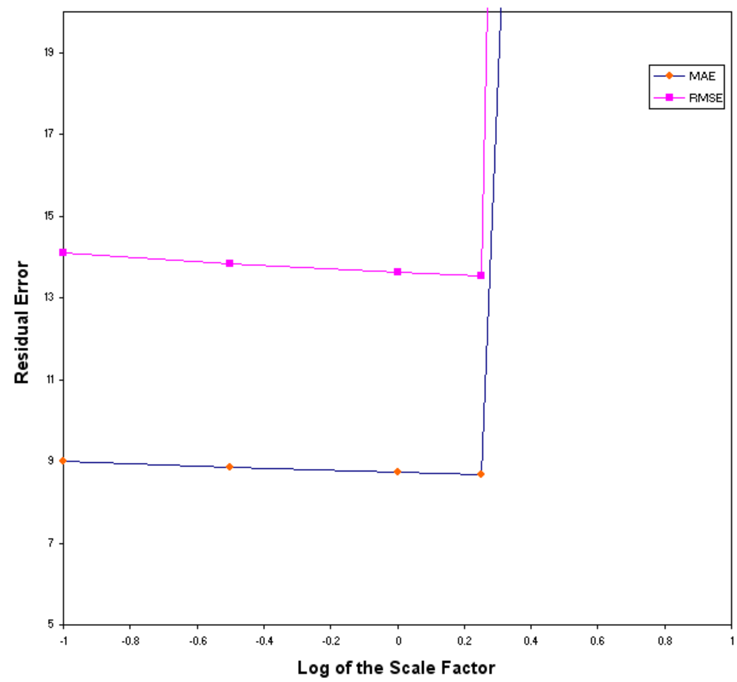

Figure 109: Sensitivity of Scarborough Aquifer Complex heads to hydraulic conductivity of the Sunnybrook Aquitard

7.6.3 Sensitivity to Groundwater Recharge Rates

Figure 110 shows the results of simulations in which the calibrated recharge rates were multiplied by scale factors ranging from 0.9 to 2.0 while all other model parameters were held constant. The model was unstable at scale factors lower than 0.9. Graphs are presented showing calibration statistics for heads in Layer 3.

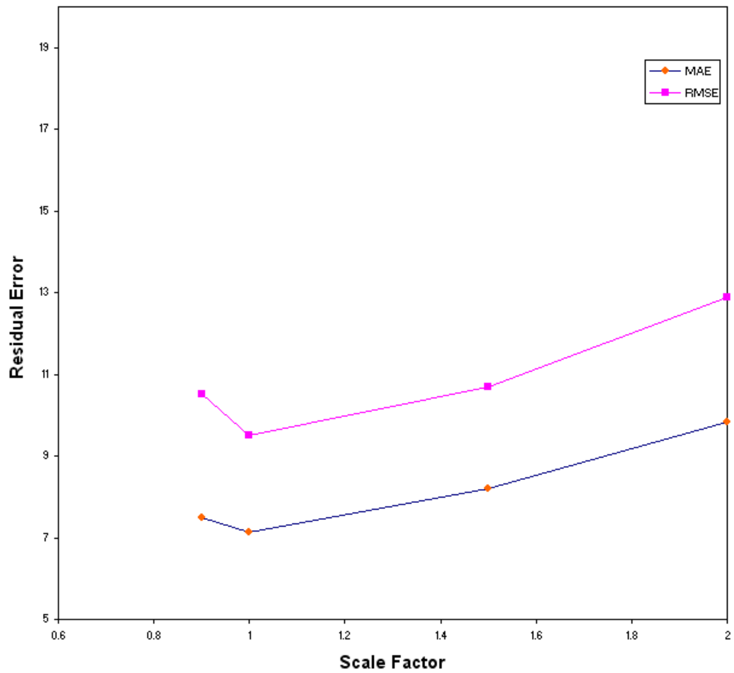

Figure 110: Sensitivity of ORAC heads to recharge rates

The graphs indicate that the model is sensitive to the recharge rates at the upper end of the range tested and extremely sensitive to any reduction in recharge rates. The calibrated value was at the minimum error value.

It should be recognized that the observation that the model became unstable in some of these simulations does not imply that the physical system will also become unstable under these conditions. What it does indicate is that groundwater levels would depart significantly from the base case. When large changes are imposed on the model, the model tends to overshoot and undershoot in the process of converging towards the true solution for the new heads and more cells go dry or re-wet than should. This, in turn, sometimes leads to even greater overshoot and undershoot. Part of the problem is related to the high contrast in hydraulic conductivity between the aquifer and aquitard layers. Running the model in a quasi-three-dimensional mode produced a more stable model but with a sacrifice in detail (e.g. it is not possible to simulate a system where the water table occurs within the confining unit with a quasi-3D model). Solutions can often be obtained with the current model by changing some of the rewetting and solver parameters, or by making an incremental change, saving the intermediate solution as an initial guess for the next incremental change, and repeating the process until the total change is achieved. This time-consuming process was not carried out in the sensitivity analysis since the trend was usually established by model results for changes in the stable range.

7.7 Model Applications

Once the sub-regional groundwater flow model was calibrated, it was used in a number of applications. Three local-scale applications include: (1) simulation of drawdowns to be created by dewatering for the 16th Avenue-9th Line sewer line extensions, (2) simulations in support of a PTTW for Ballantrae, and (3) simulations in support of a PTTW for Stouffville. Two larger-scale model applications are presented here primarily as a demonstration of the applicability of the model.

7.7.1 Application 1 - Drawdowns at Maximum Permitted Pumping

As described earlier, model calibration was conducted assuming average pumping rates for municipal wells. These rates were determined by averaging the daily pumping rates contained in the YPDT database over the period of record. The simulation discussed here examines the affect of pumping all municipal wells at their maximum permitted rates.

Maximum permitted pumping rates were specified based on the current PTTW issued by the MOE with some modifications. As noted earlier, the Yonge Street area wells (Aurora, Newmarket, Holland Landing, and Sharon-Queensville wellfields) have a cumulative average daily limit of 42,000 cubic metres per day (m^3/d). The current simulation examines the affect of removing the cumulative pumping restriction and allowing all Yonge Street area wells operate at their individual maximum permitted rates (which total 72,750 m^3/d).

Wells that are currently not used by York Region, namely those in Oak Ridges along with Newmarket Wells 9, 11, and 14, were assumed to be inactive and were not pumped in the simulations. Stouffville Wells 1,2, and 3 were pumped at the maximum rate of 2,946 m^3/d each for 13.5 hours per day (equivalent to a rate of 1,657 m^3/d for 24 hours), Stouffville Well 5 was pumped at the maximum rate of 2,290 m^3/d for 16 hours per day (equivalent to a rate of 1,526 m^3/d for 24 hours), and Stouffville Well 6 was pumped at the maximum rate of 3,110 m^3/d for 16 hours per day (equivalent to a rate of 2,074 m^3/d for 24 hours). All other non municipal wells in the study area were assumed to pump at the same rate as the calibration run. No data were available for historic pumping at the Bradford wells at the time the simulations were done so pumping at the Bradford wells was kept at the permitted rates in both simulations.

Drawdowns were calculated by subtracting the simulated heads at the maximum permitted pumping scenario from the calibration run heads. Maps of simulated drawdowns greater than 2 m in the Thorncliffe Aquifer Complex and Scarborough Aquifer Complex are shown in **Figure 111** and **Figure 112**, respectively.

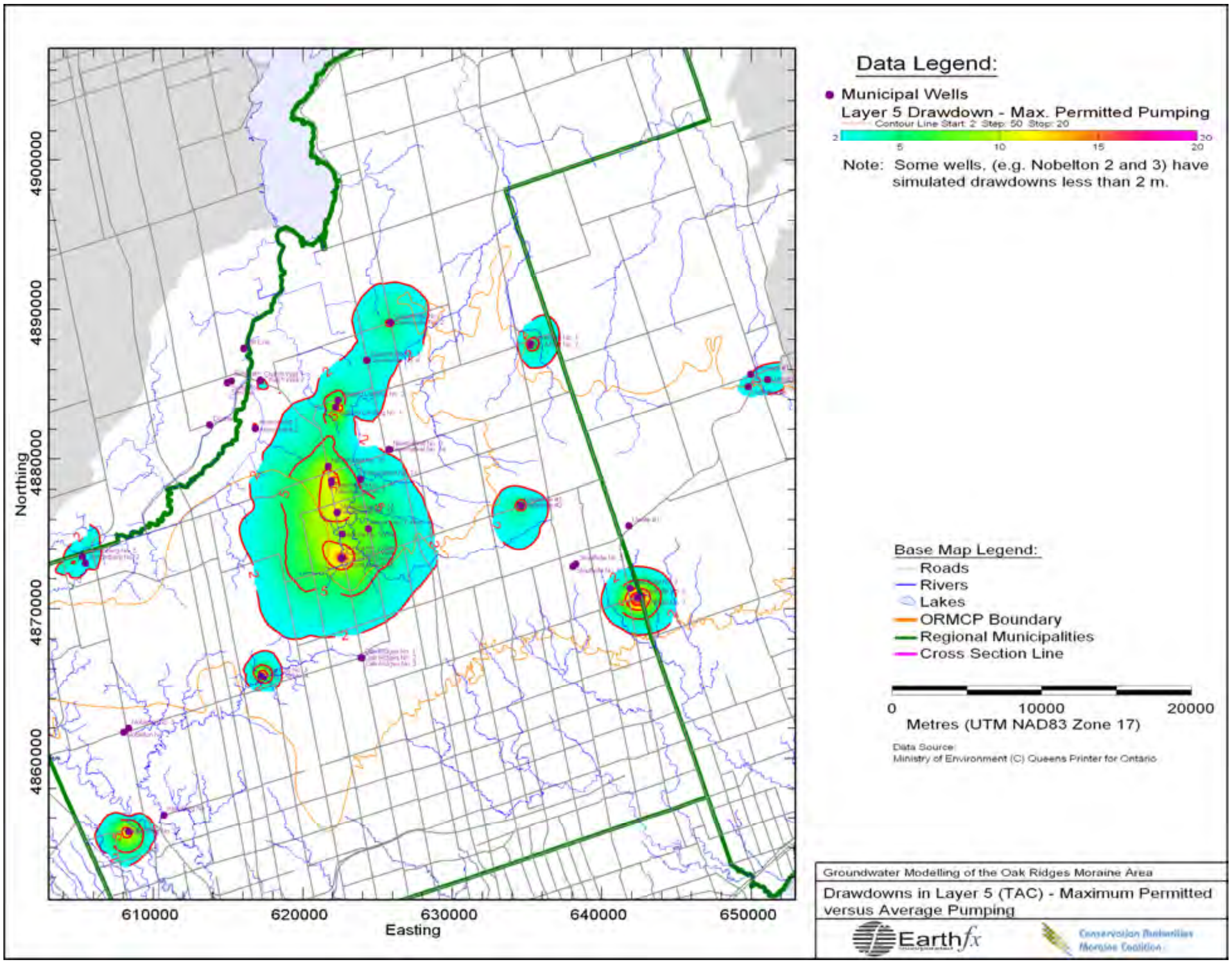

Figure 111: Simulated drawdowns greater than 2 m in the Thorncliffe Aquifer Complex with municipal wells pumping at maximum permitted rates

It should be emphasized that the simulated drawdowns under steady-state conditions do not account for storage in the aquifer. Water levels do not reach the new equilibrium values instantaneously when pumping is increased. Instead, water is derived initially from aquifer storage in the vicinity of the well through several processes including:

- expansion of water as pressure is decreased;
- compression of the aquifer (and squeezing of water out of the pore spaces) as intergranular stresses are increased; and
- drainage of water from the unsaturated zone as the water table declines.

As storage is depleted in the vicinity of the well, the water levels further away from the well decline, additional water comes out of storage, and gradients are established to transmit that water to the well. In the absence of leakage or aquifer recharge, the cone of depressed water levels would continue to expand until it intersected a hydrologic boundary. In systems with leakage and/or recharge, the cone of depression expands only until the amount of recharge intercepted and/or the amount of leakage induced from underlying and overlying aquifers balances the withdrawals from the well. Depending on the nature of the aquifer (confined, unconfined, or semi-confined), the storage and hydraulic properties of the aquifers and aquitards, and the pumping rates, the time to reach a new equilibrium can range from days to years.

The first two compressive storage effects mentioned above are relatively small; the third term is much larger and can contribute a significant volume of water. For example, lowering the potential in the confined Thorncliffe Aquifer Complex by 1 m over a 4 km radius would yield about 5,000 m^3 of water from compressive storage (assuming S = 0.0001), or about two-days worth of pumping at 2,500 m^3/d. The yield from lowering the unconfined water table aquifer by 1 m over the same 4 km radius would be 10 million m^3 (assuming S_y = 0.2), or about 11 years of pumping at 2,500 m^3/d. Thus, the speed of the propagation of the cone of depression is greater in the TAC than in the ORAC. Conversely, the time to reach equilibrium would be much longer in the ORAC than in the TAC. Small changes in the water table at a distance from the pumping well may be more difficult to detect because the aquifer is always responding to shorter-term stresses such as rainfall events or wetter versus drier years.

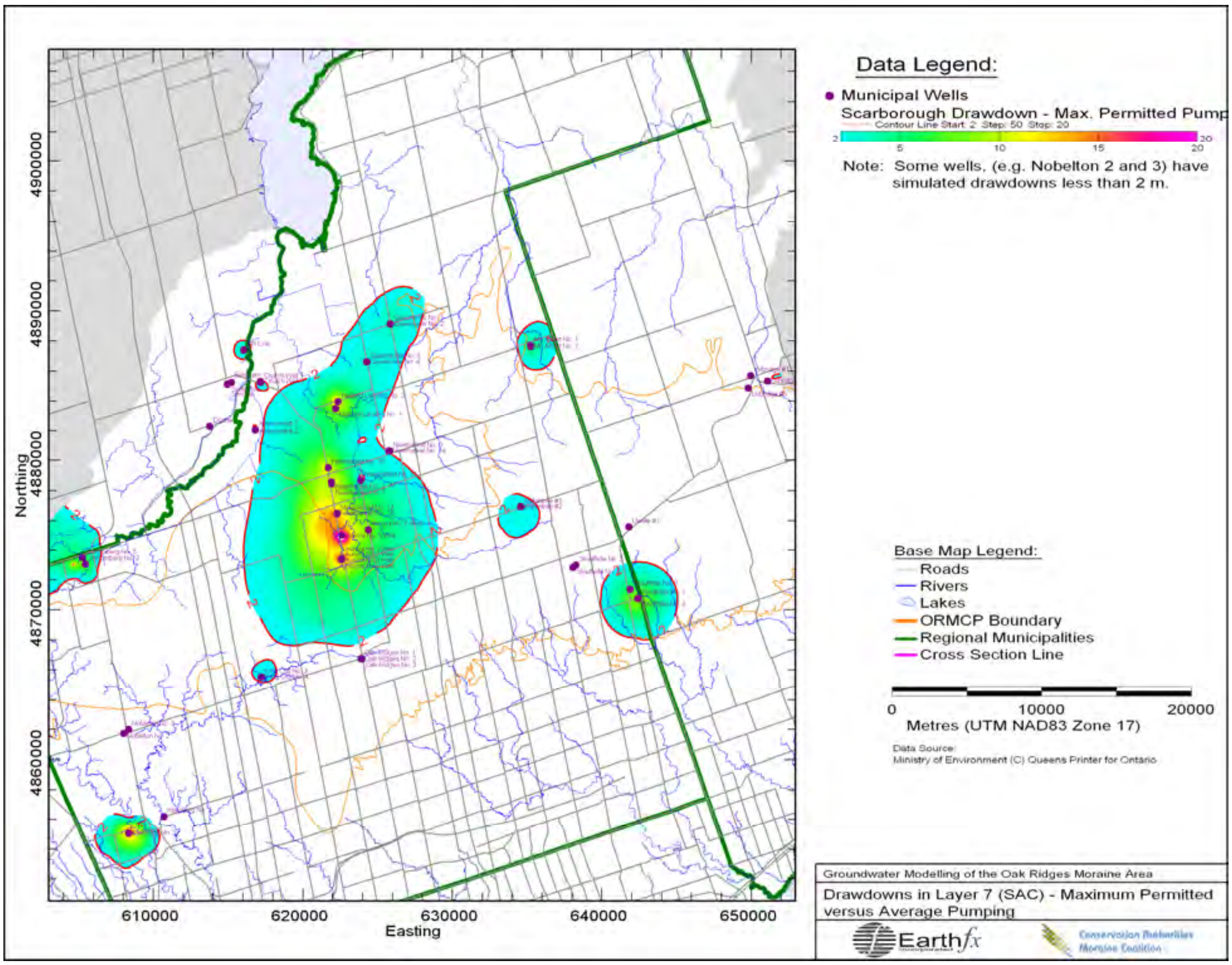

Figure 112: Simulated drawdowns greater than 2 metres in the Scarborough Aquifer Complex with municipal wells pumping at maximum permitted rates. (Note: the drawdown at Nobleton is less than 2 m and does not appear at this scale)

Using the same two modeling run results, the change in simulated streamflow was determined by subtracting the simulated discharge to streams under maximum permitted pumping from simulated discharge to streams under average pumping. The per-cent change was calculated for each cell containing a stream segment. **Figure 113** shows a colour-scaled plot of cells with a greater than 5% percent change in simulated baseflow. Large per-cent changes (purple-coloured cells) occur mostly within the 2-m drawdown limits. Also, the higher per-cent change tends to occur on the smaller tributaries. To see whether these per-cent changes were truly significant in terms of the the overall flows in the stream, the total discharge was also examined. **Figure 114** shows a colour-scaled plot of cells with a greater than a 0.01 L/s change in simulated baseflow. The figure indicates that while a large number of the tributaries show a decrease in baseflow, the magnitude of the decrease is small (generally between 0.01 and 0.1 L/s per 100 m reach of stream) except in the immediate vicinity of the municipal wells.

As noted earlier, the simulated long-term change does not account for yields from storage and the actual changes may be hard to detect because of other short-term stresses affecting baseflow. In addition, the model has not yet been calibrated to match baseflow in individual stream reaches. The calibration was done primarily to match the cumulative baseflow at downstream gauges since most stream reaches are ungauged or have, at most, one or two spot flow measurements. The model results are intended to show the strong interdependence of the groundwater and surface water flow systems and where the impacts of increased water takings on baseflow are likely to occur.

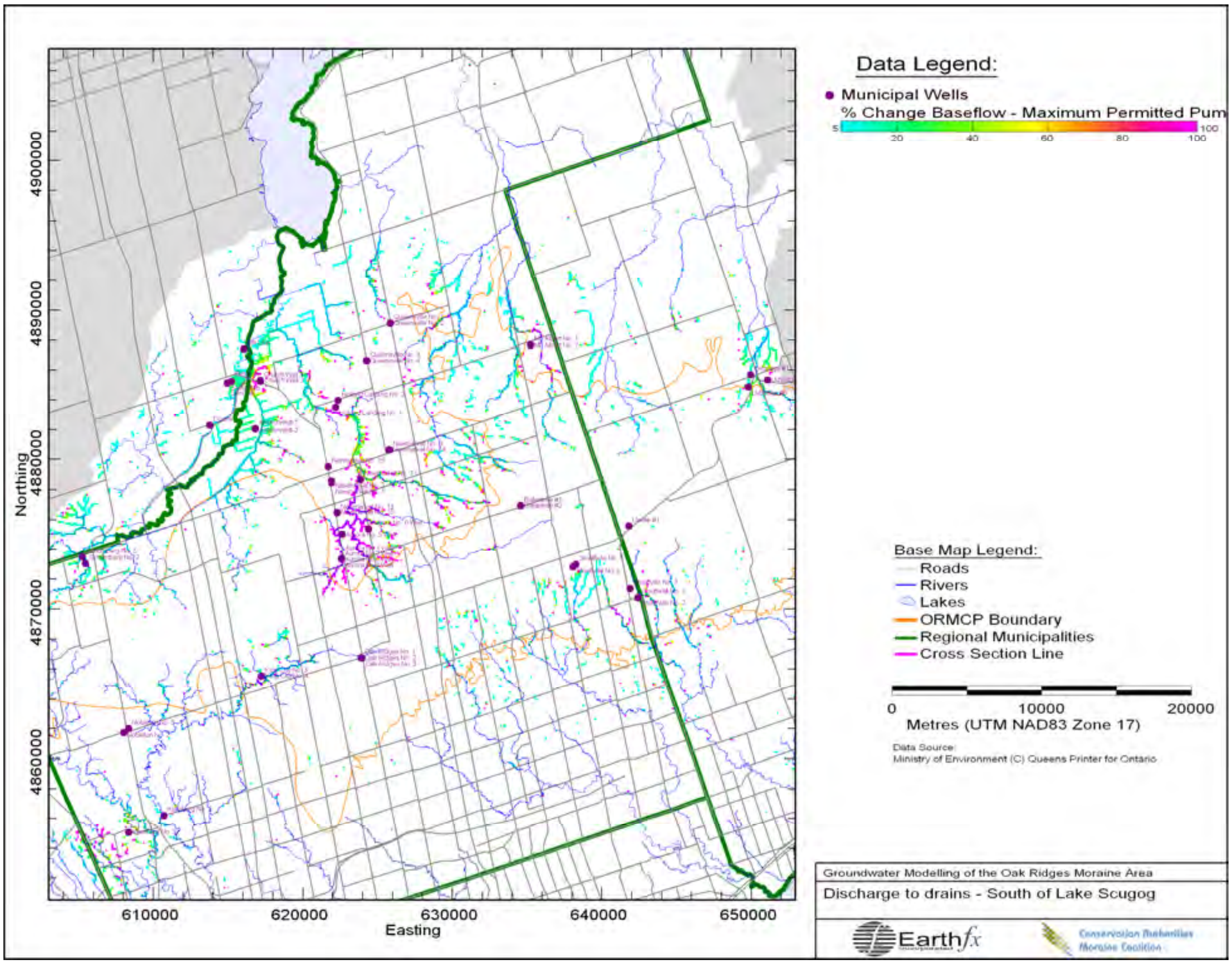

Figure 113: Percent change in simulated baseflow with municipal wells pumping at maximum permitted rates

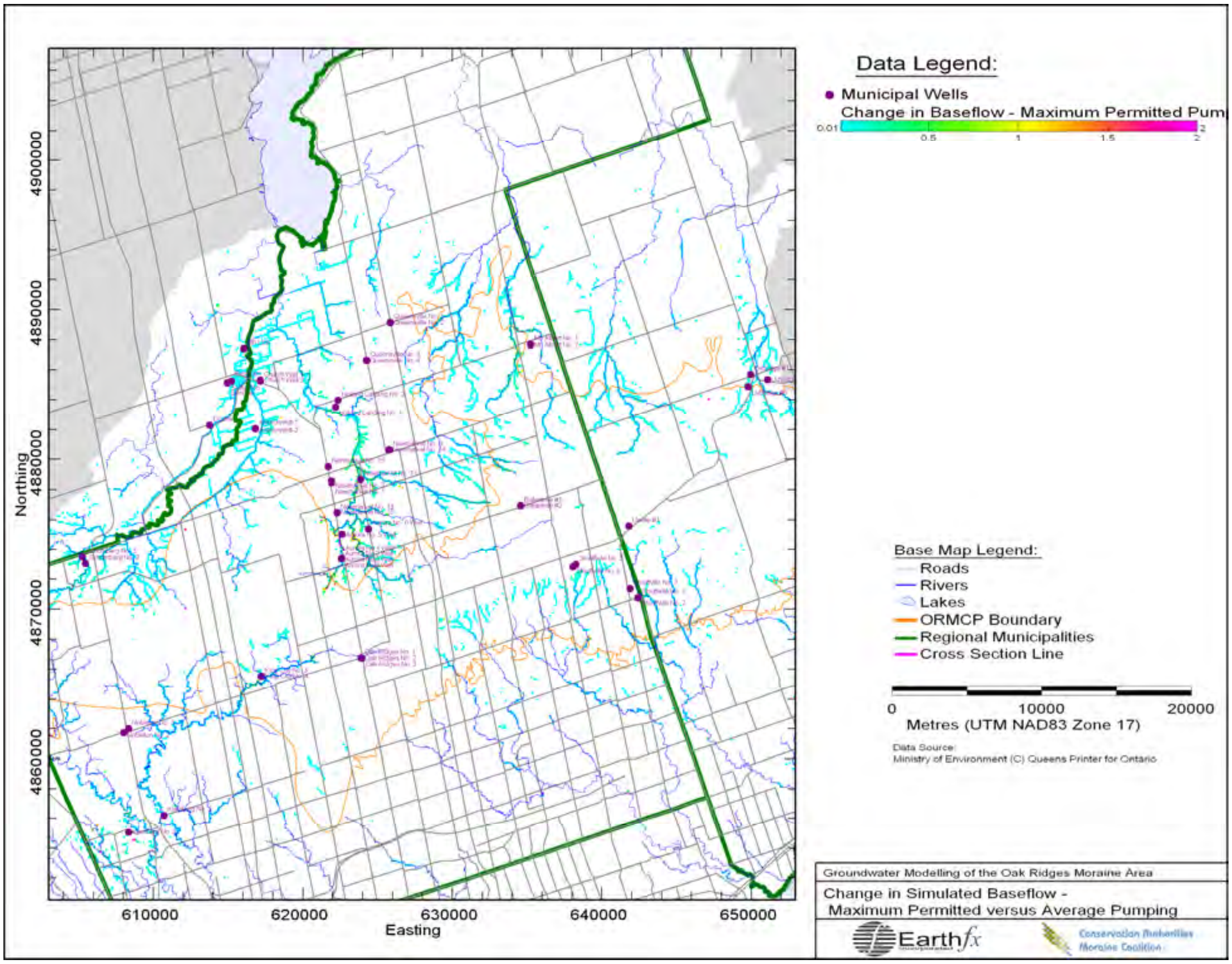

Figure 114: Change in simulated baseflow (L/s) with municipal wells pumping at maximum permitted rates

7.7.2 Application 2 - Capture Zones and Time-of-Travel Zones

The calibrated groundwater flow model was also used to delineate capture zones and time-of-travel (TOT) zones for the municipal supply wells in York Region. A steady-state capture zone is defined as the area that contributes groundwater to a production well. Time-of-travel zones are defined as the portion of a capture zone in which groundwater will travel to a production well within a specified period of time. For example, a 10-year TOT zone is the area around a well in which the furthest water particle takes 10 years to reach the well. The TOT zones are actually three-dimensional surfaces. Wellhead protection areas (WHPA) are often defined using the vertical projection of these surfaces onto a base map even though not all water particles entering at land surface will actually arrive at the well within the specified time interval.

Capture zones for a particular well can vary depending on the rate of pumping at the well, the rate of pumping at nearby wells, and other external factors such as seasonal changes in the rate of recharge or stage in rivers. In this application, capture zones were delineated assuming maximum permitted pumping rates at the municipal wells, as described in the previous section. All other model input parameters were the same as for the calibration runs. Capture zone and time-of-travel zone analyses were conducted using the USGS MODPATH code. The method is discussed in Appendix D.

Capture zones for York Region municipal wells are shown in **Figure 115**. (The capture zones presented here are intended to demonstrate the applicability of the model. Capture zones used by planning agencies to develop WHPAs may differ due to specifically requested adjustments in the model runs (e.g. different pumping rates or more/less conservative assumptions). For example, in the capture zones presented in **Figure 115**, the time of travel was doubled as a safety factor to account for uncertainty in aquifer parameters.

The shapes of the capture zones are determined primarily by the regional flow patterns, variations in aquifer properties, proximity to features such as bedrock valleys and tunnel channels, and mutual interference between wells. The capture zones/time-of-travel zones for isolated wells (e.g. Mt. Albert or King City) have relatively simple shapes, whereas the capture zones for the other wells are more strongly influenced by the presence of nearby pumping wells. These results demonstrate the importance of using a larger-scale model to analyze capture zones, since models developed for individual wellfields cannot simulate the effects of nearby wells on the shape of the TOT and capture zones.

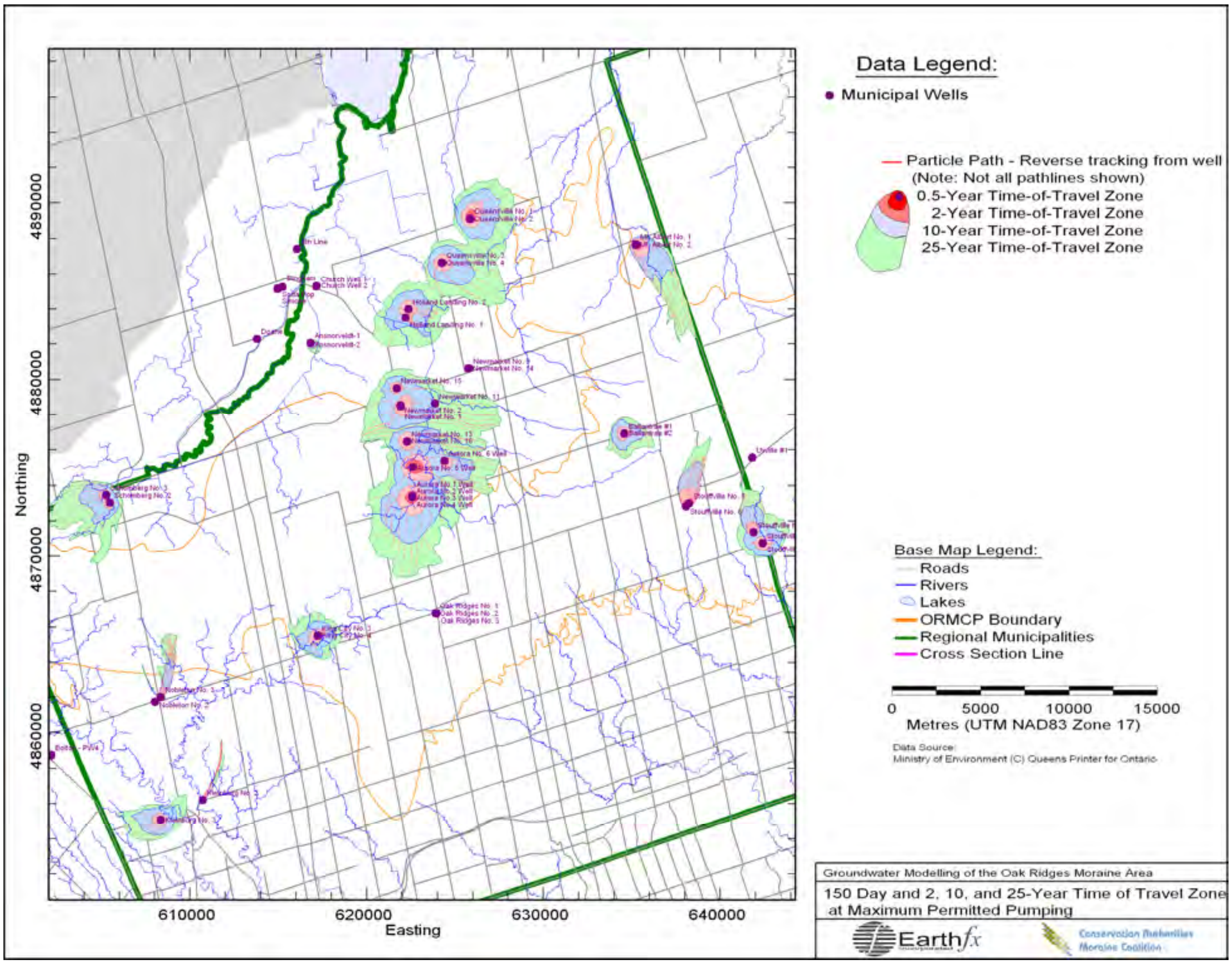

Figure 115: 150 day, and 2, 10, and 25-year capture zones for York Region municipal wells

7.7.2.1 Model Cell Size Analysis

Sensitivity analyses were conducted in the vicinity of Stouffville Wells 5 and 6 to determine whether cell size affected the accuracy of model results. The grid was refined down to a cell-size of 12.5 m. Results showed that the capture zone shifted slightly (less than 100 m), mainly due to the location of the wells shifting from the centre of the 100 m cell to the centre of the 12.5 m cell closest to the actual well location. While only this site was tested, the results indicated that the 100-m grid spacing is acceptable for capture zone analysis.

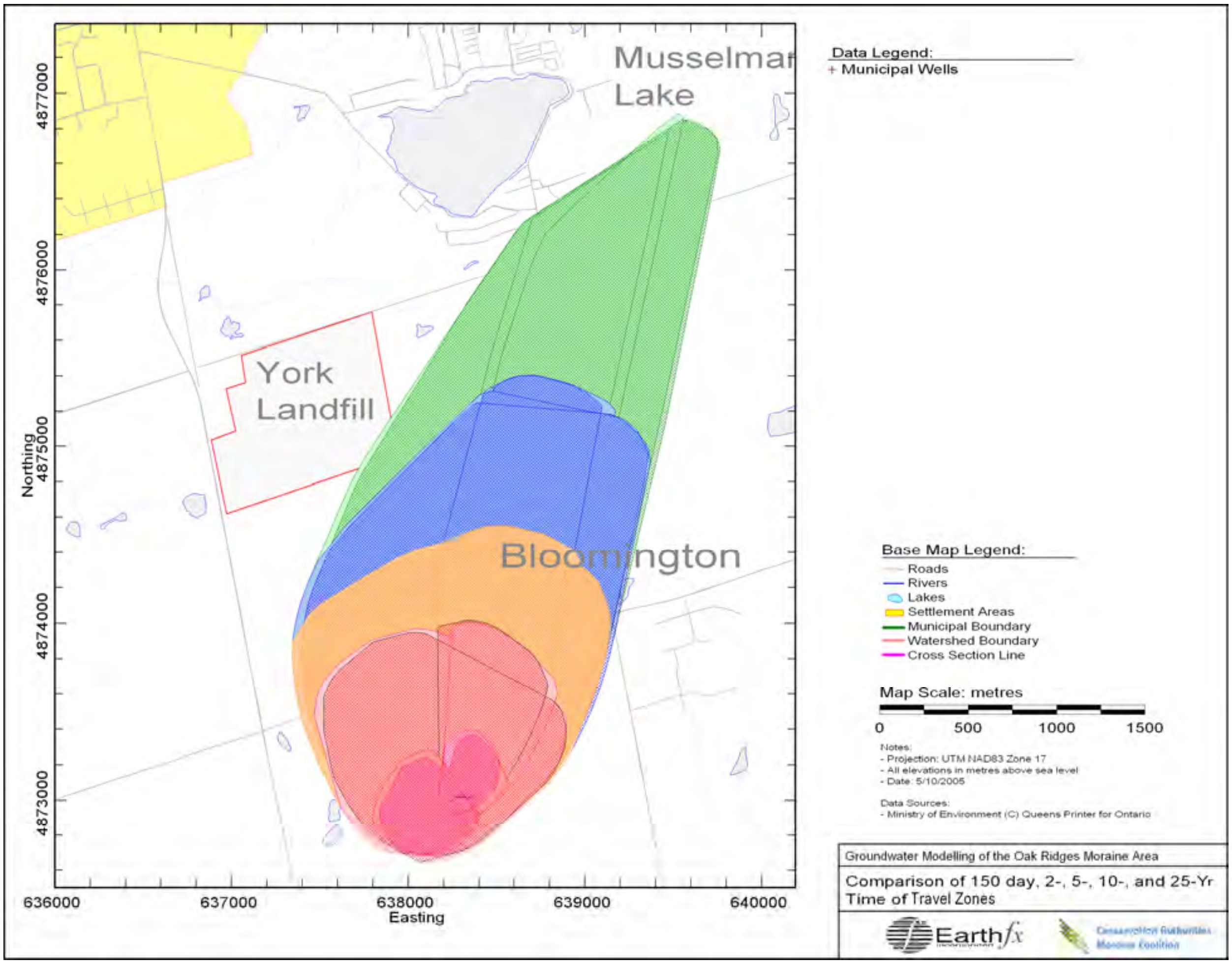

Figure 116: Comparison of capture zones between the 100 m cell size (light color) and 12.5 m cell size (dark color).

7.8 Core Model Findings

General conclusions drawn from the Core Model results confirm earlier observations drawn from the Regional Model results. These and others include:

1. the Core Model provided better representation of the groundwater flow patterns due to the finer discritization and the subdivision of the Lower Sediments;
2. groundwater flow patterns were strongly influenced by streams and the Core Model provided the discritization needed to properly represent the stream network;
3. calibrated values of recharge and hydraulic conductivity produced good matches to observed heads, gradients, and baseflows;

4. model results were extremely sensitive to the permeability of the Newmarket Aquitard and Sunnybrook Aquitard which controlled aquifer heads both above and below these layers;

5. aquifer and aquitard properties used in the model generally agree with previous estimates;

6. using spatially distributed values of hydraulic conductivity for the aquifers produced better results than using uniform values;

7. use of a recharge model, as opposed to zoned values, could provide an improved representation of the recharge distribution and allow analysis of the effect of land use change on the groundwater and surface water systems;

8. hydraulic conductivity of the Newmarket Aquitard is higher than test values from core samples due to the presence of fractures and sand bodies within the Newmarket Till that contribute to a higher effective vertical permeability; and

9. tunnel channels facilitate the exchange of water between the upper and lower aquifers.

Even though reasonable matches to the observed heads and flows were obtained, it is anticipated that this model will provide a framework for collecting and assimilating additional geologic data, water level information, and stream stage measurements in order to continually improve model calibration on a local basis. Further refinement of the model grid, adjustment of stream properties on reach-by-reach basis, and conducting a transient calibration might improve the effectiveness of the model as the project moves forward. Further work is also planned to expand the Core Model to encompass to entire ORM area.

8 Summary and Conclusions

8.1 Summary of Work

Data Compilation:

The relational database is the foundation on which the analysis and predictive modelling are based. Over 140,000 boreholes, 600,000 geologic descriptions and 1.8 million water levels were compiled and organized into a comprehensive database. This central database is meeting the needs of a broad range of users, including field staff, data managers and numerical modellers. Data consistency and integration across this broad range of applications and users has proven very effective.

The YPDT data compilation project also included the scanning of over 1500 reports and 2400 maps and images. The entire database and report library is available from a web server with interactive mapping, cross sections, borehole logs and graphing tools.

Data Interpretation and Analysis:

A detailed hydrostratigraphic model of the aquifer and aquitard layers was constructed through a combination of data visualization and analysis techniques. Over 67,000 geologic layer picks were made, with particular emphasis on delineating the tunnel channels, bedrock valley systems, and subdividing the lower sediment package. The process, based on visually reviewing thousands of detailed cross sections, was designed to “automate everything but the interpretation”. This allowed direct incorporation of the understanding of the controlling depositional processes into the analysis. The result is significant insight into the characteristic lithologic patterns and a comprehensive eight-layer digital model of the study area.

Geologic surfaces were generated using both geostatistical analysis and hydrogeologic insight to control the interpolation. Statistical and geostatistical techniques were used to search for outliers in the data and determine the bias and range of error inherent in the data.

The hydrologic and hydrogeologic data were analyzed to determine preliminary mass balances, groundwater contribution to streamflow, and target heads for model calibration. Initial estimates of groundwater recharge and aquifer and aquitard properties were also obtained through the analysis of the data and reports in the database. In many cases, the hydrologic analyses were dependent on the stratigraphic analyses. For example, it was critical to first identify the top and bottom of the Thorncliffe Aquifer Complex on a regional basis in order to do a detailed analysis of potentials in wells screened within the unit.

Groundwater Model Development:

The complex hydrostratigraphy of the Oak Ridges Moraine provided many challenges to the construction of the regional and sub-regional groundwater flow models. Foremost was how to model an extremely large and complex area without sacrificing the fine-scale detail needed for stream-aquifer interaction, analysis of well interference, and delineation of capture zones. Through detailed analysis of the available data, detailed models of the groundwater flow system were developed that matched observed water levels, flow directions, and rates of groundwater discharge to streams.

A preliminary groundwater model was first developed for the ORM study area building on the initial geologic interpretation of sediment stratigraphy by the GSC. The model was constructed on a relatively fine grid (240 m cell-size) to allow better simulation of groundwater-fed streams. Successful construction of the model showed that it was possible to model the study area on a regional basis using reasonable values for aquifer and aquitard properties and recharge. Model results showed that the system was sensitive to the vertical hydraulic conductivity assumed for the regional confining units. Results also showed that the ORAC, and to a lesser degree, the deeper aquifers, were strongly influenced by the surface water system and that proper representation of the streams was important.

Results of the Regional Model enabled development of a much more detailed sub-regional model of the core of the ORM area. Additional analysis of the data was carried out within the central part of the study area to better map bedrock valleys, tunnel channels, and to subdivide the Lower Sediments into the Thorncliffe Aquifer Complex, Sunnybrook Aquitard, and Scarborough Aquifer Complex. An eight-layer groundwater flow model was then developed for the core area which covered the TRCA watersheds (including the City of Toronto), York Region, and parts of Peel and Durham Regions. The Core Model had a refined (100 m cell size) grid with over 7.1 million cells and afforded a better representation of the thousands of stream reaches that receive groundwater discharge north and south of the ORM.

The model was calibrated to match observed groundwater levels in the three principal aquifers and to match stream baseflow measurements computed by applying hydrograph separation techniques to the long-term streamflow data. The sub-regional groundwater flow model is considered to be well-calibrated because:

- it represents the key elements of the physical system within a sub-regional context,
- the parameter values used in the model are within physically realistic ranges, and
- the model provides an acceptable match to observed data on both regional and local scales.

The model was applied in two test simulations to examine (1) the likely affect of increased pumping in York Region on groundwater levels and baseflow and (2) to delineate capture zones for the municipal wells. Results indicated that the model provides a useful tool to help address municipal well protection issues, well interference, impact on stream baseflow, and other regional and local water resource management issues. Continued refinement and expansion of the model, addition of new data, and local-scale refinement of model parameters will help ensure that the model remains useful into the future.

8.2 Key Findings

Some of the more significant findings of this study include:

8.2.1 Role of the ORM

The modelling has shown, in a quantitative manner, the importance of the ORM as a regionally significant recharge area. Modelling suggests that the recharge rates through the coarse grained sediments at the top of the ORM are as much as four times greater than recharge on the sloping till plains north and south of the moraine. Recharge through the fine-grained Halton Till sediments that cap or overlie parts of the ORM is also significantly greater than the same sediments off the moraine because of the subdued hummocky topography in these areas.

Because the high recharge is focused in a small area, elevated heads occur in the ORAC and help drive groundwater downward into the deeper aquifers. High rates of downward movement of water to the TAC occur beneath the moraine in the vicinity of the tunnel channels where the Newmarket Till has been eroded and replaced by more permeable silt layers.

Recharge over the ORM provides baseflow to streams with headwaters along the flanks of the moraine. Recharge over the ORM also provides a significant component of the leakage to the lower units. This water later emerges as baseflow to the lower reaches of many streams where the streams have cut through the confining units and are in direct hydraulic connection with the lower aquifers. While recharge over the till plain occurs at a much lower rate, it is still an important component of stream baseflow since the area covered by the till plain is much greater than the areal extent of the ORM.

8.2.2 Groundwater Discharge to Streams (Baseflow)

Nearly 90% of the recharge that occurs on the moraine discharges to the stream network. Less than 5% of the recharge discharges directly from the aquifers into Lake Ontario and Lake Simcoe. Groundwater pumping accounts for the other approximately 6% of the total recharge. Model simulations indicate that baseflow discharge patterns are highly variable, and are controlled by a complex combination of topography and subsurface layer geometry. The Humber River, which covers over 25% of the Core Model study area and is generally deeply incised, captures over 22% of the model's groundwater discharge (see **Table 17**). More surprising, perhaps, is that Pefferlaw Brook captures twice the total baseflow (15%) than the Don River (7%) even though they both cover about the same surface area. The relatively low baseflow to the Don River might be due to urbanization effects.

8.2.3 Major Flow Patterns

Flow patterns in the study area are more complex than previously thought, particularly in the central portion of York Region. While groundwater flow is predominantly north-south, perpendicular to the axis of the moraine, the presence of tunnel channels below the ORM has altered the flow system. For example, radial flow occurring from the mounds within the ORAC into the Yonge Street area and into the Holland River valley is an important feature of the flow system and water balance for these basins.

The other feature noted in both the Regional Model and the Core Model results was that the surface water divides for the larger watersheds affect flow directions in the lower aquifers as well as in the ORAC. This pattern can be seen in the observed water levels although data sparsity and quality issues sometimes make the interpretation less certain. Cross-watershed transfer of groundwater, although minor, does occur, particularly in the deeper aquifers and in the upper ends of the watersheds in the Oak Ridges Moraine. The deeper flow systems are influenced by the presence of tunnel channels and bedrock valley systems.

Model simulations indicate that the tunnel channels play an important role in the flow system as they represent areas where much of the downwards and upwards leakage between aquifer systems occurs. However, the tunnel channels should not be thought of as open windows to the lower aquifer zones. Simulations suggest that the silt frequently seen in the upper portions of the channels has an effective vertical hydraulic conductivity approximately one order of magnitude more permeable than the surrounding Newmarket Aquitard. This layer effectively

confines the aquifers in the tunnel channels and provides a degree of protection to the deeper aquifers from surface contaminants.
Modelling suggests that the bedrock valley systems are important features of the flow system in the Scarborough Aquifer Complex and that the thick sediments within the valleys could have a considerable transmissivity. Although data are sparse, the observed water levels show that flow is locally aligned with the axes of the valleys. The simulated water levels also show the effect of the valleys, although their influence on the overall regional flow patterns, which are dominated by the north-south flow and surface water divides, is limited.

8.2.4 Yonge Street Aquifer

The analysis and modelling suggest that the “Yonge Street Aquifer” is part of a larger regional flow system that is locally influenced by a combination of three hydraulic conditions, including a topographic basin, tunnel channel and bedrock valley. The topographic basin, although partially infilled with silt from various processes, appears as a “notch”, cutting into the ORM. This allows radial flow patterns to develop. The resulting convergence of flow, from both the ORAC and the Thorncliffe Aquifer Complex, provides the water that supplies the Yonge Street area wellfields. The tunnel channel cross-connects the aquifer zones, both vertically and horizontally, increasing the effective hydraulic conductivity and reducing vertical anisotropy. Finally, the underlying bedrock valley further extends the influence of the deeper pumping wells. Overall, the position of the capture zones suggests that the radial inflow into the basin, particularly from the southeast, is likely the most significant of the three factors. A similar combination of conditions exists in Uxbridge, and, to a lesser extent, in the headwater areas of the West Holland River basin near Schomberg.

8.2.5 Capture Zones and Water Use

The Core Model simulated pumping from municipal, industrial, agricultural, and golf-course irrigation wells. Estimates of average pumping rates for municipal wells were determined by averaging the recent daily pumping rates. Maximum allowable rates were obtained from the permits to take water. Estimates of other water use in York Region were provided by Golder Associates Limited and Marshall Macklin Monaghan (GAL, in review). Total pumping simulated in the model amounts to approximately 6% of the total recharge. Actual use from the non-municipal wells is probably less than the simulated rates which were based on the permitted rates.

Capture zone analysis indicates that municipal pumping from the deeper aquifers in the Yonge Street area produces relatively large capture zones. The presence of confining layers over the deeper aquifers increases the size of the captures zones but minimizes (distributes) the impact of pumping on the stream network and provides better wellhead protection. Sensitivity analyses indicated that, although minor improvements occurred when using smaller cell sizes, the use of a 100 m cells size was adequate for capture zone delineation.

9 Opportunities to Move Forward

The ORM Groundwater Modelling Study and companion studies have produced a number of significant technical products. These fall under three broad categories:

1. Data Compilation: A comprehensive relational database
2. Data Interpretation: A regional hydrostratigraphic framework developed through the visualization and analysis of the data
3. Model Development: Regional and sub-regional scale groundwater models

These products were developed using an approach that recognized that technical understanding must be built up in a layered manner (**Figure 117**). Each layer depends on the previous since model development can only proceed on a strong supporting foundation of data compilation and interpretation. These projects have addressed each layer using this approach in an integrated and regionally consistent manner.

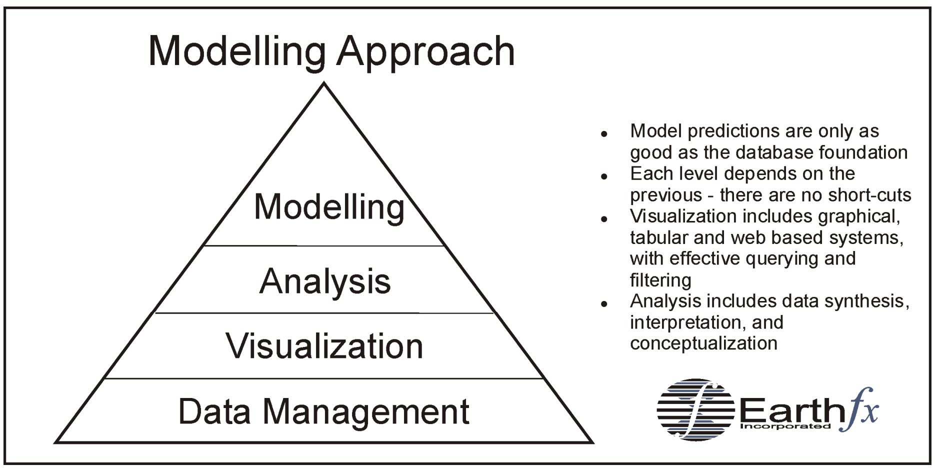

Figure 117: Modelling approach.

The database, hydrostratigraphic model layers, and groundwater flow model are significant technical products of the ORM area studies. There are many potential applications for these products because they can be used as the foundation for detailed water resources investigations, monitoring, planning and protection. All three products will need ongoing refinement and support if they are to remain relevant to the study area’s future growth and development. With this support, a cycle of validation, data compilation, analysis and model refinement can be created (**Figure 118**).

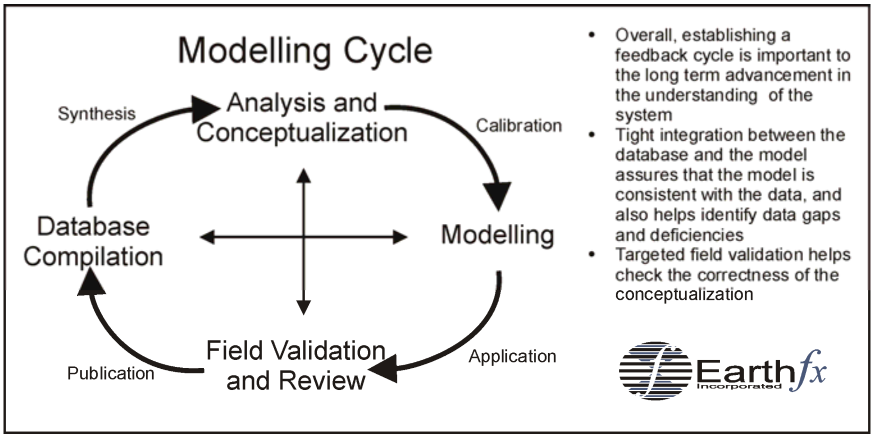

Figure 118: Feedback cycle necessary to maintaining and updating the model.

This feedback cycle (**Figure 118**) has already started, as the model is being used to address a number of groundwater and surface water issues within the study area (i.e. the "application" phase of the cycle). These applications, which range from new water supply investigations to sewer tunnel construction dewatering impact analysis, demonstrate the cost effectiveness of building a high resolution sub-regional scale model, since the same model can be used to address a number of different technical issues. Other aspects of the cycle are ongoing, such as field validation.

Two issues are particularly important to the modelling cycle: (1) integration of the database with the modelling, and (2) regional consistency of the interpretation. By connecting the database directly to the model, a better calibration was achieved because all of the diverse data types were available to be integrated and synthesized into the modelling process. This led to a more realistic model as opposed to a more conceptual flow model. There were also benefits to the database from tight integration with the model, as errors and gaps in the database were easily identified by the modelling team. This integration of the model and the database should be preserved throughout the model update and refinement cycle.

Regional consistency is another important issue for the modelling cycle. One of the benefits of the selected approach is that the regional framework can now be used to guide local-scale studies. This regional framework was unavailable to previous groundwater investigations, so each study was essentially "starting from scratch" and many treated the location and geometry of the aquifers and aquitards as a more-or-less random process. Many aspects of future local-scale studies, from project planning to interpretation, can benefit from the regional framework.

This regional consistency needs to be maintained in the modelling cycle. While applying a regional framework to a local-scale study is relatively easy, it is more difficult to consistently integrate local-scale findings back into the regional-scale conceptual framework. The model is too complex to be updated and refined based on each new borehole that is drilled. New local-scale data needs to be accumulated and then synthesized and analyzed in a similar process to that used in this project. A long-term commitment to maintaining and advancing the regional understanding is needed.

New processes and features can be added to improve the flow model. To date, the emphasis has been on building the aquifer layer geometry and performing "steady state" flow simulations. Layer geometry accounts for many of the important patterns and trends in the data. Steady state analysis leads to a conservative approach to groundwater management and planning.

The addition of advanced climate-based recharge models, transient flow effects, surface water stream routing, and wellfield optimization are logical extensions to this model. The data needed to support these advanced simulations is presently being added to the database.

Potential applications and benefits of maintaining these products and supporting a cycle of refinement and update include:

- improved resource management -- a regionally consistent approach allows the analysis of cumulative impacts of all regional water use operations;

- quantitative assessment -- while the model cannot represent all the local-scale aspects of the flow system, it can provides a quantitative tool for evaluating possible impacts of water use management decisions on the groundwater and surface water systems;

- cost effective analysis -- modelling can now be applied to assess planning and resource management issues that might not have, by themselves, justified the cost of constructing a numerical model.

- improved identification of new water resources -- the model can be used to help identify potential new water supply locations and evaluate potential impact on existing private wells (well interference).

- proactive (predictive) approach to water resources issues -- modelling can be applied much earlier in project planning and construction phases, allowing for a more proactive, and not reactive, approach to water resource issues; and

- development of sustainable management and operations -- wellfield optimization simulations can be used to select operational pumping rates that minimize impact on streams and wetlands.

10 Limitations

Services performed by **Earthfx Inc.** were conducted in a manner consistent with that level of care and skill ordinarily exercised by members of the environmental engineering and consulting profession.

This report presents the results of data compilation and computer simulations of a complex geologic setting. Data errors and data gaps are likely present in the information supplied to Earthfx, and it was beyond the scope of this project to review each data measurement and infill all gaps. Models constructed from this data are limited by the quality and completeness of the information available at the time the work was performed.

Computer models represent a simplification of the actual geologic conditions. The applicability of the simplifying assumptions may or may not be applicable to a variety of applications.

This report does not exhaustively cover an investigation of all possible environmental conditions or circumstances that may exist in the study area. If a service is not expressly indicated, it should not be assumed that it was provided.

It should be recognized that the passage of time affects the information provided in this report. Environmental conditions and the amount of data available can change. Discussions relating to the conditions are based upon information that existed at the time the conclusions were formulated.

All of which is respectively submitted,

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12 Glossary

Note: Bracketed numbers refer to the references at the back of Section 12.

Anisotropy: Pertaining to geological strata, the condition of having different physical properties in different directions; with respect to groundwater flow, the hydraulic conductivity in the vertical direction might be much lower than hydraulic conductivity in the horizontal direction. (2)

Aquifer complex: A group of stacked or adjacent aquifers interbedded with finer grained aquitard materials, that none-the-less have hydraulic connection and which effectively behave as one aquifer.

Baseflow: A term often used when referring to groundwater discharge to a stream. Water that enters the surface water system from persistent, slow varying groundwater sources (groundwater discharge) that maintains streamflow between precipitation or snow-melt (runoff) events. Runoff events manifest as short-duration peaks on a streamflow hydrograph.(3)

Baseflow separation: The technique of separating a streamflow hydrograph to distinguish between rainfall or snow-melt (runoff) events versus the longer-term discharge of groundwater. A number of graphical techniques are available for baseflow separation. (3)

Boulder pavement: An accumulation of boulders once contained in a till deposit and remaining nearly in their original position after removal of the finer materials by erosive (water/waves/current) action. (2)

Boundary conditions: An important component of the modelling process - boundary conditions are necessary to define how the model area interacts with the external flow system. In groundwater modeling, a hydrogeological setting that is fixed in some way by the modeler (i.e. not calculated by the model process). Boundary conditions are typically set at the model boundaries or where the groundwater system interacts with streams or rivers. Boundary conditions either restrict flow (no flow boundary); establish a specified head (Type 1); establish a specified flow (Type 2) or are head dependent (Type 3).

Buried bedrock valley. An erosional valley feature of the bedrock surface that has been in-filled and overlain by younger, typically unconsolidated sediments. The valley infill may include coarse-grained sediments with significant aquifer potential. These features can be quite deep and typically are not readily apparent from the ground surface.

Braided Stream: A stream that flows in several dividing and reuniting channels resembling the strands of a braid, the cause of division being the obstruction by sediment deposited by the stream. Braided streams are commonly found in areas in front of a glacier. See Outwash Plain.

Capture zones: The 3-dimensional subsurface area that contributes groundwater to a well. This zone is typically depicted in two dimensions by projecting the zone onto the ground surface. The capture zone is the entire area that contributes groundwater to the well whereas a wellhead protection area is more typically a portion of the capture zone defined by the water that is captured within a certain period of time (e.g. 25 years). Also see Wellhead Protection Area.

Central Metasedimentary Boundary Zone (CMBBZ): A prominent structure (lineament) and major tectonic boundary in the mid-Proterozoic basement rocks underlying the Paleozoic rock units in Southern Ontario. It separates discrete terrains of the basement rocks. This feature, along with other similar ones, is interpreted to have influenced the ancient Paleozoic drainage features that developed on the Paleozoic surface. (19)

Channel infill: Referring to the sediment infill of a fluvial channel, a bedrock channel or a tunnel channel system. (Davies)

Clast: An individual constituent, grain, or fragment of a detrital sediment or sedimentary rock, produced by the physical disintegration of a larger rock mass. (2)

Conductance: Conductance is a term used in MODFLOW and is the product of hydraulic conductivity and cross-sectional area of flow divided by the flow path (in the case of modeling the distance between cell nodes. See also streambed conductance and vertical conductance. (12)

Constant head boundary: A boundary condition along which the hydraulic head (water level) is specified; also called a Type 1 boundary. See also Boundary Conditions. (17)

Convergence criteria: In groundwater flow modeling, the specified target for which the change in the solution (head change) at each point must be achieved between iterations. For example, the program will stop iterating when the largest head difference during any step is less than the convergence criteria, and the model is said to have converged.

Cross-bedding (cross-stratification): A primary sedimentary structure in which a layer of consolidated or unconsolidated sediment is uniquely distinguishable, as sets of inclined laminar or trough-shaped bed forms, from the predominant horizontal layering. Cross-bedding can be formed in a number of different depositional environments but the mechanism that produces most cross-bedding is encroachment by avalanching down the lee slope of dunes, ripples, bars, fans or small deltas in response to oversteepening. (10)

Cross-watershed flow: Groundwater flow that crosses surface watershed boundaries.

Cuesta: An asymmetrical ridge, with a long gentle slope on one side conforming with the dip of the underlying strata, and a steep or cliff-like face on the other side formed by outcrop resistant beds. The Niagara Escarpment is an example of a cuesta.

Cumulative baseflow: The volume of baseflow (groundwater discharge) summed up over a number of modeling cells along a stream reach (estimated) and used as a calibration target to match observed baseflow (groundwater discharge) as derived from a long term streamflow gauge.

Debris flow: A moving mass of rock fragments, soil and mud under gravity in which the larger grains are supported by a matrix of interstitial fluid and fine sediment that has enough strength (cohesion) to prevent the larger grains from settling but not so much that the mass itself cannot flow. (4)

Deformation Till: A subglacial till that forms as a result of extensive subglacial deformation. The resultant till is commonly massive and homogeneous when fine-grained. It may be the dominant type of till in many glaciated terrains, where the fine-grained nature of the till and moisture content lead to low shear strength, and possible failure or deformation. In coarse-grained sediments, deformation does not appear to be as pervasive. (21)

Dendritic stream network: A stream network in which the streams branch randomly at almost any angle, resembling in plan view the branching habit of trees. Dendritic streams indicate that the underlying deposits offer uniform resistance to erosion. (2)

Diamict / Diamicton: Any poorly-sorted clast-sand-mud mixture regardless of depositional environment, whether glacial or other. This contrasts to the often misused term till, which is used to describe any poorly-sorted clast-sand-mud mixture whose particles have been brought into contact by the direct agency of glacier ice. Lithified diamict is termed diamictite. (5)

Discharge: The rate of stream flow at a given time in terms of volume per unit time. (2). See also groundwater discharge.

Discritization: This is the first step in the modelling process in which the area under consideration is parceled into a grid of rectangular cells or blocks (for a finite-difference model). (12)

Diffusely-bedded: Term applied to a sedimentary deposit with very faint, almost absent bedding structures. Such deposits are often deposited rapidly from sediment-charged flows such as would occur in the lower portion of a turbidite sequence, or at the discharge point of a subglacial debris flow. (1)

Distal: Sedimentary material that is deposited farthest from the source. Proximal would be used to refer to sedimentary material deposited closest to the source area.

Drain: In MODFLOW, the term for a kind or river or canal represented in the model that acts in only one direction to drain water (i.e. receive groundwater discharge) from the groundwater system. Drains cannot leak water back to the groundwater system to underlying aquifers. In contrast, MODFLOW Rivers can recharge underlying aquifers.

Drift: A generic term for all material transported and deposited by glaciers, either directly from the ice or through the agency of meltwater. It generally applies to Pleistocene deposits in large regions that no longer contain glaciers. (2)

Dropstone: A clast within a glaciolacustrine or glaciomarine deposit that was dropped or rafted from floating ice and which is significantly coarser in grain size than the sediment into which it was dropped. (6)

Drumlin: A low, smoothly rounded, elongate hill of compact till, or rarely other kinds of glacial drift that were formed by glacial erosion or deposition (2). The mechanism of formation (erosion or deposition) is currently subject to debate; two popular but opposing views are that they were eroded or deposited directly by glacial ice (7), or they were eroded by catastrophically released meltwater flows (8).

Esker: A serpentine ridge of roughly stratified sand and gravel that was deposited by a stream flowing in or beneath the ice of a stagnant or retreating glacial and was left behind when the ice melted. Lengths can vary from less than 100 m to more than 500 km (counting gaps) and in height from 3 to more than 300 m. (2)

Facies: A sedimentological unit with a unique lithological, structural and organic aspect detectable in the field that will ultimately be given an environmental interpretation. The facies definition by itself is quite objective and based on the total field aspect of the sedimentological units themselves. (1)

Fining-upward sequence: A textural description of consolidated or unconsolidated clastic sediments in which the overall sediment grain size decreases with increasing elevation or "fines-up". Such sequences can occur on a scale of less than a meter (e.g. individual bed) to many tens of meters or more.

Finite-difference method: A numerical method that, in formal terms, uses the Taylor series expansions to derive approximations for first and second-order derivatives in the groundwater flow equation. The method can also be seen as a conservation of mass technique that computes a flow balance for each cell based on the hydraulic head in the adjoining cells. The USGS Modflow code is one example of a finite-difference based groundwater modeling code.

Fluvio-deltaic system: A continuum of depositional environments from upstream fluvial (river) deposition to downstream deltaic deposition at the terminus of the fluvial system in a lake or ocean. Sediments deposited in these environments tend to be fairly coarse-grained due to the intensity of flow in these systems. Grain size tends to decrease from the fluvial system to the deltaic system since the fluid velocity and therefore sediment carrying capacity decreases as the fluvial system enters a standing body of water. (10)

Flux (also Darcy's Flux): The rate of flow (m^3/s) per unit area (m^2); used to quantify the discharge of groundwater to drains and rivers in groundwater modeling.

Fossiliferous: Pertaining to a sedimentary rock unit containing fossils.

Gaussian relationship: Used in a variance analysis in geostatistics, this relationship is a model for fitting the theoretical variogram showing little variation within short distances of the data point. Variance increases rapidly with distance before approaching the sill asymptotically. When using the Gaussian model, a small nugget must be added, otherwise the kriging matrix becomes ill conditioned and results may be very erratic. (12)

Geostatistics: The statistics of spatially correlated data; the basic concept of geostatistics is that of scales of spatial variation - spatially independent data show the same variability regardless of the location of data points. However, spatial data in most cases are not spatially independent. Data values which are in close proximity geograpically show less variability than data values which are farther away from each other. The exact nature of this pattern varies from data set to data set; each set of data has its own unique function of variability which is generally computed as a function called the semivariance.

Glaciofluvial: Pertaining to a depositional environment comprising a fluvial system within an overall glacial environment. A glaciofluvial system typically occurs in front of an advancing or retreating glacier and carries glacial meltwater.

Glaciolacustrine: Pertaining to a glacial lake setting. A glacial lake is partially or entirely fed by meltwater or is held by a morainal or ice dam. (2)

Groundwater discharge: Water that discharges from the groundwater system to the surface as springs, seeps or upwellings. If volumes are significant the discharge can become baseflow of a stream. Areas of groundwater discharge have upward hydraulic gradients.

Groundwater divide: A line, on either side of which, the water table surface slopes downward. It is analogous to a drainage divide between two watersheds or drainage basins at the land surface.

Head-dependent discharge boundary: One type of boundary condition in which the flow across the boundary is dependent on a known head external to the boundary. Typically used to represent the connection between surface and groundwater systems where the hydraulic conductivity of the streambed sediments is generally lower than that of the aquifer. Can also be used to represent leakage from overlying or underlying semi-confined aquifers.

Hummocky topography: Pertaining to an area where the topography is undulatory with a predominance of closed depressions that minimize surface water runoff and enhance groundwater infiltration.

Hydraulic connection: Referring to the connectedness between areas or aquifers or the ability of groundwater to move from of one aquifer setting to another (or to the surface (e.g. stream)).

Hydrostratigraphy: The classification of the stratigraphic units into aquifers or aquitards including the combination of vertically continuous geologic units with similar hydraulic properties into a single unit.

Ice marginal flow till: Refers to massive and poorly-sorted or stratified till-like deposits resulting from a debris flow or sediment gravity flow associated with an ice marginal glacial setting. Flow tills can contain: floating or rafted boulders, rip-up clasts, flow shears, and load and dewatering structures. (21)

Interglacial: Pertaining to the time between glaciations. (2)

Interlobate: Situated between two or more glacial lobes (e.g. Ontario Lobe, Huron Lobe); frequently pertains to sediments accumulated in interlobate environments. (2)

Intermittent stream: A stream that does not flow year round but rather only in times of high rainfall or during the spring melt. Can be contrasted with perennial streams which flow year round and are typically sustained by groundwater flow between rainfall events. (3).

Interpolate: In the case of groundwater investigations, it refers to estimating, by kriging or some other geostatistical technique, values (e.g. heads, elevations, chemical concentrations etc.) at locations where no measurements have been taken, using nearby locations where measurements have been taken.

Interstadial (interstade): A warmer substage of a glacial stage, marked by a temporary retreat of the glacial ice. (2)

Intrinsic variation: Refers to the inherent error in the water levels within the database. In geostatistics, the intrinsic variation can also be referred to as the “nugget” and indicates that two wells screened in the same aquifer and found side by side can still have water levels that are different by on the order of 5 to 10 m. This inherent error has been introduced by a number of factors discussed in the report.

Isopach: A line drawn on a map through points of equal thickness of a designated stratigraphic unit or group of stratigraphic units. (2)

Isostatic rebound: Isostasy is the concept that the Earth's surface seeks a balance between the weight of lithospheric rocks and the buoyancy of underlying nearly-molten rock. Gentle regional movement of the lithosphere occurs in response to short-term (thousands to millions of years) loading and unloading, as by ice, erosion or sediment deposition. Isostatic rebound therefore refers to the uplift of the lithosphere after the loading of glacier ice is removed. Isostatic rebound is still occurring in Ontario today following the retreat of the last continental ice sheet about 10,000 years ago.

Isotope: One or two or more species of the same chemical element, i.e., having the same number of protons in the nucleus, but differing from one another by having a different number of neutrons. The isotopes of an element have slightly different physical and chemical properties, owing to their mass differences, by which they can be separated (2).

Kriging: An interpolation technique for obtaining statistically unbiased estimates of surface elevations from a set of control points. Kriging uses a mathematical model of the semi-variogram to calculate estimates of the surface at a grid node. Named after the South African engineer, D.G. Krige, who first developed the method. (12)

Lake Algonquin: A glacial lake that occupied parts of the basins of Lake Huron and Lake Michigan about 12,000 years ago. (19) Glaciolacustrine sediments associated with Lake Algonquin are common in the NVCA and LSRCA areas.

Lake Iroquois: A glacial lake that occupied the Lake Ontario basin at about the same time as Lake Algonquin (12,000 years ago). Glacial Lake Iroquois drained southeastward via an outlet at Rome, New York. (19) Remnants of the Lake Iroquois shoreline remain evident in the form of beaches, bars, cliffs and boulder pavements. (16)

Laminae: The thinnest recognizable layer in a sediment or sedimentary rock, differing from other layers in colour, composition or particle size. (2)

Laurentian Channel: The channel of a major river that existed in preglacial times which drained the present Great Lakes area. The river flowed from Georgian Bay to Lake Ontario and then eastwards. (18) The eroded channel and its sediment in-fill are now covered by glacial sediment. The in-fill sediments are found within a typically wide, shale-floored buried bedrock valley, often with significant aquifer potential.

Lodgment till: A till deposited at the base of the ice sheet (i.e. a basal till) commonly characterized by compact structure and containing stones oriented with their long axis generally parallel to the direction of the ice movement. (2)

Lithology: The description of rocks or sediment on the basis of such characteristics as colour, mineralogical composition and grain size. (2)

Massive: Pertaining to rocks or overburden deposits of any origin that are more or less homogeneous in texture or fabric, displaying an absence of layering, bedding or stratification. (2)

Melt-water scour: An erosive mark (e.g. flute) or excavation produced by concentrated erosive action by glacial meltwater. (2)

Microclimate: A microclimate is a local area where the climate differs from the surrounding region. Examples include areas near bodies of water which may experience cooler temperatures due to the lake cooling of the local atmosphere, or heavily urban areas where might experience warmer temperatures as a result of brick, concrete, and asphalt absorbing the sun's energy, heating up, and reradiating that heat to the ambient air. (22)

Model calibration: The process in numerical groundwater flow modelling during which key parameters (e.g. recharge or hydraulic conductivity) are adjusted so that modeled predictions more closely aligned with observed field measurements.

Moraine: A mound or ridge of glacial sediments, chiefly till, deposited by direct action of glacial ice. Includes ground moraines, lateral moraines, medial moraines and terminal moraines. (2 & 13)

No-flow boundary: A boundary condition in Modflow across which no groundwater flows such as at a watershed divide.

Nugget: In geostatistics the variance at the point where the variogram curve crosses the y-axis. It is related to the local-scale variation in the data and includes the inherent measurement error (the “nugget” is named after the distorting effect that the presence of randomly distributed gold nuggets have on local-scale variation in gold ore concentration). In the case of water level data, the nugget represents both local-scale measurement errors and natural variations in the data.

Numerical groundwater flow model: A groundwater flow model is a mathematical representation of a physical groundwater system. In a numerical model, the governing partial differential equation and boundary conditions are approximated by a set of algebraic equations. The study area is sub-divided into many small blocks and the flow equations are written and solved for the aquifer head in each block. Two common techniques, the finite-difference method and the finite element method, are used in approximating the groundwater flow equation.

Outcrop: Typically refers to a segment of bedrock exposed to the atmosphere, however in the context of Southern Ontario also refers to an exposure of unconsolidated glacial sediment that is cut or eroded (e.g. by a road or stream) and where sedimentary structure, bedding etc. can be readily observed. (13)

Overburden: In Southern Ontario refers to the unconsolidated sediments, often of glacial origin, overlying bedrock. In the mining and aggregate industries, it refers to the uneconomical material overlying an extractable economic deposit (e.g. dolostone) that must be removed prior to mining. (2)

Over-consolidated: A very dense sediment that has resulted in response to an increased load and the squeezing out of pore water. The Newmarket Till is typically over-consolidated, especially where the overburden thickness is significant and glacial loading caused Newmarket pore waters to drain into the underlying Thorncliffe Aquifer (Thorncliffe Fm.) .

Paleoflow indicator: An indicator of water flow (current) direction at the time of the deposition of a sediment unit. The flow direction is inferred from sedimentary structures in the consolidated or unconsolidated sediment deposit. (2)

Picking: Refers to the process of interpreting the top of a geological unit on a well log in cross-section view. The process involves assigning an X,Y,and Z value, as well as a geological name, to a database table.

Pinched/pinchout: The termination or end of a stratum or vein that narrows or thins progressively in a given direction until it disappears and the consolidated or unconsolidated units it once separated are in contact. (2)

Polyline vertex points: The points on a drawn polyline, either in plan view or cross-section that are used, along with picks at well locations, to constrain the interpolation of a surface.

Potentiometric surface: A contoured map of hydraulic head in a confined aquifer that provides an indication of the directions of groundwater flow in that aquifer. (11)

Pre-processor: A numerical modelling term that applies to the software program where various GIS based map files are imported and made compatible with the modeling software being used. Pre-processing refers to the electronic assembly of maps and data necessary to run a groundwater model.

Prodelta: The part of the delta that is below the effective depth of wave erosion, lying beyond the delta front, and sloping gently down the to the floor of the basin into which the delta is advancing and where clastic river sediments cease to be a significant part of the basin-floor deposits. (20)

Prograding: said of a sedimentary facies (such as a shoreline or a delta) that is being built forward or outward into a sea or lake by deposition and accumulation. (2)

Pushdown analysis: An analytical technique employed during the construction of surfaces. In the most common example of the bedrock surface, deep wells that do not intersect bedrock are used to “pushdown” the bedrock surface thus ensuring that the bedrock surface is interpreted below the bottom of these deep wells.

Rafting: Transportation of rocks by means of attachment to ice (in glacial settings). (2)

Range: In geostatistics, the distance beyond which there is no longer any significant correlation between the measurements at two locations. (The range is the distance at which the sill is reached.) This is the point at which the correlation drops to zero and the variance is equal to the sample variance.

Recharge: The inflow of water to a ground-water reservoir from the surface (e.g. infiltration of precipitation and its movement to the water table). Also, the volume of water added by this process.

Reflector: In geophysics, an interface between layers of contrasting acoustic, optical or electromagnetic properties. Waves of electromagnetism, heat, and sound can be reflected at such an interface. In seismic geophysical studies, a reflector typically represents a change in lithology, a fault or an unconformity. (23)

Rhythmite: A individual unit of a rhythmic succession, in which there is a repetition, through sedimentary succession, of a sequence of two or more rock units in a particular order and indicating a frequent recurrence of the same sequence of conditions. (2) In glacial sediments, the rhythmites may be varves, (i.e., couplets resulting from an annual seasonal variation) or may be the result of subaqueous debris flows or other similar phenomenon. The use of the word rhythmite (as opposed to varve) is more generic.

Runoff: In the basic, most common usage, runoff refers to overland flow which travels downslope towards the nearest surface water body. That component of precipitation that does not infiltrate into the ground surface (recharge) nor evapotranspirate back to the atmosphere. (11)

Sapping: Refers to the process of erosion along the base of a cliff, where soft erodable layers are found beneath a more resistant caprock. Sapping wears away the softer underlying layers and allowing the rocks above to fall in large blocks. This process is responsible for the erosion of the Niagara Escarpment. (2)

Seismic profile: A vertical profile through the subsurface derived from the use of artificially generated seismic waves (by mini-vibrators or shotgun blasts) in the search for economic deposits (oil and gas) or in engineering / hydrogeological studies. (2)

Seismic Reflection: The seismic reflection method is based on the measurement of the travel time of seismic waves refracted at the interfaces between subsurface layers of different velocity. Seismic energy is provided by a source ('shot') located on the surface. Energy radiates out from the shot point, either traveling directly through the upper layer (direct arrivals), or traveling down to, and then laterally along higher velocity layers (refracted arrivals) before returning to the surface. This energy is detected on surface using a linear array of geophones. Observation of the travel-times of the refracted signals provides information on the depth profile of the refractor.

Semi-confined aquifer: Also referred to as a leaky aquifer, this type of aquifer is overlain by an imperfect aquitard that allows some inflow of water to the aquifer. (11)

Sensitivity analysis: One of the last steps in numerical groundwater modelling that is completed after the model is built and calibrated, the sensitivity analysis is carried out by adjusting key parameters both upwards and downwards and observing the results with respect to the calibration targets. The objective of the sensitivity analysis is to assess whether the model assumptions are valid and whether the input data are reasonable.
Sheet-flow: A broad flow of water produced in a sub-glacial meltwater flood event that is not contained within well-defined channels. The duration of these flows is typically short and they are thought to progress into more channelized flow.

Sill: In geostatistics, the variance at a distance greater than the range and therefore equal to the sample variance. The beginning of the sill represents the distance at which there is no longer any statistical correlation.

Sonic log: A type of acoustic geophysical log that displays travel time of P-waves versus depth. The tool emits a sound wave that travels from the source to the formation and back to a receiver. (23)

Specific capacity: The pumping rate at a given well divided by the drawdown. This unit (typically measured as gallons/minute/per foot of drawdown) is a measure of well yield. (9)

Spotflow: is a spot or instantaneous measurement of the flow or discharge in a stream. The objective of a spotflow measurement is to delineate stream reaches that receive groundwater discharge and therefore the discharge values are obtained after a period of time (typically three days) with no measurable precipitation so that the recorded flow values should represent baseflow.

Stade: A substage of a glacial stage (period of time) marked by a glacial readvance. (2)

Steady-state flow: Steady-state flow occurs when at any point in a flow field, the magnitude and direction of the flow velocity are constant with time. (11) A steady-state numerical groundwater flow model, therefore, is one in which the magnitude and direction of the flow velocity in every grid cell are constant and do not change with time.

Strahler classification system: A methodology for quantitatively designating stream orders developed by Strahler in 1952. Streams with no tributaries are designated first-order streams; the confluence of two first-order streams is the beginning of a second-order stream and so on. (3)

Stratified: Formed, arranged or laid down in layers or strata, especially said of any layered sedimentary consolidated or unconsolidated deposit. (2)

Striation (striated): One of multiple scratches or minute lines, generally parallel, inscribed on rock surface by a geological agent, such as a glacier. (2)

Streambed Conductance: In MODFLOW, the term used to represent the geometric and hydraulic properties of a streambed. In each cell of the model, it is calculated as the length of the streambed multiplied by the width of the streambed multiplied by the hydraulic conductivity of the streambed all divided by the thickness of the riverbed sediments.

Subaqueous: Said of conditions, processes, or deposits that are situated under water, especially fresh water. (2)

Subglacial: Formed or accumulated in the bottom parts of the glacier; said of the meltwater streams, till, moraines, etc that form immediately beneath a glacier. (2)

Surface-water divide: The surface trace of the boundary that delimits a watershed. (3) This surface trace occurs at a topographical high such that runoff occurring on either side of the high would flow to different watersheds.

Thalweg: A line, as drawn on a map, connecting the lowest points of a valley. (20) Used in this report to represent bedrock valleys.

Till: An unconsolidated, typically structureless sediment containing all grain sizes from clay to boulders deposited by glacial action. Some debate exists regarding the use of the term since till-like sediments can also be formed in non-glacial sedimentological environments (e.g. debris flows). The term diamict might be more appropriate as it is more generic and does not imply an interpretation of the depositional setting (i.e., glacial versus non-glacial). (13)

Till plain / till sheet: An extensive area, with a flat to undulating surface, underlain by till often with subordinate end moraines. (2)

Transient flow: or non-steady flow occurs where, at any point in the flow field, the magnitude or direction of the flow changes with time. A transient groundwater flow model, therefore, would be one with a time component such that the magnitude and direction of the flow in any of the grid cells could change with time in response to a change in stress. (11)

Transmissivity (T): a term derived by multiplying the hydraulic conductivity (K) by the aquifer thickness (B) that was developed primarily for the analysis of well hydraulics in confined aquifers (e.g. pumping tests). (11)

Triaxial permeability: A laboratory measure of permeability in the three principal directions, x, y and z.

Trunk and tributary valley system: Refers to a valley system, typically fluvial in origin, in which there is one main valley (trunk) and a number of tributary valleys.

Tunnel channel: Refers to a channelized erosional feature of glacial origin created by meltwater flood events of varying magnitude. In the report the term is sometimes used interchangeably with sub-glacial meltwater feature. An example of a prominent tunnel channel in Southern Ontario is the Holland Marsh.

Unconformity: A break or gap in the geological record, such as an interruption in the normal sequence of deposition of sedimentary deposits. An unconformity in sedimentary deposits often occurs with a regional erosional surface such as that interpreted at the top of the Newmarket Till which is attributed to tunnel channel related erosion. (2)

Underflow: refers to deeper more regional groundwater flow that does not discharge to local streams etc. but which crosses watershed divides. This underflow must be considered when undertaking water budgeting studies.

Variogram analysis: An analytical technique used with kriging for quantifying and describing spatial variance using the normalized semi-variance statistic. The plot of semi-variance versus distance is called the experimental semi-variogram, or just the variogram. (12)

Varve: A sedimentary lamina or sequence of laminae deposited in a body of still water within one year's time, specifically, a pair of layers seasonally deposited in a glacial lake. A glacial varve normally includes a lower "summer" layer consisting of light-coloured sand or silt, which grades upward into a thinner "winter" layer consisting of clay-rich darker sediment. (2)

Vertical conductance: Similar to conductance as defined above, however in MODFLOW, the user is allowed to adjust the vertical conductance manually to better represent flow across aquitards,

Waning stage: referring to the final stages of a meltwater flood event. (Davies)

Watershed (also drainage basin, river basin or catchment): The land area where precipitation runs off into a network of streams, rivers, lakes, and/or reservoirs that all drain via a common main channel to a lake or ocean. A watershed can be delineated by tracing a line along the height of land on a map.

Wellfield optimization: The strategic operation of wells within a wellfield such that water production is maximized while drawdown and other negative effects are minimized. Numerical models can be used to assist in this optimization.

Wellhead protection area (WHPA): The portion of a capture zone to which a municipality wishes to apply landuse restrictions or other planning restrictions in order to protect the quality of groundwater moving to a municipal well.

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APPENDICIES

APPENDIX A

YPDT – CAMC PROJECTS

1 Appendix A: YPDT-CAMC Concurrent and Related Projects

1.1 YPDT-CAMC Project Overview

To advance the understanding and management of the groundwater system across the ORM, the YPDT-CAMC study group completed a Phase 1 investigation in 2001 consisting largely of an inventory of groundwater initiatives carried out in the southern Ontario area. More recently, the partnership spearheaded a series of technical studies, including the current regional groundwater modelling investigations as well as strategic data acquisition initiatives.

A significant component of the YPDT strategy is to set up a consistent set of model guidelines and policies for managing and protecting groundwater resources across the ORM area. A number of concurrent and related technical projects support this strategy with a focus on regional mapping, data compilation and conceptual model validation and modelling.

1.2 Concurrent and Related Projects

The YPDT-CAMC study group has initiated the following studies:

1.2.1 Database Construction

The YPDT Database Construction project provided a foundation for analysis: a single database and GIS mapping system ensured that there was seamless and consistent data used throughout the studies. A fundamental principal of groundwater modelling is that the model is only as good as the data on which it was built.

Integrated data management and modelling were central to the approach used for these projects and will provide many benefits for future analysis and interpretation. As the project moves forward, existing data need to be rechecked for quality assurance and quality control (QA/QC).

1.2.2 Groundwater Modelling Projects

As noted in Section 1.1.1, this report represents the combined results of three of modelling studies as presented in Section 1.2.

1.2.3 Stream Flow Measurements

Stream measurements have been taken by staff at the various partner agencies and these data are uploaded to the YPDT-CAMC database on a regular basis. In addition,a specific YPDT-CAMC study was undertaken in 2002 to infill measurement gaps in the stream network with a synoptic set of spot flow measurements (Conestoga Rovers and Associates, 2003).

Objectives of the spot flow measurement program include:

- the determination, in the field where streams start, and the flux or amount of water flowing, to get an indication of how significantly, and where, a particular stream is connected to the groundwater system;
- using the flux measurements to support water budget understanding
- using the flux measurements as useful “ballpark” calibration targets for numerical groundwater flow modeling – especially necessary across this study area due to the poor density of long term stream flow gauging stations.

1.2.4 Stratigraphic Drilling

Several continuously cored boreholes have been constructed in strategic locations to better understand the geologic framework in the study area and to determine groundwater flow patterns.

Through the 1990s the Geological Survey of Canada (GSC) constructed five continuously cored boreholes within the Oak Ridges Moraine area. Following on the GSC’s protocols for these boreholes, the YPDT-CAMC study has undertaken sediment core logging at six locations:

- YPDT–CVC-1 – Peel Region - Heart Lake Road and Old Base Line Road
- YPDT–Grasshopper Rd – Durham Region - Grasshopper Road north of Concession Road 9
- YPDT–Uxbridge – Durham Region - Reach Road at the Uxbridge municipal well site
- YPDT-High Park – Toronto – Corner of Keele St. and Bloor St.
- CAMC-Rice Lake – Northumberland County – County Road 23 north of Centreton
- YPDT - Earl Bales Park – Toronto - Bathurst St. and Sheppard Ave.

The process of logging and compiling the information is an ongoing effort with the Ontario Geological Survey (OGS) and the GSC. Partner agencies also continue to contribute to this effort.

1.2.5 Borehole Geophysics

To help develop an understanding of the depositional processes and subsurface geology within the YPDT area, a suite of seven geophysical logging tools were lowered down the high quality boreholes. The geophysical logging program provides a consistent and repeatable suite of measurements that both supplement and enhance the interpretation of the borehole sediments.

The geophysical logging program included the following elements:

- logging of BHs with gamma, density, neutron, P-wave (sonic), magnetic susceptibility, conductivity and temperature tools. These tools either measure inherent properties of the geological layers (e.g., gamma radiation, electrical conductivity), or emit an energy source that is either absorbed or deflected by the geological material and is then detected by a receiver on the tool (e.g., magnetic susceptibility, neutron, sonic, density)
- both the absolute level of the response as well as the pattern of the response are being used to help correlate the units between boreholes.

1.2.6 Seismic Reflection Surveys

Surface geophysical studies involve sending energy from the ground into the subsurface and detecting the return of that energy as it is reflected or refracted back from subsurface units. This allows the structure of the subsurface (e.g., buried valleys, pinch-outs, lenses, bedrock surface) to be interpreted. To date, seismic studies have been undertaken in the Caledon East Area (~12 km); the Schomberg area (~9 km); the Barrie/Angus area (~16 km) and the Port Perry area (~6.5 km).

1.2.7 Well Location Update

The MOE well record database has a number of wells which did not have well location coordinates. In 2002 over 4214 wells were field checked and located using a GPS methods.

APPENDIX B

GSC DIGITAL STRATIGRAPHIC MODEL

Appendix B: GSC Stratigraphic Model

The stratigraphic framework for the Oak Ridges Moraine area has advanced considerably over the last 10 years due to the work of the Geological Survey of Canada (Sharpe et al., 1999). The GSC has developed a conceptual stratigraphic model (**Figure 16** in the main report) and spent a considerable effort collecting high quality geologic and geophysical data and interpreting drillers logs in the Ontario Ministry of the Environment (MOE) water well database. Their work led to the development of the GSC Version 1 digital geologic surfaces which include (from youngest to oldest):

- Halton Till (Russell et al., 2002a);
- Oak Ridges Moraine Deposits (Russell et al., 2002b);
- Newmarket Till (Sharpe et al., 2002b);
- Lower Sediments (including York, Scarborough, Sunnybrook and Thorncliffe units) (Sharpe et al., 2002c); and
- Bedrock (Brennand et al., 1997).

The GSC published maps of the stragraphic surface elevations and isopachs as large format drawings. These surfaces were provided to the study team in digital format as 30-m digital elevation models. These surfaces form the basis for the ORM Regional Flow Model, discussed in Section 6 of the report. The surfaces are reproduced in this appendix to facilitate discussion and analysis of the Regional Model results. The surfaces provided by the GSC have all been re-sampled to the 100 m grid for presentation purposes.

The first surface is the digital bedrock surface (**Figure B119**) which was derived from Brennand et al., 1997). **Figure B120** shows the thickness of the entire sediment package (derived from Sharpe, 2002a). This is followed by maps showing the top of the Lower Sediments (**Figure B121**), thickness of the Lower Sediments (**Figure B122**), the top of the Newmarket Till (**Figure B123**), Newmarket Till thickness (**Figure B124**), the thickness of the Oak Ridges Moraine deposits (**Figure B125**), and the Halton Till thickness (**Figure B126**).

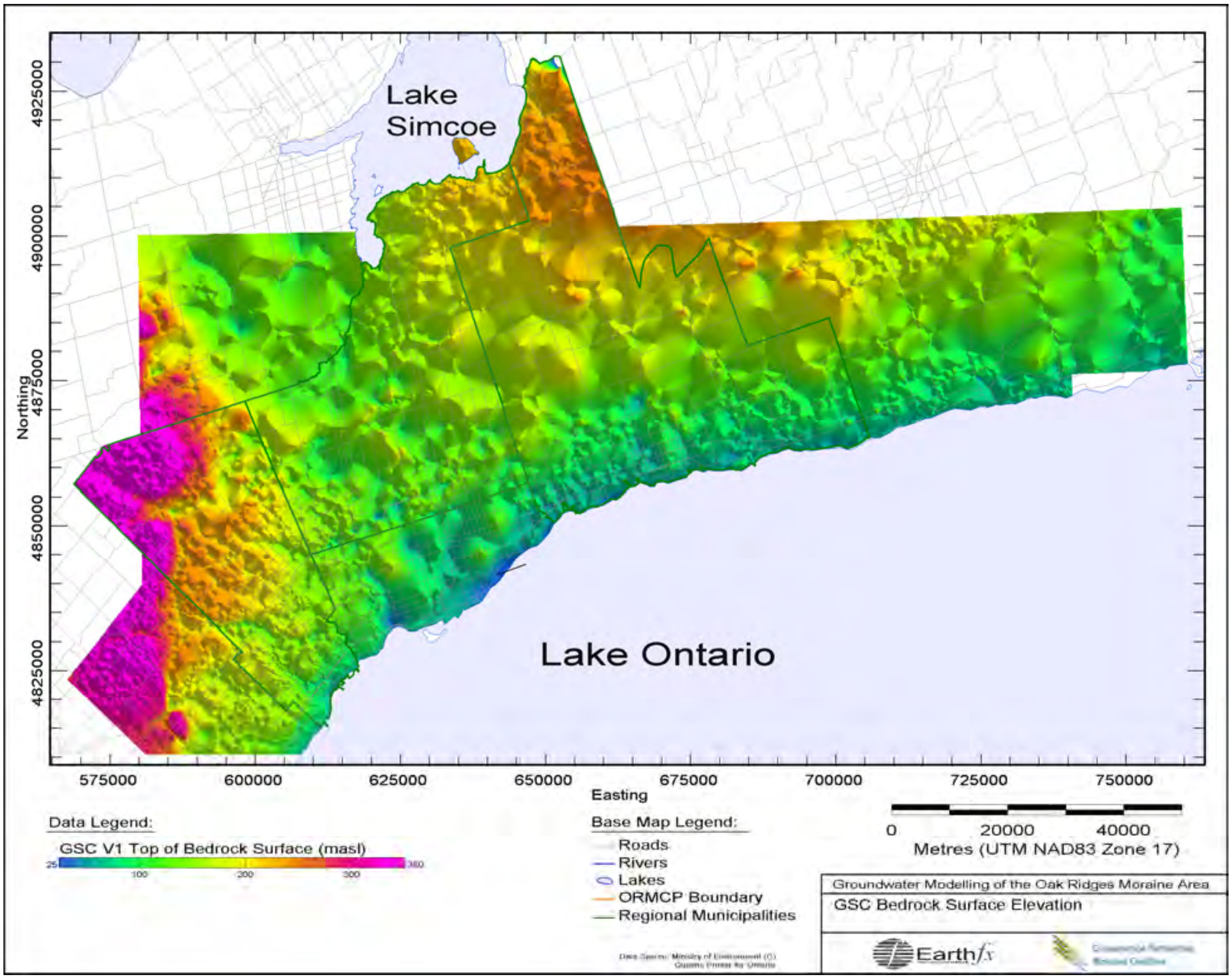


Figure B119: GSC bedrock surface elevation (Brennand *et al*., 1997)

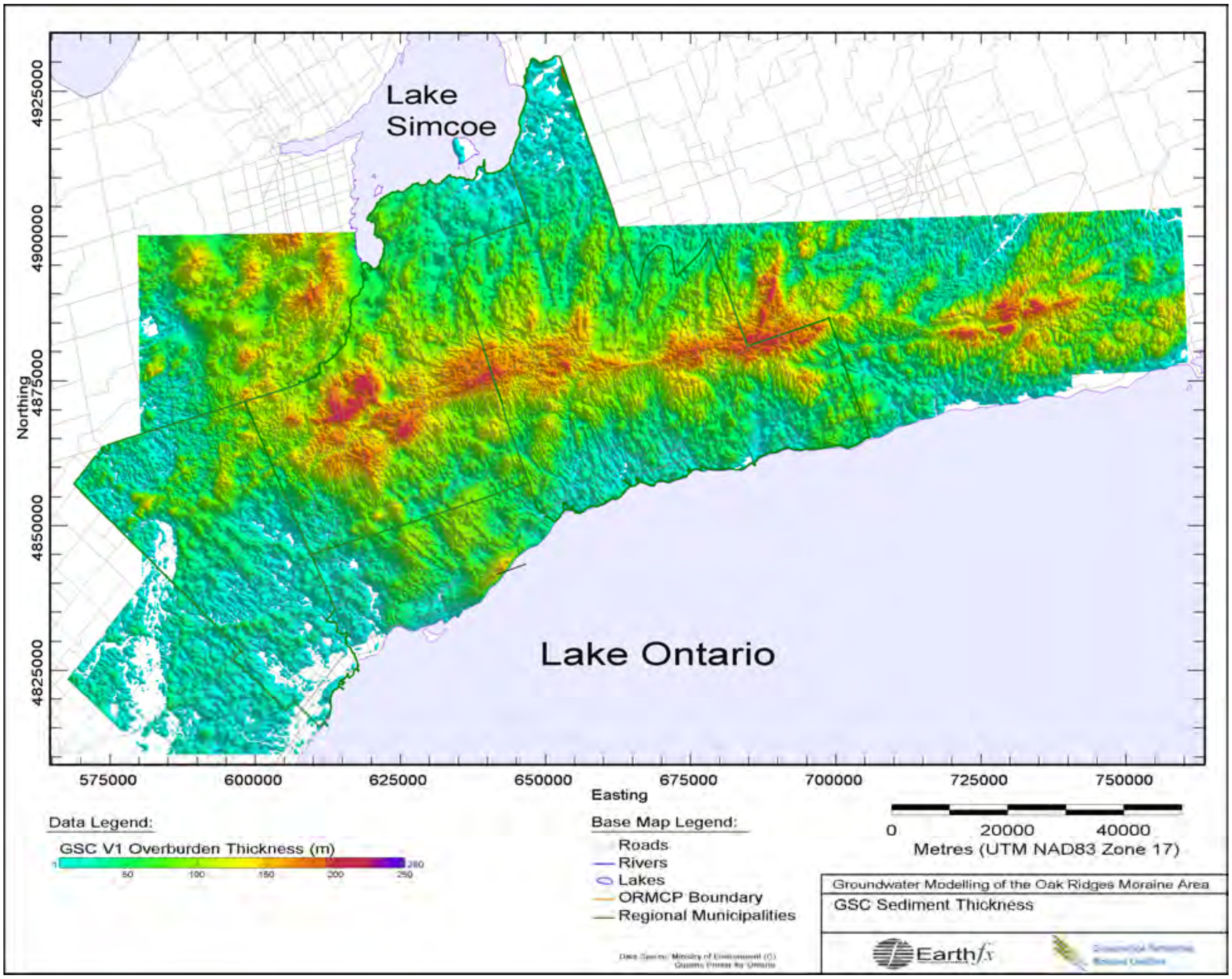


Figure B120: Sediment thickness (derived from Sharpe, 2002a)

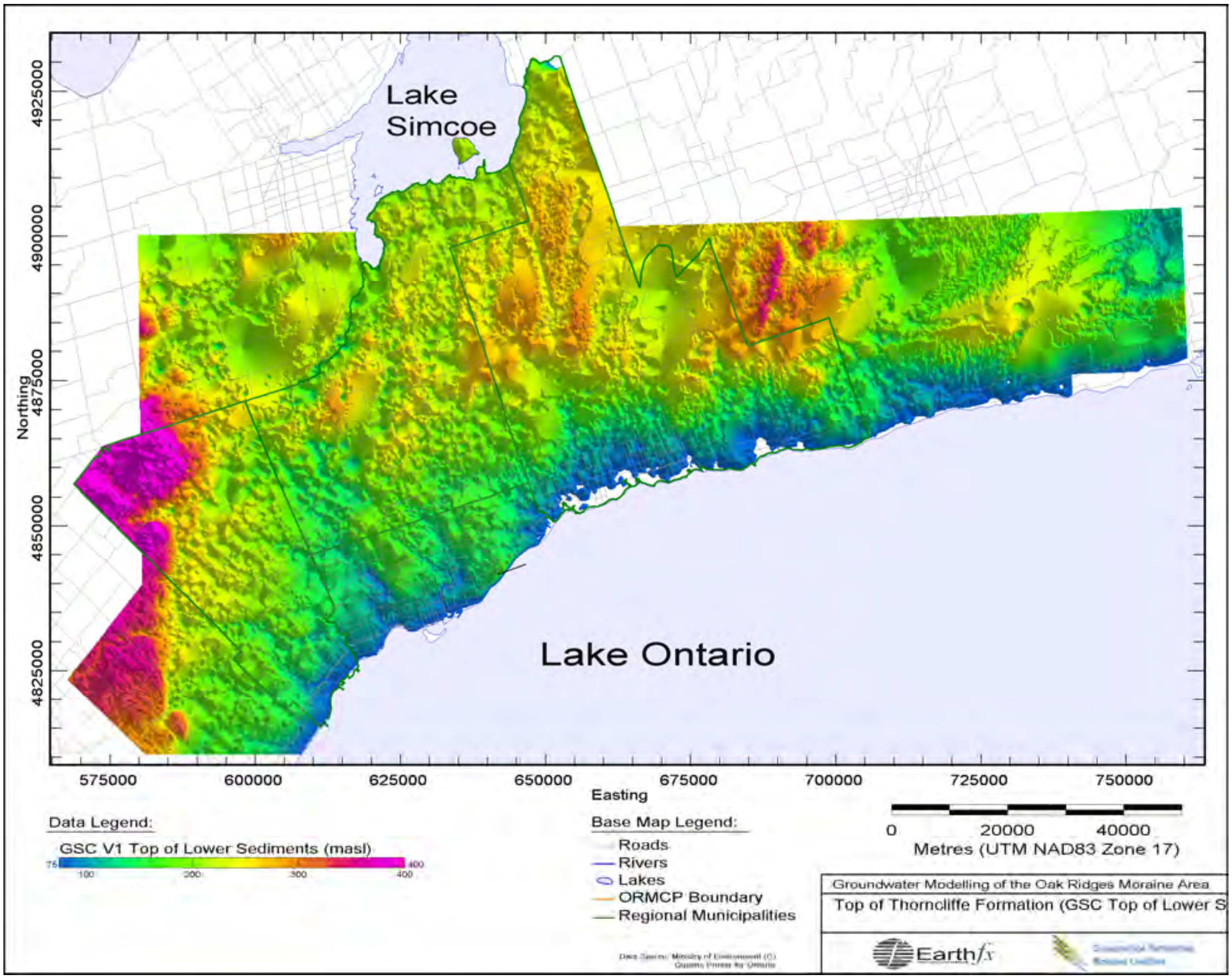


Figure B121: Top of the Thorncliffe Formation (from GSC Top of Lower Sediments, Sharpe et al., 2002c)

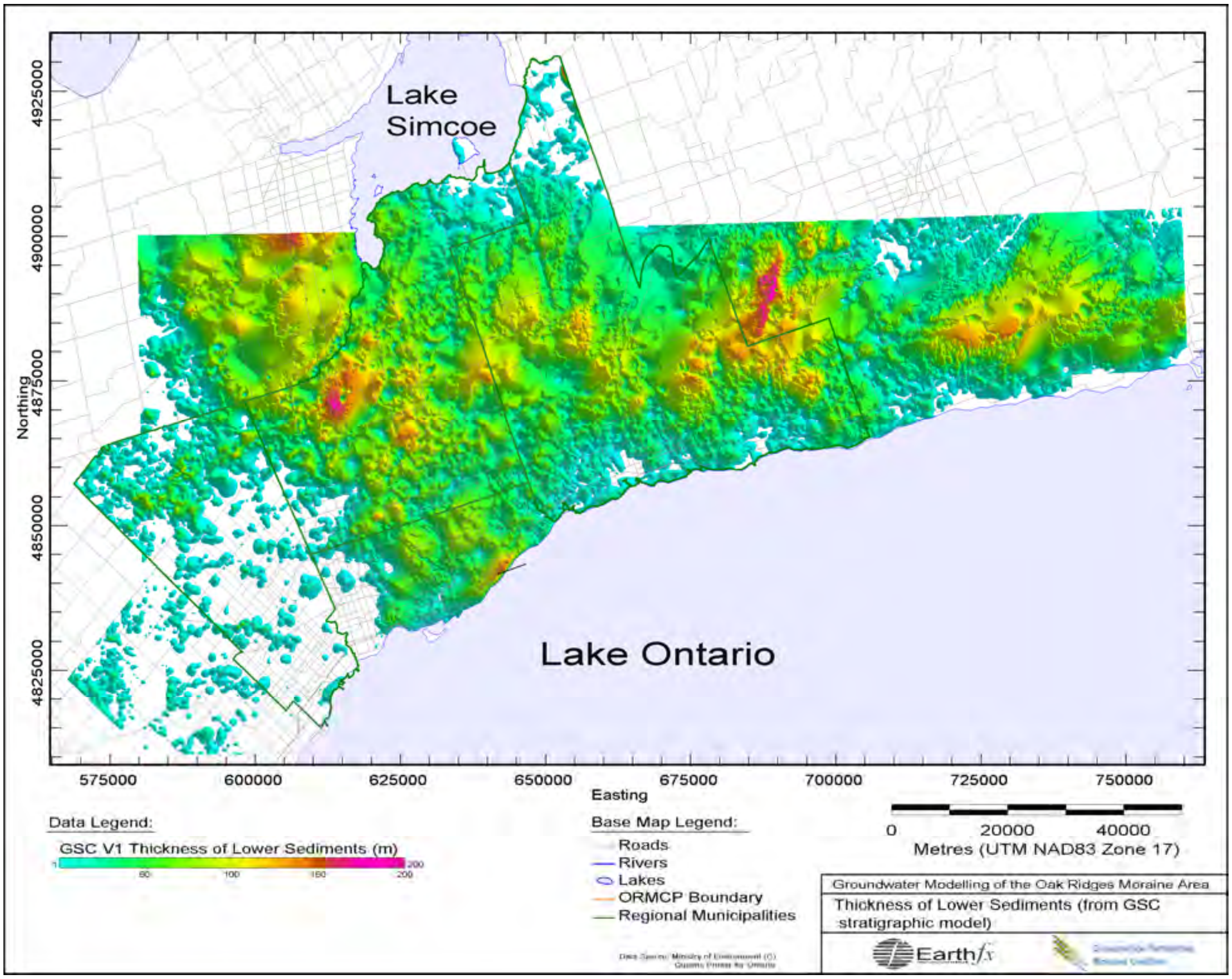


Figure B122: Thickness of the Lower Sediments (from GSC stratigraphic model, Sharpe et al., 2002c)

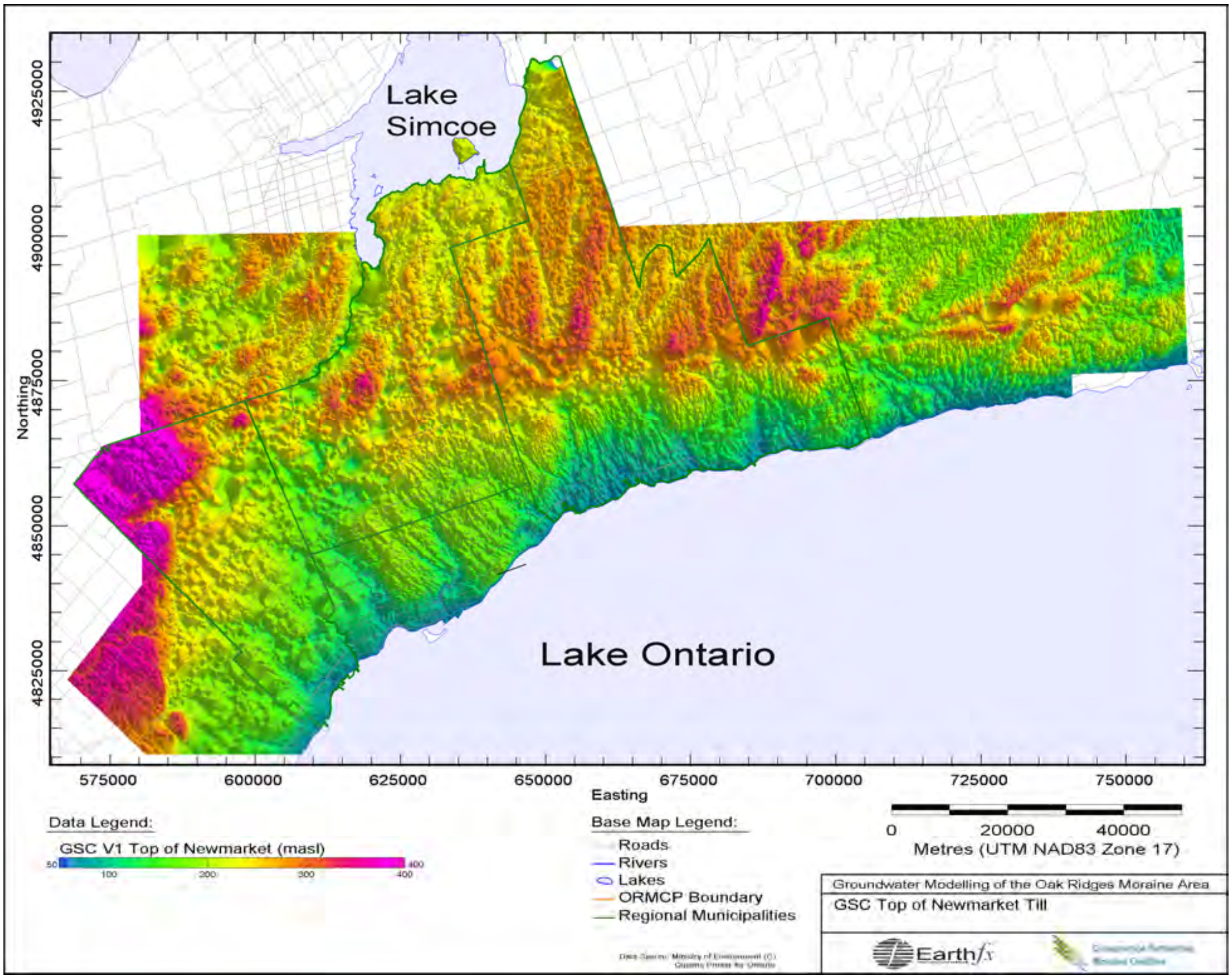


Figure B123: GSC Top of Newmarket Till (derived from Sharpe et al. 2002b)

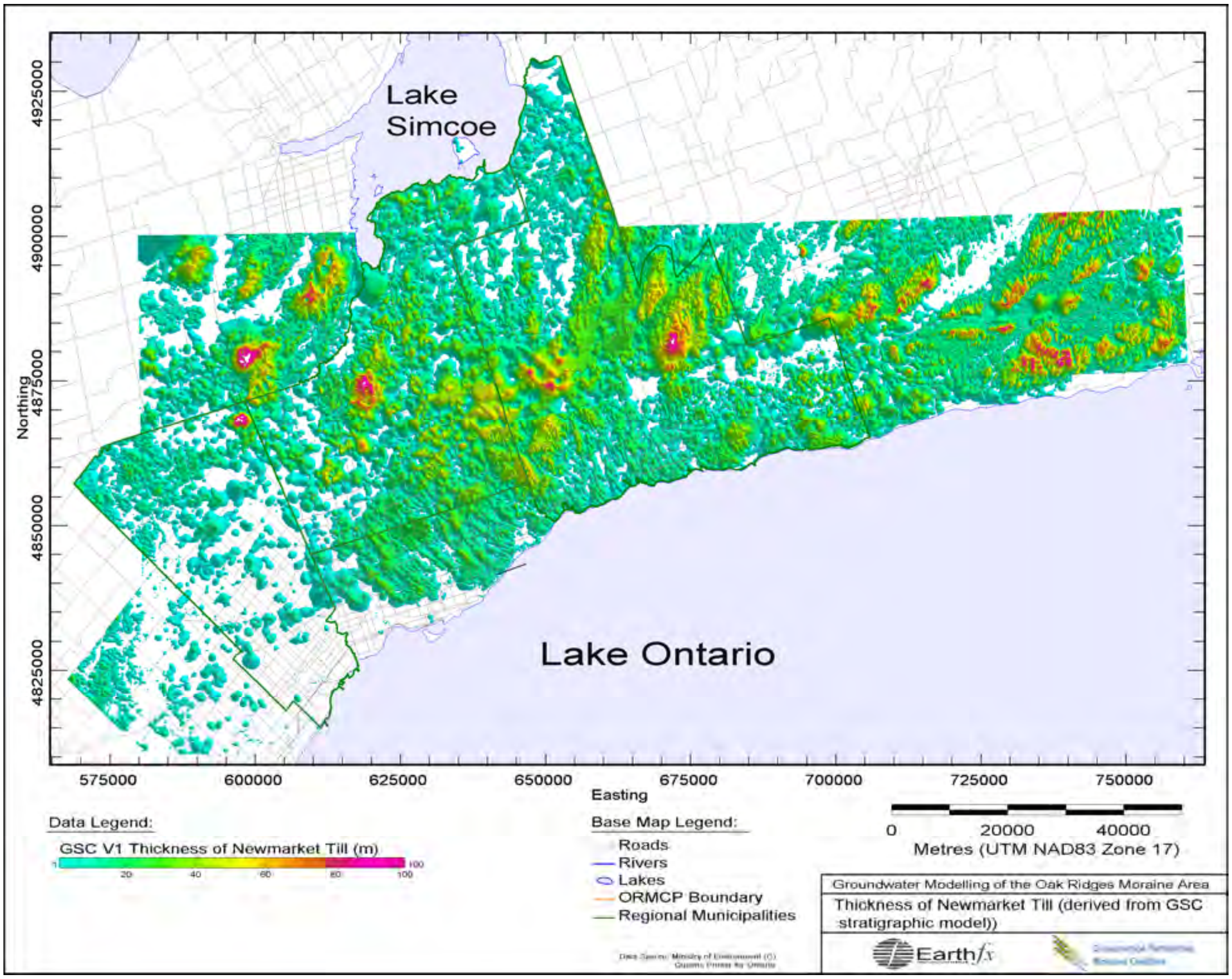


Figure B124: GSC Newmarket Till thickness (derived from Sharpe et al. 2002a)

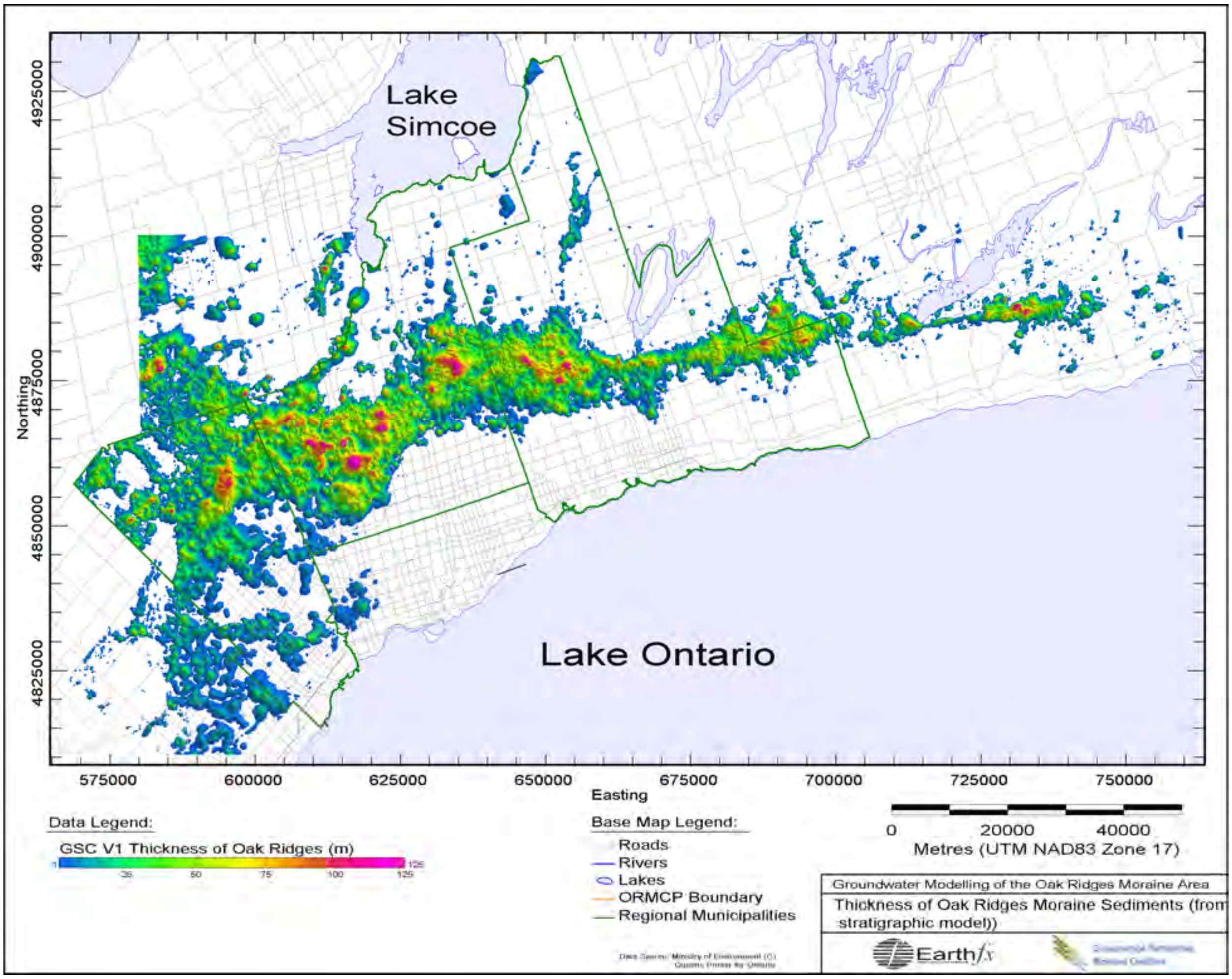


Figure B125: ORM sediment thickness (derived from Sharpe et al. 2002a)

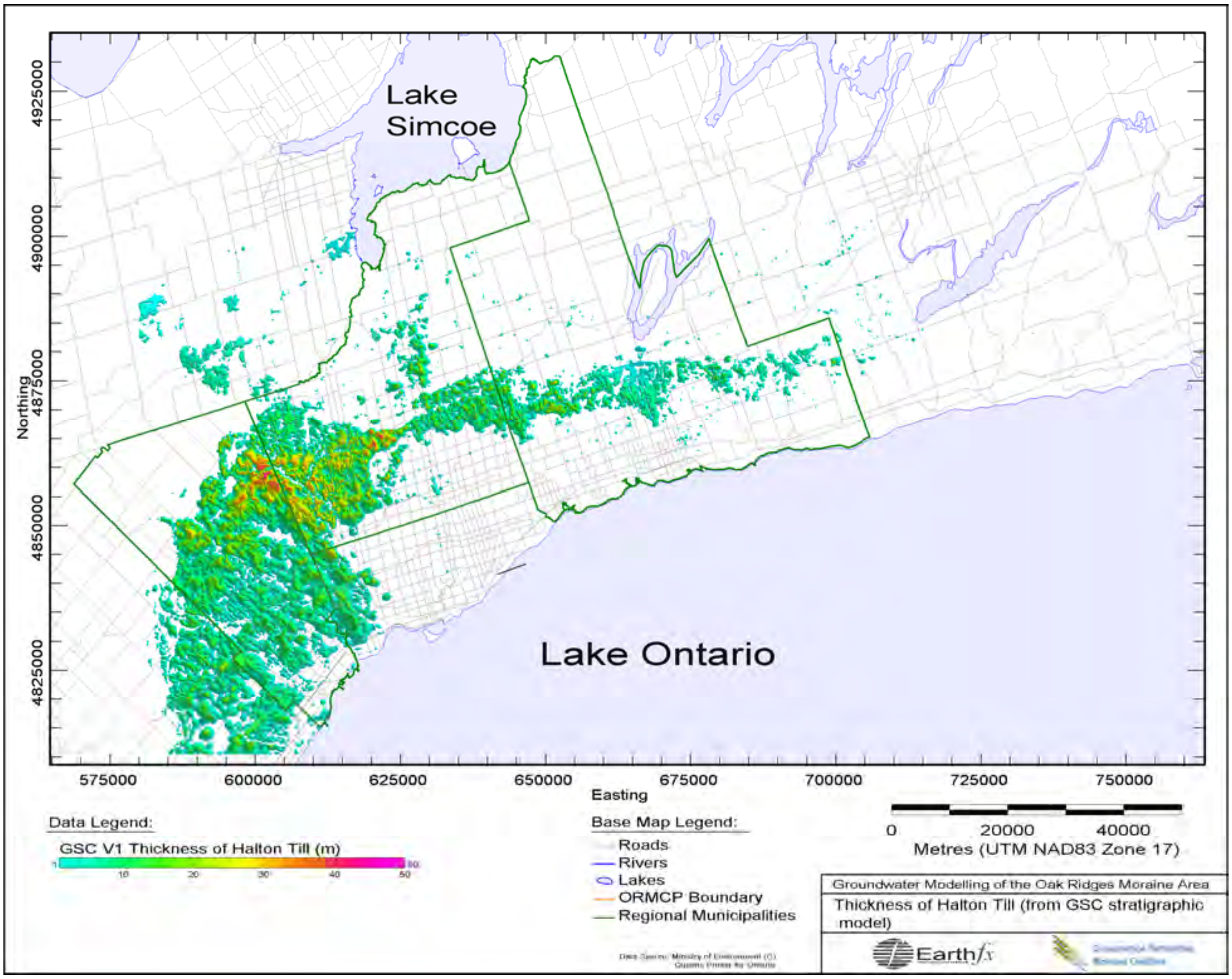


Figure B126: Thickness of Halton Till (derived from Sharpe et el. 2002a)

APPENDIX C

DATA COMPILATION

Appendix C: Data Compilation

3.1 Introduction

This Appendix briefly discusses some of the data sets (sources, geographical coverages, challenges, etc.) that were obtained and used in the construction of the numerical groundwater models. One of the primary objectives of any groundwater modelling study is to provide a framework for data analysis. Model construction requires systematic compilation, analysis and verification of a broad range of hydrogeologic data. If the model does not match the observed data, it either means that the conceptual understanding of the system is flawed or incomplete, or that there are gaps, errors, or inconsistencies in the data. A fundamental principal of groundwater modelling is that the model is only as good as the data on which it was built.

As outlined in Section 1.3.1, integrated data management and modelling were central to the approach used for the study and will provide many benefits for future analysis and interpretation. This approach, however, provided a number of unique challenges, as the ORM groundwater database was being constructed and new data were being compiled throughout the modelling phase. Synchronizing the model with the numerous database updates occurring throughout the project proved time-consuming as existing data needed to be rechecked for quality assurance and quality control (QA/QC).

3.2 YPDT Tabular Database

The YPDT tabular database was the foundation on which the modelling and analysis was based. A comprehensive discussion of the database construction project is provided in the companion report “YPDT Hydraulic Data Management System”, (Earthfx, Inc., November 2003).

The current contents of the database include:

- 135,000 MOE water well records (See **Figure C127** showing all borehole locations)
  - 1,800,000 water level measurements
  - 600,000 geological descriptions
- 13,000 consultant-drilled geotechnical and monitoring wells (with lithology, blow counts, moisture content, and other descriptive data)
- 250 surface water monitoring stations
  - 2,000,000 surface water flow measurements
- 200 municipal supply wells
  - 290,000 pumping rate measurements
- 520 climate stations
  - 3,000,000 meteorological (temperature, rainfall, snow on ground) readings

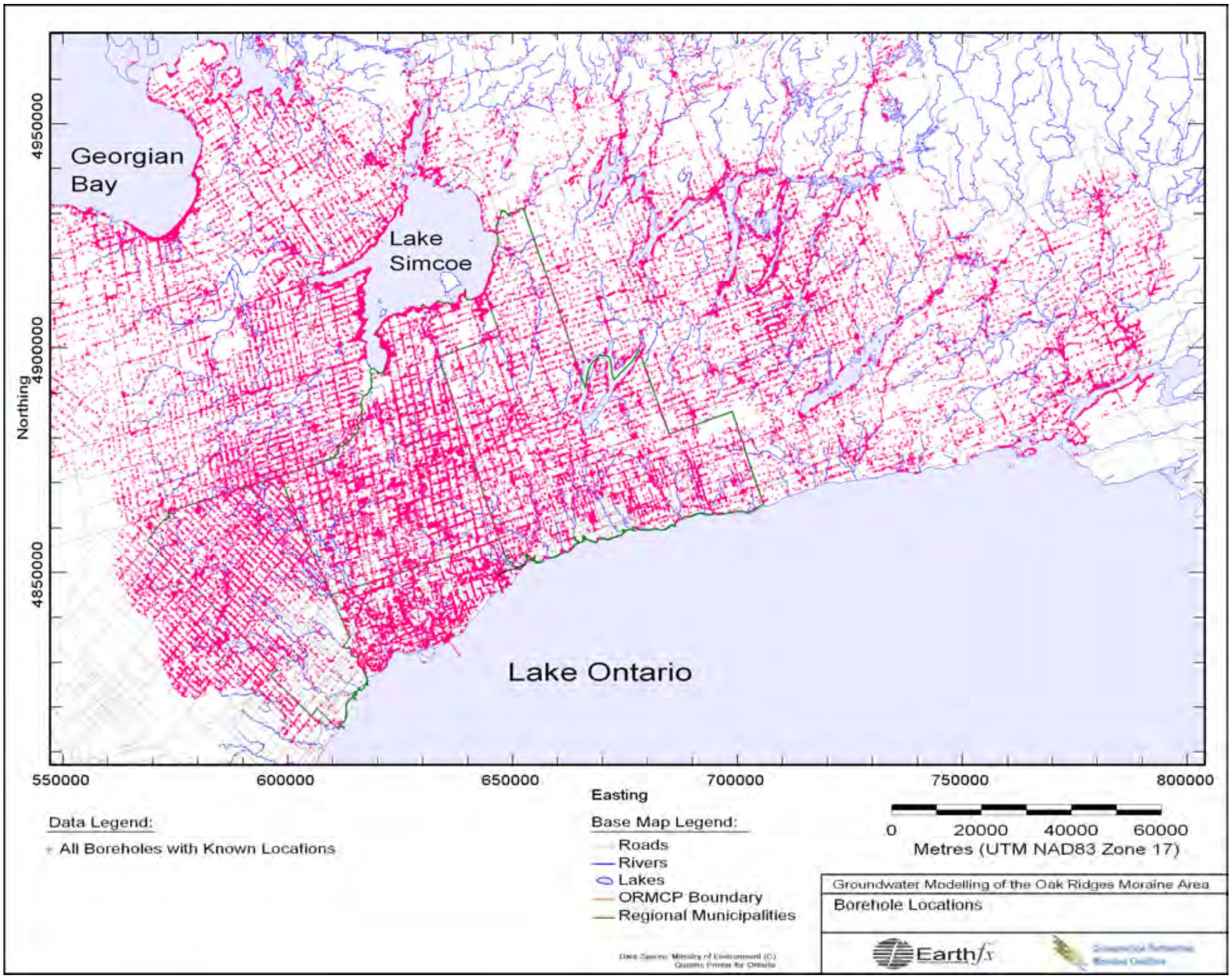


Figure C127: Borehole locations

The organization of the data in the database was based on the Earthfx Data Model, described in the above noted document. A relational structure was used, since this format can serve multiple applications including groundwater modelling. A portion of the data model is shown in **Figure C128**.

Effective analysis and QA/QC of this massive dataset was the single most challenging aspect of the model data preparation process. The complexity, inconsistencies, data volume, visualization and management problems present challenges in finding patterns and obtaining insight from this dataset.

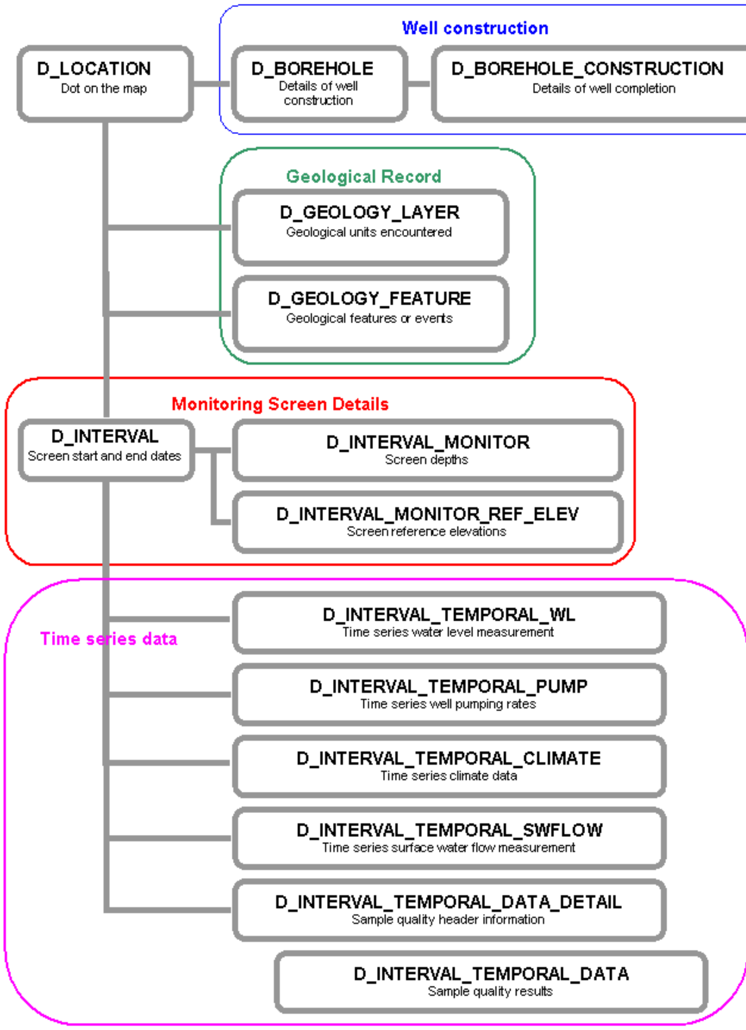


Figure C128: A sample portion of the Earthfx Data Model, showing key location and monitoring tables

3.3 GIS Data

The majority of the project's spatial information was provided by the MNR, MOE and OGS. The regional municipalities and conservation authorities also contributed important datasets related to water use, water levels, streamflow and geography. The spatial data includes:

- Digital elevation models at 30 m and 10 m resolution (provided by MNR)
- Roads and other cultural coverages (provided by municipalities and MNR)
- Classified stream networks (provided by MNR)
- Watershed boundaries (provided by MNR and CA's)
- Surficial and bedrock geology maps (provided by OGS and GSC)

In total, over 13 gigabytes (GB) of data (excluding aerial photography) were made available to the study.

3.4 Geological Survey of Canada Data

The Geological Survey of Canada (GSC) provided critical data and technical insight to the study. In addition to numerous maps and technical reports, the most significant contribution from the GSC was the five-layer digital stratigraphic model (Sharpe et al., 2002a) that formed the basis for the regional model layers (see Appendix B).

3.5 YPDT Report Library

A component of the database construction project involved the electronic scanning of all available reports related to the model study area and storage of them in Adobe Acrobat PDF file format. In addition, tiled digital photographs were taken of the large format maps and cross sections that accompanied many of the reports. Over 1,500 technical reports were scanned, along with 2,400 larger format maps and figures. A metadata database containing information on each report has been prepared. The entire report library is available to the partner agencies on-line at the project web site (discussed below).

Many hours were spent reviewing and assimilating the massive amount of information stored in the report library. Many key boreholes and conceptual insights were found within the historic reports. The report library represents millions of dollars worth of projects and data collection and additional “mining” of the report library to extract key new information is a major recommendation arising from this phase of the project. Considerable effort will be required to fully capture the historic data, but this will be far less expensive than returning to the field to re-collect the same information. (In other words, those who forget the past are condemned to collect the data again.)

3.6 VIEWLOG Web Server

A full-featured web site was set up to provide partner agencies with access to the complete dataset. The web site includes an on line map server (shown in **Figure C129**) that provides:

- Borehole logs for all wells in the database
- On-line maps of surficial geology, water levels, and geologic surfaces
- Ability to create interactive 2-point cross sections

In addition, users can query the complete database for data sites (e.g. monitoring wells, stream gages, or climate stations) matching various criteria and generate graphs for user-specified time intervals (as shown in **Figure C130**).

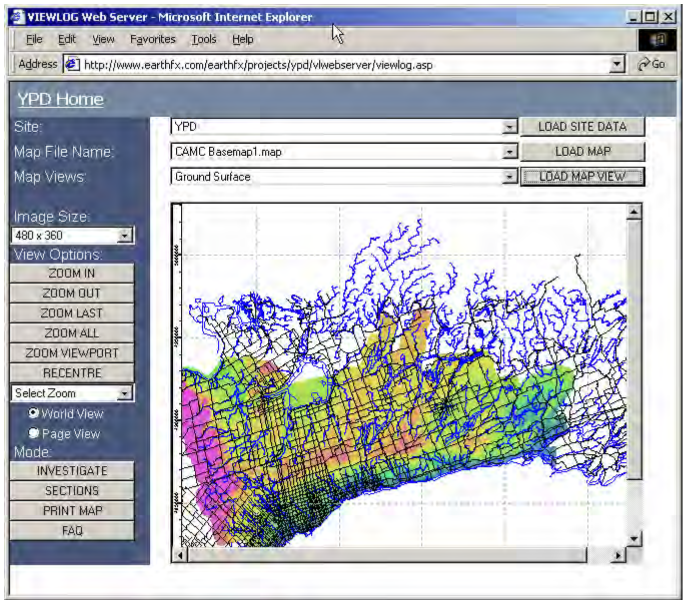


Figure C129: Interactive mapping through the project web site.

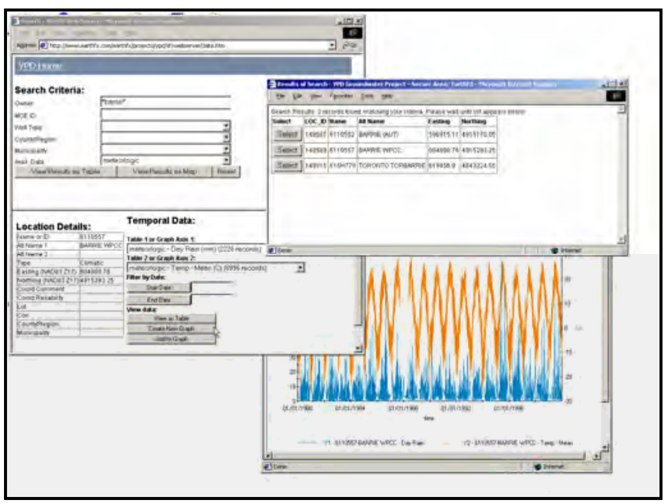


Figure C130: Spatial and attribute queries written to select data for on-line hydrographs

3.7 Data Summary

In summary, a large volume of information was compiled into a format that supported the modelling efforts, and yet, it is also suitable for a wide variety of future applications. It should be noted that while a "critical mass" of information has already been compiled the benefits of ongoing maintenance of the database and additions of new information should be clear.

More important, however, is that the database has already been intensely used to support real analysis. Without real use, a database is only an unverified repository of data. This database has been checked and studied and many errors have been flagged and corrected. For example, over 60,000 geologic unit picks have been made to support the hydrostratigraphic interpretation. Those boreholes in which picks were made could be selected out for subsequent geostatistical analysis, for example, because they have passed a basic visual screening.

Finally, the database, in a form that is directly connected to the model, is one of the more significant products of the overall study.

APPENDIX D

METHODOLOGIES

Appendix D: Methodologies

Numerous hydrogeological techniques and data processing steps were utilized to prepare the data for the hydrostratigraphic and numerical models. In addition, another set of methodologies were employed in the modelling phase of the work. The methodologies employed in various aspects of this study were briefly mentioned in the main report and are described in more detail in this appendix.

4.1 Methods related to Geological Layer Construction

4.1.1 Introduction

Construction of aquifer and aquitard layers geometry was one of the most challenging aspects of this study. Simple interpolation of sparse point data (well picks) rarely produces layer surfaces that realistically represent the structure and continuity of complex hydrogeologic features such as channel and valley systems. To fully represent the complexity of the aquifers and aquitards in the Oak Ridges Moraine area, borehole lithology picks were supplemented with information obtained from, subtle hydrogeologic indicators (such as well screen placement and well depth) as well as from expert intuition and geologic conceptual understanding of the sedimentological processes. This information was integrated into the model construction process using 3-D polylines to constrain the interpolation processes.

Database integration, data flexible visualization, efficient layer picking tools, and geostatistical analysis functions provided by the VIEWLOG software made it possible to review and synthesize the large amounts of borehole data (discussed further below). The resulting hydrostratigraphic model not only honoured the borehole and well data, but also encapsulated the conceptual understanding of the processes that formed the Oak Ridges Moraine.

4.1.2 Data Correction and Data Biases

Ontario Ministry of Environment driller's logs form the majority of the borehole information in the database. The accuracy and reliability of individual wells in this data set is sometimes questionable, however, the logs provide a significant amount of useful subsurface information. Care was taken to screen the data visually and correct for obvious or known errors, thereby minimizing the intrinsic biases in the driller's logs.

Some of the location and elevation errors in the MOE's database were addressed through field validation (using GPS) of over 5,000 of the wells which had not previously been located (Beatty and Associates 2003). Borehole elevations were compared against, and adjusted to the high resolution DEM (10 m cell size) to minimize elevation errors. Highly erroneous or unreliable wells (MOE quality code greater than 6) were excluded from the analysis.

Water well records in the western Oak Ridges Moraine were compared against detailed core logging from geotechnical, hydrogeological and sedimentologically-logged boreholes (Sharpe et al., 2002). Logan et al. (2001) showed the value of using these high-quality records to "train' the well records (e.g. Logan et al., 2001). Thus, higher quality "golden spike" wells and seismic picks were used extensively during layer refinement. The high quality "golden spike" wells, seismic picks, and outcrop data (as well as any other higher quality data) were identified (and given greater weight) using a variety of qualitative measures. Well ownership was also examined and any wells drilled by a consultant or for a municipality were assumed to be of higher quality and were given more weight in the interpretation. Frequently, wells with poorer or better quality information could be readily identified by visually comparing clusters of wells on cross section (e.g. poorer wells would have a single geological description through the entire depth of the well).

A standardized scheme to re-code driller's log descriptions was developed by three GSC geologists for the Oak Ridges Moraine area (Russell et al., 1998). Re-coded lithologic information helped identify drillers' tendencies in reporting data but could not be relied upon without referring to the high-quality data. A significant bias was the use of the term "clay" by the water well drillers. In reality, analysis suggested that reported "clay" material was more likely to be silt or fine sand. Similarly, drillers rarely use the term till but use terms such as "hardpan" or "hard" or report occurrences of "clay gravel". Re-coded lithologic log information was displayed on cross section during interpretation and picking, however, presentation of the original (un-coded) raw MOE lithologic descriptions was still considered essential to the identification of unit boundaries and key indicator patterns.

Other percieved biases and patterns were identified during the geological surface refinement process. As most drillers are hired simply to "find water", they frequently stop drilling as soon as they encounter a significant aquifer zone. Since tapping into the top few metres of a significant aquifer is all that is necessary to meet the needs of most domestic well owners, very little of the permeable aquifer material is sampled and documented within the driller's logs. As a result, the majority of driller's logs are typically a record of aquitard materials, with only the bottom-most screened sand or gravel unit representative of aquifer material. Despite these biases, highly significant patterns were identified within the logs, as discussed in the following sections.

4.1.3 Data Visualization and Analysis Software Tools

VIEWLOG was the borehole analysis/GIS software used for all data visualization, synthesis and interpretation tasks in this study. The software provides an integrated set of GIS mapping functions (including 3-D gridding and contouring), dynamic cross section generationing, real-time 3-D fly-throughs, and borehole data display, editing and picking functions, as shown in **Figure D131**. The software directly connects directly to the relational database containing the borehole logs, well construction, and water level data. This allows the user to dynamically query and filter the visual presentation based on database criteria.

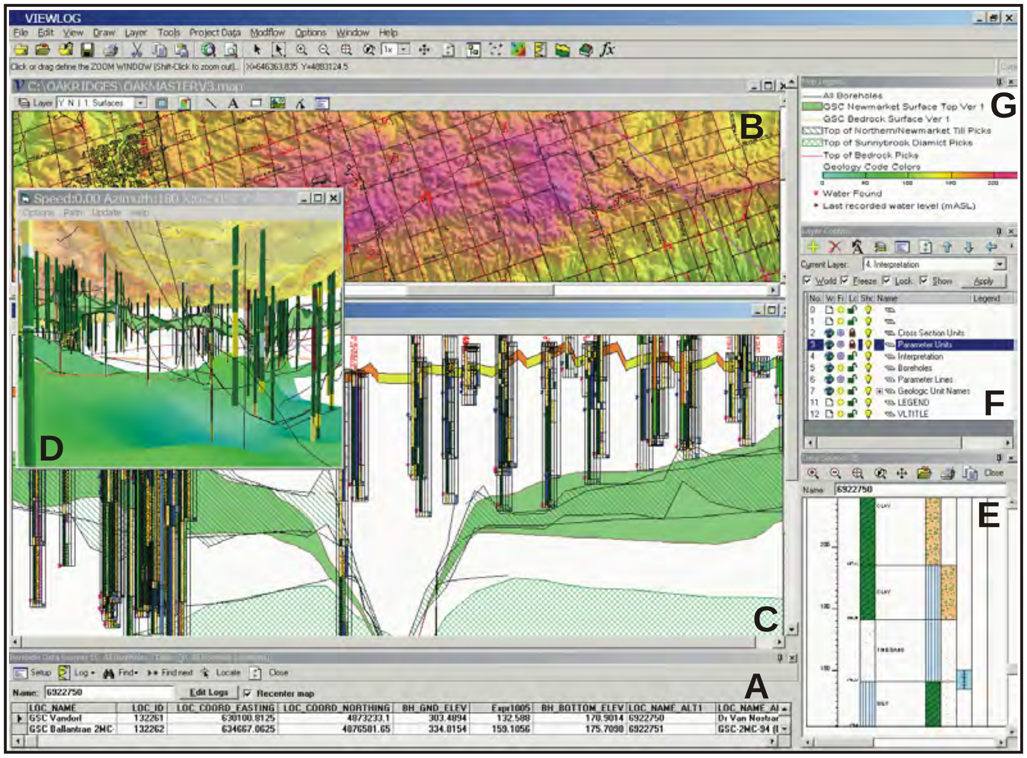


Figure D131: On-screen interpretation required the visual integration of large volumes and types of information. (A) database table editing window, (B) plan view map with hill-shaded DEM, (C) cross section with 3--D constraint polylines, (D) real-time 3--D fly-through window, (E) well log details popup window, (F) map layer control menu, and (G) legend.

Despite the fact that the data is highly three-dimensional in nature, most interpretation was performed on cross sections. Real-time 3-D viewing provides a more qualitative view of the data, however, for detailed and accurate layer picking, cross sections provide a more suitable framework. The use of the software's dynamic cross sections, which can be easily shifted back and forth through the dataset, was another important feature of the layer refinement process. At any point during the interpretation, the vertical exaggeration could be adjusted and the borehole offset changed to add or remove boreholes from the section. The cross sections could also be dynamically sliced through one or more geologic models, allowing units from the stratigraphic and hydrostratigraphic models to be easily compared. Finally, to further assist in the layer refinement, the surficial geology was also included on all sections as a color-coded band (using standard lithology colors) immediately below the ground surface.

Considerable effort was spent optimizing the presentation of the borehole data on cross section. The software permits the display of any number of columns of lithology (raw codes, GSC recoding, etc.) and hydraulic information (well screen, static water level, etc.) at each well location. Lithology symbol patterns and colors were chosen to fully represent the range of material codes and allow for the identification of subtle patterns and correlations (**Figure D132**). A pop-up window containing the well details, in tabular or graphical form, was also available during the interpretation process. It was determined that the most effective display on cross section was to use all three columns of MOE geological descriptions (Mat 1, Mat 2, Mat 3), hydrogeologic indicators such as well screen interval in a fourth column, and the GSC recoded lithology in a fifth column.

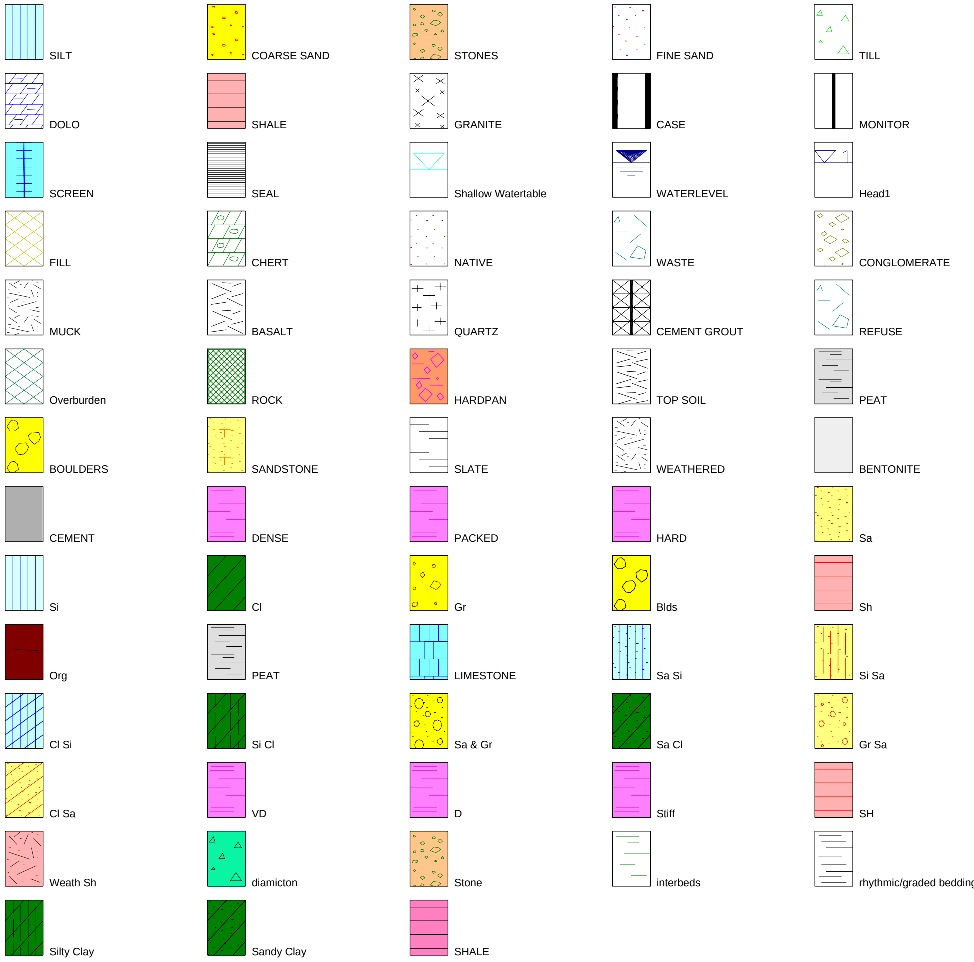


Figure D132: Lithology symbol and color patterns.

The software's 3--D polyline drawing functions were used to capture the expert's intuition during the interpretation process. Polylines are simply lines of contact separating different hydrostratigraphic or geologic units. Ensuring the continuity of channel and valley systems was necessary to correctly simulate the flow of water through these features. While well picking formed the majority of the interpretation task, 3--D polylines were used to constrain and control the surface generation process (**Figure D133**). Polylines were added either perpendicular or parallel to the axis of a channel or valley feature. Each polyline was assigned to a hydrostratigraphic unit, and the individual vertex points in that polyline were then included (along with the well picks) in the gridding process for that particular unit. For example, the drainage pattern in bedrock valley systems was created by adding polylines down the inferred thalweg cross section. The truncation and pinch out of layers at the edges of the tunnel channels was defined using polylines perpendicular to the axis of the channel feature. Plan view manual contouring was also integrated as necessary.

Figure D133 presents a sample cross section and shows how 3-D polylines were used to constrain tunnel channel geometry. The thin black lines in the figure that generally follow the unit boundaries are the constraint polylines. These constraint lines, together with the borehole picks, produce the unit boundaries (final interpolated units are show as solid color filled zones).

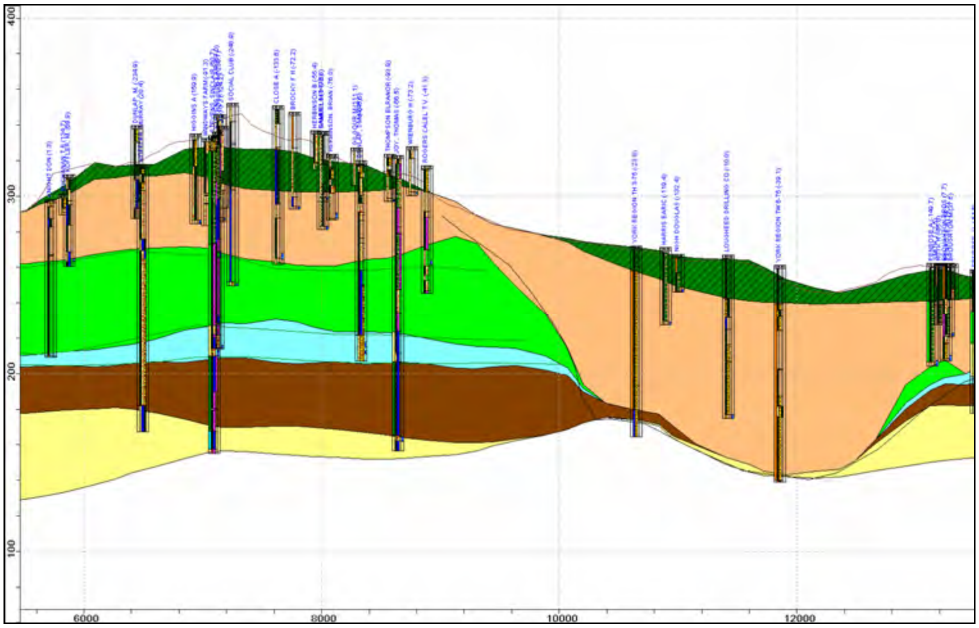


Figure D133: Sample cross section showing 3--D polylines used to constrain tunnel channel geometry.

4.1.4 Interpretation Methodology

Creation of the refined hydrostratigraphic surfaces involved an iterative process of interpretation, gridding and refinement. Complex structures and patterns emerged slowly, as time was spent viewing and interpreting the data. Group meetings were frequently held to review and discuss the emerging understanding of the system.

Since hydrostratigraphic interpretation and refinement were occurring simultaneously, data management and database synchronization also turned out to be an important issue during the interpretation phases of the model refinement. Meetings provided an opportunity to coordinate data management and ensure consistency among the interpreters.

Elements of the GSC's rules-based approach to the generation of the stratigraphic surfaces (Logan et al., 2001) were incorporated into the hydrostratigraphic interpretation methodology. In particular, their conceptual approach to the handling of "push downs" was particularly useful. A push down condition exists when a borehole partially penetrates a geologic unit: the next lower unit must exist below the bottom of the partially penetrating well, but how far below is unknown.

The main interpretive methodologies used were: i) cross-section picking; ii) an emphasis on hydrologic indicators; and iii) the use of 3--D constraint polylines. In summary, the following steps were used to generate the hydrostratigraphic surfaces:

4.1.4.1 Step 1: Picking and Pattern Identification

Hydrostratigraphic units were picked on thousands of dynamically generated cross sections through the Core Model area. Sections were viewed, at minimum, along every concession road, which are spaced approximately every 2 km. In more complex areas sections every 500 m were interpreted. Over 67,000 layer picks were made in boreholes along these sections.

Key patterns in the drillers logs emerged during this process, and were highlighted using characteristic lithology symbols and colors. An important part of the display was the optimization of certain colours with specific MOE geological descriptors, allowing specific patterns in the material codes to be identified. Some of the important patterns include:

Hardness: the terms “dense”, “hard”, and “packed” were used interchangeably by different drillers. Intervals with these terms were colour coded pink (**Figure D132**) on section. These descriptors appeared to be commonly applied to the Newmarket Aquitard unit. The bright pink colour was therefore used as a guide to identify this unit.

Clay+ stones or Clay+ gravel: The combination of the clay and stones (or clay and gravel) also emerged as a reliable till indicator. In this case clay had to be the primary material and stones the secondary material.

Coarse material + Well Screen: Coarse grained material alone (i.e. sand) cannot always be assumed to be representative of a good aquifer. In many cases the sand might be quite silty. Sand, combined with a well screen, was considered much more likely to be representative of a good aquifer.

Well screen position: In many cases well screens are clustered at a particular depth position, suggesting a good aquifer zone.

Well material similarity and detail patterns: The visual comparison of materials from a group of wells could, in many cases, lead to a better and more reliable interpretation. The “noise” and variability in the individual well descriptions could be visually filtered to identify a formation contact. A related issue was the level of descriptive detail in an individual well. For example, wells with too few material codes or long sections of very simple descriptions were, in some cases, considered “suspect” (suggesting that the driller was not attentive to the geological changes that were present).

Silt + and lack of hard material code: The GSC suggested (Russell et al., 1998) that in many cases clay materials identified by drillers was, in actual fact, silt. However, where silt was described in the MOE logs, it was observed that there was a link between the location of these wells and the location of potential tunnel channels. This correlation, especially where the term “hard” as a material modifier was absent, led to a general interpretation that “silt“ was a potential indicator of tunnel channel sediments.

4.1.4.2 Step 2: Addition of 3 D Polyline Constraints

During the cross section interpretation, 3-D polylines were added to constrain the gridding process. These polylines ensured the continuity of geologic structures. Polylines were also used to help constrain “push down” conditions (described below). In total, over 12,000 polyline vertex points were defined.

Polylines were used to define both the base and the width of the bedrock valley systems. A combination of deep bedrock wells and deep “push-down” wells were used to initially define the position of the bedrock valley systems. The shape of the valley was then defined with additional polylines. With very limited data in the deep valley systems, particularly the main branch of the Laurentian River, some assumptions had to be made about the channel width and the slope of the valley walls. Modern analogs were reviewed, including the Niagara River (the Laurentian was suspected to be of a similar size and flow rate). Bronte Creek and 16 Mile Creek, which are relatively deeply incised into the Queenston Shale, and the Credit River were also considered. The primary question was whether the river would incise deeply in the soft shale, or would the river meander and undermine the valley walls, resulting in shallow, broad valley. Evidence for both conditions was found, and a basic valley width for the main channel was assumed to be approximately 4 km wide. Initially polylines were drawn along the thalweg of the valley. Several sets of parallel polylines were then drawn on both sides of the thalweg line and positioned at successively higher elevations to “shape” the valley to this 4 km wide feature. The resulting bedrock surface was checked and modified based on the actual well data. A recent seismic survey across the main channel near Schomberg suggests that the channel is at least this wide (CAMC, in preparation). The width of other tributaries was evaluated on a case by case basis and conformed to local available well data. Care was also taken to ensure that the tributaries also correctly connected into the main channel.

North of the moraine, the high resolution DEM was used as an additional source of information when interpreting the tunnel channels. Constraint polylines were used to extend the surficial expression of the tunnel channels down into the geologic model, however with limited data, depth control was limited. In the case of the tunnel channels, interpretation lines perpendicular to the channel were drawn that truncated units (e.g. Newmarket Aquitard, Thorncliffe Aquifer, etc.) at the edges of the inferred channel. The depth of the channels (and the polylines that shape the valleys) was determined by looking for wells with geological intervals that were discontinuous with wells outside of channel areas. In addition, a coarse aquifer within the valley was also sought as an “anchor” that might indicate the coarse depositional phase that is typical at the base of the channel sediments.

In summary, polylines provide an important control over the gridding process, however they need to be used carefully and only where necessary. Verification of the layer geometry is ongoing, through both drilling and seismic surveys across the study area. With time, polyline constraints can be removed as hard data is collected and substituted. At present, however, polylines represent a key link between the conceptual model and numerical model.

4.1.4.3 Step 3: Pushdown Check

Handling of “push down” conditions was particularly important to the interpretation of the bedrock surface because of the sparseness of the data and the potentially strong influence of the Laurentian River valley system. A “push down” condition occurs where a deep well, which does not encounter bedrock, indicates that the bedrock surface must be lower than the estimated interpolation level. The deep “push down” well does not actually encounter bedrock, however it proves that bedrock is some distance below the bottom of the borehole. The bedrock surface must be “pushed down” below the base of that well, even though the bedrock is not actually encountered in that well.

Deep “push-down” wells were used both before and after polyline drawing step. Both bedrock wells and deep push-down wells were reviewed to initially identify the bedrock valley thalweg positions. One the thalwegs were defined (as outlined above), additional push-down checks were performed to ensure that these deep indicator wells were fully integrated into the surface generation process.

Specific display techniques were used to help visualize the push-down conditions. Sediment boreholes (e.g. those that do not encounter bedrock) were plotted on plan view with a bottom-hole elevation represented by scaled and gradationally color coded symbols. This allowed deep push down holes to clearly appear as large, bright symbols. Bedrock valley thalwegs were then interpreted on plan view, and cross sections were generated along those thalwegs. Polylines were added to the thalweg cross sections to ensure that the bedrock surface correctly represented the decreasing elevation of the valley system.

Other push-down surface checks were performed in a manner similar to the GSC methodology (Logan et al., 2001). In general, the following steps were used:

- Bedrock picks were made at all wells that intercept bedrock
- The initial bedrock surface was interpolated using all bedrock picks
- The non-bedrock (sediment) wells were evaluated by plotting them on plan view with a bottom-hole elevation represented by scaled and gradationally color coded symbols, thus showing deep overburden wells as large, bright symbols.
- Using the initially interpolated bedrock surface and the deep, brightly coloured, non-bedrock wells, bedrock valleys were identified and bedrock valley thalwegs were drawn on plan view.
- Cross-sections were generated along the bedrock valley thalwegs and bedrock polylines were drawn on-section to represent the bedrock surface. The polylines were drawn to connect the bedrock picks and to ensure that the bedrock surface was beneath the deeper sediment wells. The lines were also drawn to ensure that the bedrock surface correctly represented the decreasing elevation of a fluvially eroded valley system.
- The secondary bedrock surface was then interpolated using the bedrock picks at the bedrock wells and the vertex points of the bedrock surface polylines created along the bedrock valley thalwegs.
- This surface was checked against the non-bedrock wells to see whether any of the non-bedrock wells intersected the secondary bedrock surface.
- Where non-bedrock wells were deeper than the secondary bedrock surface the elevation of the well bottom was added as an additional bedrock point to "push down" the final bedrock surface.
- Additional polylines were added on cross-sections parallel to the bedrock valley thalwegs to better "shape" the bedrock valleys.
- The final bedrock surface was interpolated using all of the above: bedrock picks; polyline vertex points; and the deep non-bedrock wells that pushed down the bedrock surface.

4.1.4.4 Step 4: Variogram Analysis and Interpolation

Once the picking, polylines and push down analysis was complete the surfaces were generated using variogram analysis and kriging. Variogram analysis is discussed in detail in Section 5.2.

4.1.4.5 Step 5: Rules-based Post Processing

Finally, the surfaces were crosschecked using a series of rules. The rules ensured, for example, that the interpolated layers did not cross. The rules were developed and applied in an order that reflected the distinctive characteristics of each hydrostratigraphic interface (i.e. unconformity, etc.) and the confidence and distinctiveness of the lithologic signature. For example, the ground surface was assigned the highest level of confidence, followed by the bedrock surface, top of the Newmarket Till, and then the remaining units. The following were some of the surface post processing rules:

- If Bedrock > Ground then Bedrock = Ground
- If Newmarket > Ground then Newmarket = Ground

- If Newmarket < Bedrock then Newmarket = Bedrock
- If Thorncliffe > Newmarket then Throncliffe = Newmarket
- If Thorncliffe < Bedrock then Thorncliffe = Bedrock
- If Sunnybrook > Thorncliffe then Sunnybrook = Thorncliffe
- Etc…

Other surface cross checks were included, including reconciliation with the surficial geology units. Note that the order the equations were processed was also important, as each surface check relied on the preceeding checks and constrants. The approach was not simply a top-down correction, for example constraining the Halton till was one of the last checks performed. Note that other model-layer specific checks were also performed, as outlined in Appendix D, Section 4.2.5.1.

4.1.5 Conclusions

Layer picking is a complex and challenging task that requires a concerted effort to understand existing conceptual models and adapt and refine them as necessary. The model construction process is complicated by the low quality and conflicting information contained in the MOE well database. Good conceptual models are needed to guide the interpretation process, but actually representing the conceptual insight within the numerical model is a particular challenge.

It is important to point out that the hydrostratigraphic surfaces produced through this study are by no means perfect or complete, and will be in need of continual improvement into the future. Although every effort was made to ensure that the aquifer and aquitard layers developed under this project are consistent with the data, the area covered is simply too large to be able to go into detail everywhere. This concept of continual improvement is in keeping with the overall spirit of the YPDT groundwater management study.

From a flow modelling perspective, continuity and pinch-out of layers is more important than the precise elevation of the surfaces: the models respond to transmissivity changes, including both layer thickness and hydraulic conductivity.

The methodologies used in this project are consistent with those used in other large agencies, including the Alberta Geological Survey, South Florida Water Management District, USGS and Danish Geological Survey, to name only a few. The GSC is also using the same toolset for adapting and refining their stratigraphic surfaces.

4.2 Methods Related to Modelling

4.2.1 Geostatistical Analysis of Water Level Data

Potentiometric surfaces under pumping and non-pumping (pre-development) conditions, on a local and regional scale, served as targets for model calibration. Creating these water level maps was difficult because of historical changes in land use and wellfield operation over time and because of variability in MOE well record data quality. This section discusses the source of errors in the well records and the geostatistical methods used to evaluate the magnitude of these errors.

The MOE water well records contain a measurement of the “static water level” in the well at the time of construction. Differences in static water levels between two nearby wells can be the results of many factors in addition to the natural gradients in the potentiometric surface. Some of these include:

1. Well Placement Error:
   - positional survey errors
   - elevation survey errors

2. Monitor and Well-Construction Problems:
   - wells straddling aquifer boundaries (long well screens)
   - leaking well seals (cross-aquifer leakage)

3. Water Level Measurement Accuracy:
   - water levels measured while still recovering from drilling or testing
   - reporting and transcription errors
   - interference from other nearby pumping wells
   - perched water table conditions

4. Seasonal and Long-Term Variation:
   - natural seasonal variation in groundwater recharge
   - long-term climatic cycles (drought years, etc.)
   - seasonal variation in nearby pumping
   - long-term changes in pumping (due to increased/decreased groundwater use)

These factors range in magnitude but must be considered before spatial and temporal patterns can be interpreted and modelled. There is little to be gained by attempting to calibrate the model to a level of accuracy that is greater than the intrinsic error in the data. The methodology for geostatistically analyzing the water level data involved the following steps:

- Generate and view the experimental variogram based on the water level data;
- Fit a theoretical curve to the experimental variogram by adjusting the curve fit parameters (i.e. nugget, range and sill). The theoretical curve is called the variogram model.
- Interpolate the water level data to the model grid using the kriging, a geostatistically-based interpolation method. This ensures that the spatial correlation observed in the data was preserved.
- Generate and review the kriged variance and standard error surfaces.

Analysis of variance with distance, referred to as variography or variogram analysis, is a geostatistical technique that can also provide an estimate of the systematic error in the data set. While variogram analysis alone cannot differentiate between these sources of error, it can quantify the magnitude of the error and provide useful insight into the spatial patterns in the variation. Variogram analysis can help answer the following questions:

- What is the intrinsic variation (noise) in the data and what degree of uncertainty does it add to the interpretation of the data?
- What does the variability say about regional-scale patterns in the data?
- How far should the data be extrapolated between wells?
- How closely can the model be expected to match the observations?

The error analysis is particularly important to model calibration where model results are compared to the field observations. The model can never achieve a perfect match to the field data when there is a significant intrinsic error in those measurements.

Variogram analysis provides useful insight into the spatial variability and spatial correlation in the observed data. In simple terms, the experimental variogram (**Figure D134**) is a plot of the variance (on the y-axis) versus the separation or “lag distance” between measurements (on the x-axis). The variance is given by:

$$\gamma = \frac{1}{2m}\sum_{i=1}^{m}[z(x_i) - z(x_j)]^2 \qquad \text{(Eq. D1)}$$

where

$z(x_i)$ = measured value (i.e. water level) at well i,
$z(x_j)$ = measured value at a second well separated by a specified distance, and
m = number of pairs of data points separated by the specified lag distance.

γ in Equation D1 is sometimes called the semivariance because of the factor of 2 in the denominator. A theoretical variogram is usually fit to the experimental data which is often too noisy to use directly. The theoretical variogram curve should, ideally, intersect the origin (i.e., there should be no difference in the observations if the second well is extremely close to the first). The variogram should then increase with increasing distances between observation points and then reach a maximum level which is referred to as the sill. With water level data, this means that closely spaced wells have generally similar readings and the variance between closely spaced wells should be small. As the spacing between the wells increases, greater variation in the readings would be expected and the variance would increase. Finally, when the lag distance increases to a point where there is no longer any correlation between readings, the variance should become equal to the sample variance.

$$s^2 = \frac{1}{n}\sum_{i=1}^{n}[z(x_i) - \bar{z}(x_i)]^2 \qquad \text{(Eq. D2)}$$

where

$\bar{z}(x_i)$ = the mean of all measured values (i.e. water level),
s^2 = variance
n = number of measured values.

Beyond this distance (the “range distance”), the variance does not increase and the magnitude of the variation in water levels becomes independent of the distance between the wells.

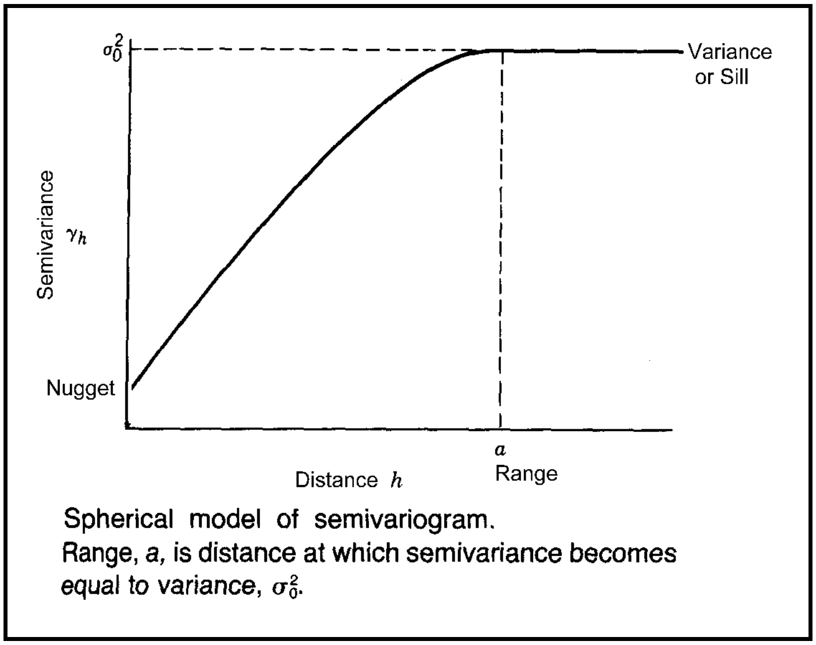


Figure D134: Variogram components.

Three important parameters were derived from the analysis of variance in the water level data, including:

- **Range**: the distance beyond which there is no longer any significant correlation between the measurements. (The range is the distance at which the sill is reached.)

- **Sill**: the variance at a distance greater than the range. It should equal the sample variance.

- **Nugget**: the variance at the point where the variogram curve crosses the y-axis (lag distance = 0).

The nugget is related to the local-scale variation in the data and includes the inherent measurement error (the “nugget” is named after the distorting effect that the presence of randomly distributed gold nuggets have on local-scale variation in gold ore concentration). In the case of water level data, the nugget represents both local-scale measurement errors and natural variations in the data.

The nugget is particularly important to the model evaluation process. For example, a common model calibration statistic is the root mean square error (RMSE) given by

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(z_m - z_o)^2} \qquad \text{(Eq. D3)}$$

where
z_m = model value at a point,
z_0 = observed value at the same point.

which is broadly equivalent to the square root of the error variance. In a perfect calibration, the RMSE would equal zero unless there was some intrinsic error in the observed data. Thus, the minimum RMSE can never be smaller than the square root of the intrinsic variance which, in turn, can be quantified by the magnitude of the nugget. For example, the nugget of the ORAC water levels was estimated to be 20 m^2, so the intrinsic error in the data is about ±4.5 m. This indicates that the calibration, as measured by the RMSE, cannot practically be lower than 4.5 m.

4.2.2 Data Interpolation

The geologic surfaces and potentimetric surfaces produced in the study were developed by interpolating point data (e.g. geologic picks or water levels) to a regular grid. The interpolation method used exclusively was kriging. Kriging is a distance-weighted averaging technique that builds on the analysis of variance techniques described in the previous section.

Kriging involves the solution of a system of linear equations, using coefficients obtained from the theoretical variogram model, to determine a set of optimal weights. The equations can be written using all data points (applicable to small data sets) or a search can be done to find the nearest n number of data points to the centre of each grid cell. In most of the project analyses, the nearest 32 data points were used. This helped to ensure that small clusters of wells would not dominate the local interpolation, and that data from a broader area were considered. A quadrant search technique was employed, whereby the nearest eight data points in each quadrant were selected, in order to avoid the effects of clustered data.

One advantage of kriging is that it is an exact interpolator (when the nugget is zero) and the kriged value represents the best linear unbiased estimate (BLUE). Another advantage is that the kriging technique also determines the kriged variance and standard error of the interpolation which helps to quantify the uncertainty in the data and the reliability of the estimate. For example, the standard error of estimate map produced for the interpolated ORAC water levels (**Figure 57**) indicated that the estimated water estimates (**Figure 56**) were within ±4.5 m of the true value with a confidence level of 68% (or ±9 m with a confidence level of 95%).

Selection of the proper shape of the theoretical variogram model can affect the analysis of error and the interpolation process. There are several different shapes of theoretical variograms that are commonly used and they vary in the way they describe the decrease in correlation with distance. Four shapes, shown in **Figure D135**, are:

- Linear -- the linear model describes a straight-line variogram with no sill or range. It assumes that the data lie on the early (linear) portion of a more typical variogram.
- Spherical -- the spherical model is a modified quadratic function, it is best applied where data occurs in equal-sized patches of high and low values.
- Exponential -- the exponential model approaches the sill more gradually than the spherical model; it is best applied where data occurs in variably-sized patches of high and low values.
- Gaussian --the Gaussian model is similar to the exponential model but assumes that data are highly correlated over short distances and then begins to decrease with distance. Potentiometric data in the ORM study area tended to fit a Gaussian variogram which was the model selected for the water level data.

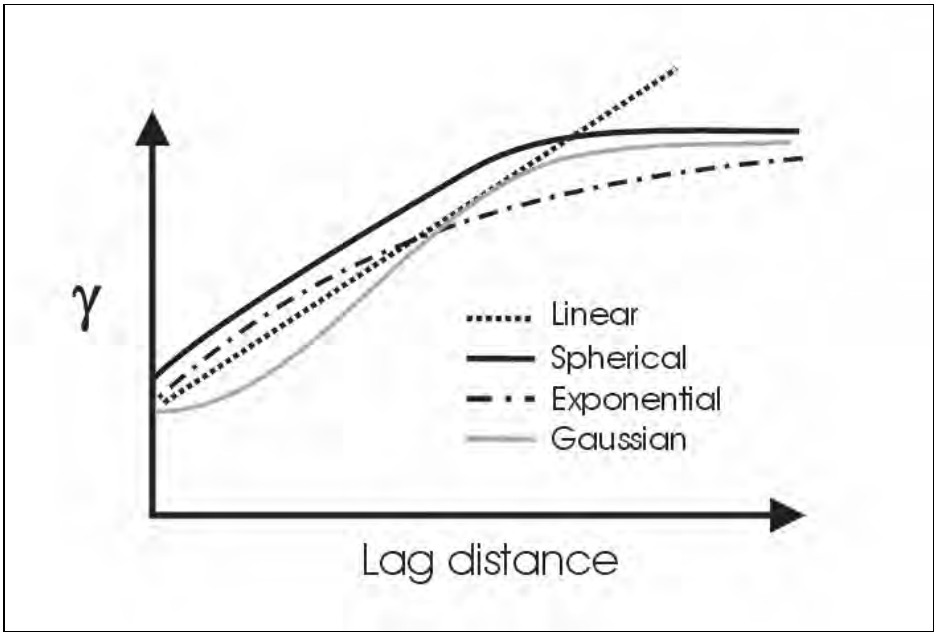


Figure D135: Common variogram shapes

Selection of the variogram model can affect the results of the interpolation. **Figure D136** compares the kriged ORAC water levels using a linear variogram with no nugget to the kriged water levels using a gaussian variogram with a 20 m^2 nugget (the values obtained from the analyses). The linear variogram with no nugget produced a pock-marked surface (**Figure D136**a) while the kriging with the Gaussian variogram (**Figure D136**b) with the nugget produced a more smoothly varying surface. The right hand image tends to emphasize the trends and patterns that are geostatistically significant but allows the interpolated values to differ slightly from the observed; the left hand side image preserves the local scale “noise” in the data.

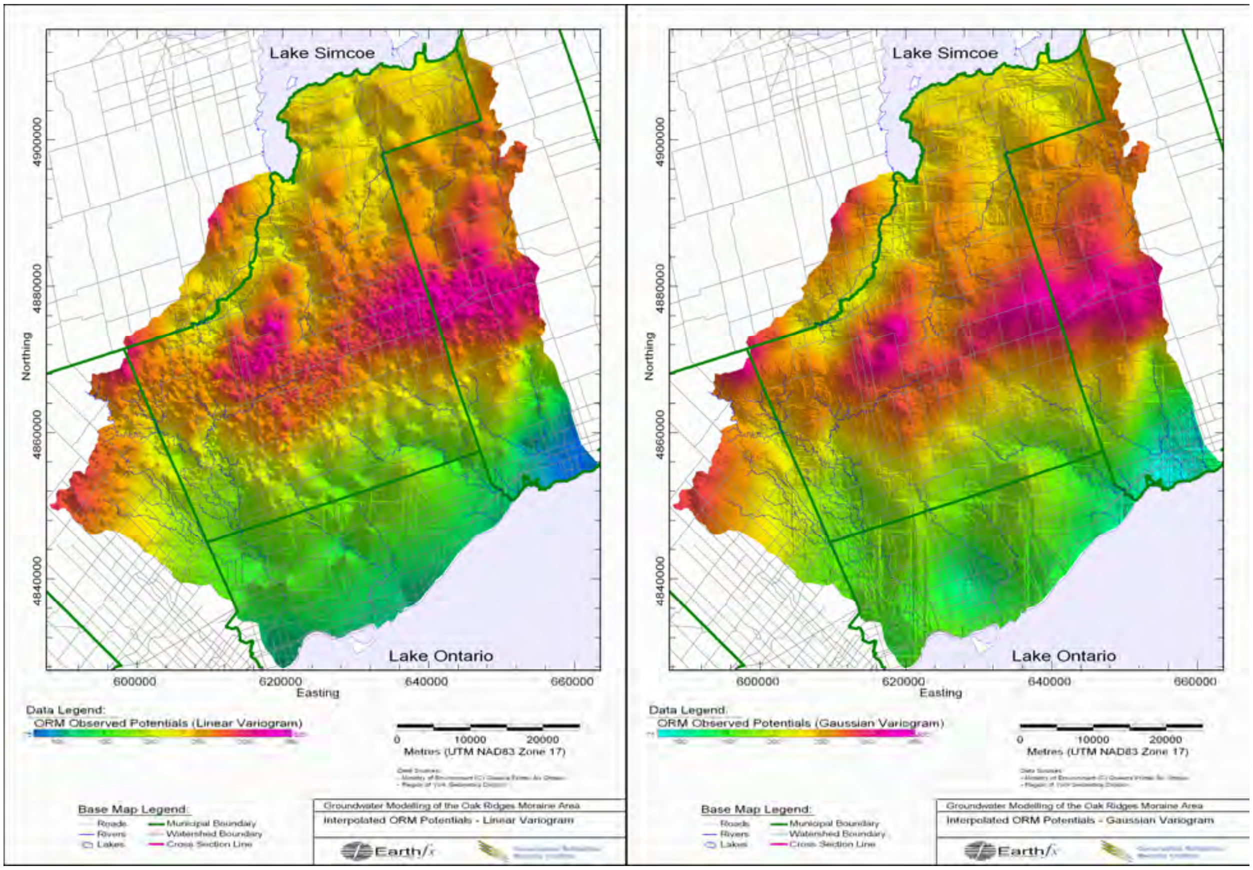


Figure D136: Comparison of ORAC water level kriging results using (a) a linear variogram with no nugget and (b) a gaussian variogram with a 20 m^2 nugget.

Changing the variogram model properties can also affect the results of the interpolation. Scaling the variogram (to create a larger or smaller sill) has no affect on kriging estimate but affects the kriged variance. Increasing the range tends to increase the influence of more distance data points and can lead to smoother maps. Increasing the nugget component acts as a smoothing term and adds variance at a lag distance of 0, thereby making estimates near the known data points less accurate.

4.2.3 Baseflow Separation

Flow in a stream is composed of two components: (1) overland runoff and (2) baseflow. Baseflow, as referred to in this study, represents the component of groundwater discharge to a stream. Numerous theories and techniques have been proposed for analyzing individual storms and for automating the process when applied to multi-year data sets. The methods generally separate baseflow from the total flow by removing the peaks (which represent storm-generated overland runoff) from the streamflow hydrograph. Several techniques, based on work by the U.S. Geological Survey and on methods developed specifically for southern Ontario were tried and found to produce comparable results. In this study, annual average groundwater contribution to streams was estimated from long-term streamflow measurements using a baseflow separation technique developed by Clarifica Inc. and employed on several streams in the TRCA area (Clarifica, 2002).

The method first takes the daily average flows for the period of record and calculates a running minimum 6-day flow by looking forward one day and backwards 4 days. Next, the running five-day average of the 6-day minimum flow is computed looking forward one day and backwards 3 days. Finally, the running average value is compared against the measured flow for that day and the minimum of the measured flow and the running average value is selected to ensure that the calculated baseflow is not greater than the observed flow.

Figure 68 shows an example of baseflow separation at the Holland River at Holland Landing gauge. **Table 3** in the main report presented average total flow and estimated baseflow at all Environment Canada HYDAT gauges with sufficient record. Only gauges with a period of record greater than 5 years were selected. Only data from 1980 to 2000 were available in the database initially, so these values were used in developing the calibration targets. Data for the entire period of record have since been added to the database.

4.2.4 Regional Model Methodologies

The following items related to the Regional Model were mentioned briefly in the main report and are discussed in a little more detail here.

Halton/Kettleby Till – the Halton/Kettleby Aquitard was not represented as a separate model layer in the Regional Model. The unit is characterized in the GSC stratigraphic model as a thin surficial deposit along the southern flanks of the Oak Ridges Moraine. Although the water table may lie within this unit along the flanks of the moraine, from a regional perspective, it was not seen as a major component of the lateral groundwater flow system. The unit tends to restrict recharge to the underlying ORAC deposits. Accordingly, a recharge rate of 90 mm/yr was assigned to the ORAC in areas overlain by Halton Till. These rates were modified in the Core Model to distinguish between Halton Till with and without hummocky topography.

Sunnybrook Aquitard -- MODFLOW uses a “vertical conductance” term to control the exchange of water between model layers. The general formulation for calculating vertical conductance was given by McDonald and Harbaugh (1988) in Eq. 7.1. MODFLOW can also represent the presence of a confining unit between two layers without actually including the confining unit as a separate model layer. In this case, the vertical conductance term is just replaced with:

$$VC_{UL} = \frac{K'}{B'} \qquad \text{(Eq. D4)}$$

where: VC_{UL} = vertical conductance between an upper and lower layer;
K' = vertical hydraulic conductivity the confining unit
B' = thickness of the confining unit

A constant value of 5.0×10^{-9} m/s per m was used to represent the vertical conductance of the Sunnybrook Aquitard in the Regional Model.

Boundary Conditions – Boundary conditions for Layer 5, the weathered bedrock layer, were defined as shown are shown in **Figure 69**. Boundary conditions for Layers 2, 3, and 4 were initially set to be identical to those in Layer 5. Minor changes to the boundaries were required, for example, where the boundary head (e.g. the elevation of Lake Simcoe) was below the interpolated elevation of the layer bottom. In that case, the cells in the "dry" layer were changed from constant head cells to inactive cells.

Periodically, the "starting heads" (i.e. the initial guess for the final steady-state heads) were updated to speed model convergence. Cells that went dry in Layers 1 through 4 at the end of the previous solution would be set as inactive in the updated boundary condition maps. Rewetting was allowed for internal cells.

Re-wetting parameters – **Table D19** describes the rewetting parameters used in the Regional Model.

Table D19: Rewetting parameters in the Regional Model

Parameter	Explanation	Range	Value
IWDFLAG	Flag that determines if the wetting capability is active.	0 -- rewetting is off. 1 – rewetting is on.	1
WETFCT	Scale factor used in calculating the head set at a cell when it converts from dry to wet.	0.0 to 1.0	0.5
IWETIT	Iteration interval for attempting to wet cells.	1 to NITER (Number of iterations)	1
IHDWET	Flag that determines which equation is used to calculate initial head at cells that rewet:	0 – h = BOT + WETFCT (H_n - BOT), 1 -- h = BOT + WETFCT |WETDRY|	1
WETDRY	An array combining the wetting threshold and a flag indicating which neighboring cells can cause a cell to become wet. When the sum of BOT and |WETDRY| at a dry cell is exceeded by the head at an adjacent cell, the cell can rewet.	< 0 -- only the cell below a dry cell can cause the cell to become wet. > 0, the cell below a dry cell and the four horizontally adjacent cells can cause a cell to become wet. = 0 -- the cell cannot be wetted. The absolute value of WETDRY is the wetting threshold	-0.1

Stream properties – Some simplification was necessary to automate the process of assigning stream properties. Stream reaches were first assigned a Strahler classification number and then each stream reach was assigned an average width and bed thickness (B') based on the Strahler number. Segments were assigned a streambed hydraulic conductivity (K') value related to the aquifer layer it was assumed to penetrate. Stream segments that were within the line defined by the extent of the ORM sediments were placed in Layer 1. Stream segments that were outside the line were assigned to Layer 3. Streambed conductance (K'/B') values were in the range of silt to silty-fine sand, as shown in **Table D20**

Table D20: River and drain properties used in the Regional Model

Strahler Code	Aquifer Layer	MODFLOW Package	Streambed Conductance (s^{-1})	Streambed Thickness (m)	Stream Width (m)	Surface Water Elevation (masl)
1	1 or 3	DRAIN	5×10^{-6}	1	1	DEM – 1.0 m
2	1 or 3	DRAIN	5×10^{-6}	1	2	DEM – 1.0 m
3	1 or 3	DRAIN	5×10^{-6}	1	4	DEM – 1.0 m
4	1 or 3	DRAIN	5×10^{-6}	1	6	DEM – 1.0 m
5	1 or 3	DRAIN	5×10^{-6}	1	8	DEM – 1.0 m
6	1 or 3	DRAIN	2.5×10^{-6}	2	15	DEM – 1.0 m
7	1 or 3	DRAIN	1.25×10^{-6}	4	30	DEM – 1.0 m

Line segments representing all streams on the digital maps supplied by MNR were imported into VIEWLOG. The length of each drain segment within each cell was obtained by "intersecting" the model grid with the line segments representing the streams. Controlling drain elevations were estimated from the DEM that had been resampled to the Regional Model grid. VIEWLOG calculated the conductance values and, after processing each drain segment, created the drain input data file for MODFLOW. A total of 146,218 drain segments were used.

Hydraulic Conductivity Assignments – Hydraulic conductivity of Layer 1, which represented the ORM sediments, was divided into three zones based on the mapping of surficial geology as shown in **Table D21**. Zone 6 which represents sands and gravels had the highest hydraulic conductivity while finer-grained materials assumed to underlie the Halton Till on the flank of the ORM were assigned a lower value. Hydraulic conductivities for the lower layers (representing the Thorncliffe and Scarborough Formations and weathered bedrock) were assigned values as shown in **Table 7**

Table D21: Hydraulic conductivity ones for Layer 1 in the Regional Model

Geology Code	Map Unit	Soil Type	Layer 1 Hydraulic Conductivity (m/s)
4	Halton Till covered ORM	Fine Sand	2.5×10^{-5}
5	Moraine Deposits	Fine Sand and Gravel	5×10^{-5}
6	Glacial River Deposits	Sand and Gravel	1×10^{-4}

4.2.5 Core Model Methodologies

The following items related to the Corel Model were mentioned briefly in the main report and are discussed in more detail here.

4.2.5.1 Constructing Core Model Layers

The MODFLOW code requires continuity of aquifer layers whereas the hydrostratigraphic model has units that pinch out. If an upper layer was mapped as not being present (for example, an area where the Halton Aquitard was never deposited or had been eroded away) the thickness of the upper layer was set to zero and the cell was designated as "inactive". MODFLOW cells marked as inactive are excluded from the groundwater flow simulations and recharge to the cell passes through to the uppermost active cell.

Model surfaces for intermediate layers were checked for zero thickness and a set of rules was developed to make minor adjustments to layer tops and bottoms to ensure a minimum 1.0 m thickness for aquifer layers. Aquitard layers were also assigned a minimum 1.0 m thickness but the hydraulic conductivity and other properties of the underlying layer were assigned to the 1.0 m thick layer.

Aquitard layers were also assigned a minimum 1-m thickness where they pinched out, but hydraulic properties of the underlying aquifer were assigned to the cells in the pinch-out areas. Adjustments were also made to the hydraulic properties of the aquitard units to account for weathering where they are exposed (generally multiplied by a factor of 10, as shown in **Table 14**). The model layer geometry shown in **Figure 85** reflects the minor adjustments made to ensure layer continuity (for comparison, see the hydrostratigraphic cross section in **Figure 47**).

Where an aquitard layer was at surface, the upper 2.0 m were assumed to be weathered and fractured. For example, if the Halton Aquitard is at surface and was 6.0 m thick, the upper 2.0 m were placed in Layer 1 and assigned properties of weathered till while the remaining 4.0 m stayed in Layer 2 and was assigned properties of unweathered till. If the Halton Aquitard was less than 2.0 m thick, the cells in Layer 1 were declared inactive and the entire thickness was placed in Layer 2 but assigned properties of weathered till.

Layer 1 typically represented thin sediment units such as the glacial Lake Iroquois beach deposits or other deeper lake sediments from glacial Lake Iroquois and Lake Algonquin. Other units incorporated into Layer 1 include sediments such as the Peel/Schomberg pond sediments as well as other glacial or recent miscellaneous surficial sediments. Where any of the older sediments were exposed at surface, cells in Layer 1 were set to be inactive.

Layer 2 typically represented the unweathered Halton/Kettleby Aquitard. Where the Halton/Kettleby Aquitard was exposed at surface and was less than 1 m thick, cells in Layer 1 and 2 were designated as inactive. Where the Halton/Kettleby Aquitard is at surface and greater than 2 m thick, the upper two metres were assigned to Layer 1 to represent a more fractured and permeable weathered zone. Where the Halton/Kettleby Aquitard was less than 2 m thick, cells in Layer 1 were set to be inactive and Layer 2 represented the weathered zone. Where any of the older sediments were exposed at surface, cells in Layer 2 were set to be inactive. Horizontal flow as well as vertical flow within the Halton/Kettleby Aquitard was simulated, although vertical permeability of the confining unit was assumed to be smaller than horizontal permeability.

Layer 3 typically represented the Oak Ridges Aquifer Complex. Where the unit was less than 1 m thick but overlain by younger deposits, it was assigned a minimum 1-m thickness. Where any of the deeper sediments were exposed at surface or if the ORM deposits were at surface but less than 1 m thick, cells in Layer 1 through 3 were designated as inactive.

Layer 4 typically represented the unweathered Newmarket Aquitard. Where the Newmarket Aquitard was exposed at surface and was less than 1 m thick, cells in Layer 1 through 4 were designated as inactive. Where the Newmarket Aquitard was at surface and greater than 2 m thick, the upper 2 m of the unit were assigned to Layer 3 to represent a more fractured and permeable weathered zone. Where the Newmarket Aquitard was at surface but less than 2 m thick, cells in Layers 1 through 3 were designated as inactive and Layer 4 was assumed to contain the weathered zone. Where the Newmarket Aquitard was overlain by younger units but was less than 1 m thick, Layer 4 was assigned a minimum 1-m thickness and the hydraulic properties were assigned based on the properties of Layer 5. Where older sediments were exposed at surface, cells in Layers 1 through 4 were assigned a zero thickness and designated as inactive.

Layer 5 typically represented the Thorncliffe Aquifer. When the unit was less than 1 m thick and overlain by younger deposits, it was assigned a minimum 1-m thickness. If any of the deeper sediments were exposed at surface or if the Thorncliffe Aquifer was at surface but less than 1 m thick, cells in Layer 5 were designated as inactive.

Layer 6 represented the Sunnybrook Aquitard. When the unit was less than 1 m thick and overlain by younger deposits, it was assigned a minimum 1-m thickness and hydraulic properties were assigned based on the properties of Layer 7. The unit is exposed only over a small area along the Lake Ontario shoreline and in the Humber River Valley, so a weathered Sunnybrook Aquitard was not simulated. If any of the deeper sediments or bedrock units were exposed at surface or if the Sunnybrook Aquitard was at surface but less than 1 m thick, cells in Layer 1 through 6 were designated as inactive.

Layer 7 represented the Scarborough Aquifer. When the unit was less than 1 m thick and overlain by younger deposits, it was assigned a minimum 1 m thickness. If weathered bedrock was exposed at surface, or if the Scarborough Aquifer was at surface but less than 1 m thick, cells in Layers 1 through 7 were designated as inactive.

Layer 8 represented the upper weathered part of the bedrock.

4.2.5.2 Boundary conditions

Boundary conditions for Layer 8, the weathered bedrock layer, were defined as shown in **Figure 86**. Boundary conditions for Layers 1 through 7 were initially set to be identical to those in Layer 8. Adjustments to the boundaries were required, for example, where the boundary head (e.g. the elevation of Lake Simcoe) was below the interpolated elevation of the layer bottom. In that case, the cells in the “dry” layer were changed from constant head cells to inactive cells. Cells were also set to be inactive where upper layers pinched out.

Periodically, the “starting heads” (i.e. the initial guess for the final steady-state heads) would be updated to speed model convergence. Cells that went dry in Layers 1 through 7 at the end of the previous solution were set as inactive in the updated boundary condition maps. Rewetting was allowed for in internal cells.

4.2.5.3 Re-Wetting Criteria

The following table describes the rewetting parameters used in the Core Model. Rewetting parameter values affected model convergence speed and mass balance error. Generally, a trail-and-error procedure was used to determine the optimal combination of rewetting parameters.

Table D22: Rewetting parameters used in the Core Model

Parameter	Possible Range	Value
IWDFLAG	0 -- rewetting is off. 1 – rewetting is on.	1
WETFCT	0.0 to 1.0	0.5
IWETIT	1 to NITER (number of iterations)	1
IHDWET	0 – h = BOT + WETFCT (H_n - BOT), 1 -- h = BOT + WETFCT $\lvert$WETDRY$\rvert$	1
WETDRY	< 0 -- only the cell below a dry cell can cause the cell to become wet. > 0, the cell below a dry cell and the four horizontally adjacent cells can cause a cell to become wet. = 0 -- the cell cannot be wetted. The absolute value of WETDRY is the wetting threshold	-0.1

4.2.5.4 Assignment of K to aquifers

Estimates of hydraulic conductivity for the aquifer layers in the Core Model were derived from the available well data. Several different methods were tested in the process of developing the model. These included estimating properties from aquifer performance tests in the study area, from specific capacity data provided in the MOE database, and from lithologic descriptions in the MOE database.

Of the three methods, the aquifer performance test data were presumed to have the greatest reliability. However, there are only a limited number of tests and the tests do not provide sufficient insight on the distribution of hydraulic conductivity on a regional scale. These transmissivity values were therefore used only to adjust aquifer properties in the vicinity of the municipal wellfields.

Specific capacity of a well is defined as the pumping rate divided by the drawdown. The MOE water well data include results of specific capacity tests conducted at the time of well installation. Not all wells have values and many tests are of short duration (i.e. less than 1 hour). Specific capacity data were analyzed using a modified Theis relationship to determine transmissivity given by:

$$T = \frac{Q}{4\pi s} W\left(\frac{r^2 S}{4T t}\right) \qquad \text{(Eq. D5)}$$

where s is the drawdown at time t, Q is the pumping rate, r is the well radius, S is the storage coefficient, T is the transmissivity, and W is the well function. The method used the specified well radius and pumping rate, the drawdown at the end of 30 minutes, and an assumed value for the storage coefficient equal to $1x10^{-5}$. Equation 7.1 was solved iteratively by guessing an initial value for T in the well function term and then calculating an updated value for T from Equation 7.1. The method usually converged within a few iterations. Hydraulic conductivity was determined by dividing transmissivity by the well screen length. Logs (base 10) of the hydraulic conductivity estimates were interpolated to the model grid using a kriging technique.

Analysis of specific capacity offered greater spatial coverage than the aquifer test data. However, it was recognized that (1) the short duration tests provide only a local measurement of hydraulic conductivity in the vicinity of the well screen, (2) the results are biased upward since drillers typically set the well screen in the most productive zone they encounter, (3) the method is affected by the screen and gravel pack properties when testing highly permeable formations, and (4) the method makes a number of simplifying assumptions that may introduce errors. Nevertheless, maps produced using this method were surprisingly consistent and helped delineate areas of higher and lower permeability.

A method used by Martin and Frind (1998) to estimate hydraulic conductivities in the Waterloo Moraine was modified and applied to this study. Equivalent horizontal and vertical hydraulic conductivities for each aquifer layer were estimated from the lithologic descriptions in the MOE database through a series of steps. Queries were written to extract each combination of primary (Material 1) and secondary (Material 2) material codes from the database. Since there are over 90 different material codes, there are 90^2 possible combinations. The GSC (Russell and others, 1998) had developed methods to simplify the lithologic descriptions and we followed these methods with minor revisions. For example, many of the combinations were eliminated by inspection (e.g. limestone with quicksand) and others that provided limited information (e.g. pre-drilled or topsoil) were discarded. Some description codes that occurred infrequently were combined (e.g. medium sand and sand). Initial estimates of hydraulic conductivity were then assigned to the reduced set of material code combinations based on published ranges (e.g. Freeze and Cherry, 1979). Queries were written to determine the thickness of each lithologic unit or partial unit within each aquifer zone. Equivalent hydraulic conductivities for each aquifer layer were then calculated based on the following equation:

$$K_h = \frac{\sum_i^n K_i d_i}{\sum_i^n d_i} \qquad \text{(Eq. D6)}$$

Logs (base 10) of the hydraulic conductivity estimates were interpolated to the model grid. Again, it was found that the data appeared to be much more continuous than first expected given the high variability of the data in the MOE database. The data appeared to spatially correlate reasonably well with the specific capacity data. Several limitations of this method were recognized. For example, a “clay-sand” combination might refer to zones where alternate layers of sand and clay were encountered and not necessarily a zone of sandy clay. Russell and others (1998) noted that many drillers tend to report silts as clay. In addition, descriptors such as “fine sand” or “coarse gravel”, can provide useful information regarding the hydraulic conductivity of the material but these more detailed descriptors occur rarely within the database (i.e. most drillers simply report “sand” or ”gravel”).

The lithologic material method (with corrections based on aquifer performance tests) was applied since it had the best spatial distribution and was felt to be more reliable than the specific capacity method. Corrections based on aquifer performance tests were generally carried out within 500 m of the municipal pumping wells and reflected the general shape of the drawdown cones from the tests. K's were adjusted either upwards or downwards depending on the test results. During model calibration, it was found that using the extreme high hydraulic conductivity values and extreme low values predicted by the method yielded heads that did not match observed data. Better results were obtained after we smoothed the raw results and adjusted the lowest values upward and the highest values downward and when uniform values for anisotropy ratios (Kv/Kh) were used.

4.2.5.5 Calibration and Sensitivity Analysis

The calibration process proceeded with Core Model runs using initial estimates of hydraulic conductivity, anisotropy, and recharge rates. Simulated water levels were compared with contour maps of the observed water levels and maps of the residuals were used to identify areas where simulated water levels were generally too high or too low. Numerous cross-sections were created across the study area to visually compare simulated and observed water levels and vertical gradients. Model parameters, primarily hydraulic conductivity and recharge, were adjusted in a trial-and-error process to improve the qualitative fits and reduce residuals. Qualitative checks and statistical tests were applied to determine whether the calibration met the required goodness-of-fit criterion.

A series of sensitivity analyses were carried out to evaluate the effects of parameter uncertainty on model results and to demonstrate that the model calibration was done correctly.

To conduct a sensitivity analysis, a single model parameter, such as the hydraulic conductivity of an aquifer layer, is scaled within a reasonable range. For some parameters, the scaling was done on an arithmetic scale, while for others it was done on a log scale. For example, recharge rates were scaled from 0.5 to 2.0 while hydraulic conductivity was scaled from 0.1 to 10 (i.e. 10^{-1} to 10^{1}).

The model was then run with the scaled value and residual errors were calculated and plotted. Model runs were done for a complete set of scale factors (both increasing and decreasing the parameter value) to create a sensitivity graph for the parameter. The whole process was repeated for each critical model parameter. Ideally, the calibrated model values should lie at minimum points on the residual error versus scale factor graphs. Results of tests on the most important parameters are discussed in the main report.

In several cases, model results were not obtained when the larger or smaller scale factors were applied because the model became "unstable". The observation that the model became unstable in some of these simulations does not imply that the physical system would become unstable under these conditions. Rather, it indicates that the groundwater levels would depart drastically from the initial conditions supplied to the model. When extreme changes are imposed on the model, the model tends to overshoot and undershoot in the process of converging towards the true solution for the new heads and more cells go dry or re-wet than should. This, in turn, sometimes leads to even greater overshoot and undershoot. Part of the problem is related to the high contrast in hydraulic conductivity between the aquifer and aquitard layers. Running the model in a quasi-three-dimensional mode produced a more stable model but with a sacrifice in detail (e.g. it is not possible to simulate a system where the water table occurs within the confining unit with a quasi-3 D model). Solutions can often be obtained with the current model by making an incremental change, saving the intermediate solution as an initial guess for the next incremental change, and repeating the process until the total change was achieved. This time-consuming process was not carried out in the sensitivity analysis since the trend was usually established by model results for changes in the stable range.

4.2.5.6 Capture Zone and Time-of-Travel Analysis using Modpath

The calibrated groundwater flow model was used to delineate capture zones and time-of-travel (TOT) zones for the municipal supply wells. A steady-state capture zone is defined as the area that contributes groundwater to a production well. Time-of-travel zones are defined as the portion of a capture zone in which groundwater will travel to a production well within a specified period of time. For example, a 10-year TOT zone is the area around a well in which the furthest water particle takes 10 years to reach the well. The TOT zones are actually three-dimensional surfaces. Wellhead protection areas (WHPA) are often defined using the vertical projection of these surfaces onto a base map even though not all water particles entering at land surface will actually arrive at the well within the specified time interval.

Capture zone and time-of-travel zone analyses were conducted using the USGS MODPATH code. MODPATH used the simulated heads and flow rates from the MODFLOW simulation and additional data on aquifer porosity to calculate average groundwater velocities. Average groundwater velocities are defined as:

$$v = q/n \qquad \text{(Eq. D7)}$$

where q is the specific discharge (Darcy velocity) given by Equation D7 and n is the aquifer porosity (ratio of volume of void spaces to total volume). The average groundwater velocity differs from the Darcy velocity because a porous media is actually a system of impermeable grains with void spaces and, therefore, the actual area through which flow must pass is smaller than the full cross-sectional area.

There is little information on the range and distribution of porosity values in the study area so conservative values (i.e. small values that result in greater velocities and therefore larger capture and time-of-travel zones) were assumed (**Table D23**).

Surficial Material	**Porosity Value**
Layer 1 - Recent Deposits and Weathered Halton/Kettleby Aquitard	0.125
Layer 2 – Halton/Kettleby Aquitard	0.125
Layer 3 – ORAC and Weathered Newmarket Aquitard	0.125
Layer 4 - Newmarket Aquitard	0.05
Layer 5 - Thorncliffe Aquifer Complex	0.125
Layer 6 - Sunnybrook Aquitard	0.05
Layer 7 - Scarborough Aquifer Complex	0.0125
Layer 8 - Weathered Bedrock	0.05

Table D23: Porosity values assumed for the capture zone analysis

MODPATH tracks fictitious particles released from a specified starting point as they move through the aquifer. Each time a particle crosses the boundary of a finite-difference cell, the particle location and time are recorded. The particle is tracked until it reaches a point of discharge and the process is repeated for all particles. MODPATH also has the ability to backward-track particles from a discharge point back to the point of entry to the aquifer as well as the ability to do forward tracking.

To delineate the zones, particles were placed in an 8 by 8 array on all four sides of the cell containing a production well. The 256 particles for each well were tracked backwards in space and time as they moved through the aquifers and aquitards. The TOT zones were drawn manually by connecting the ends of the particle tracks at specified times.

APPENDIX E

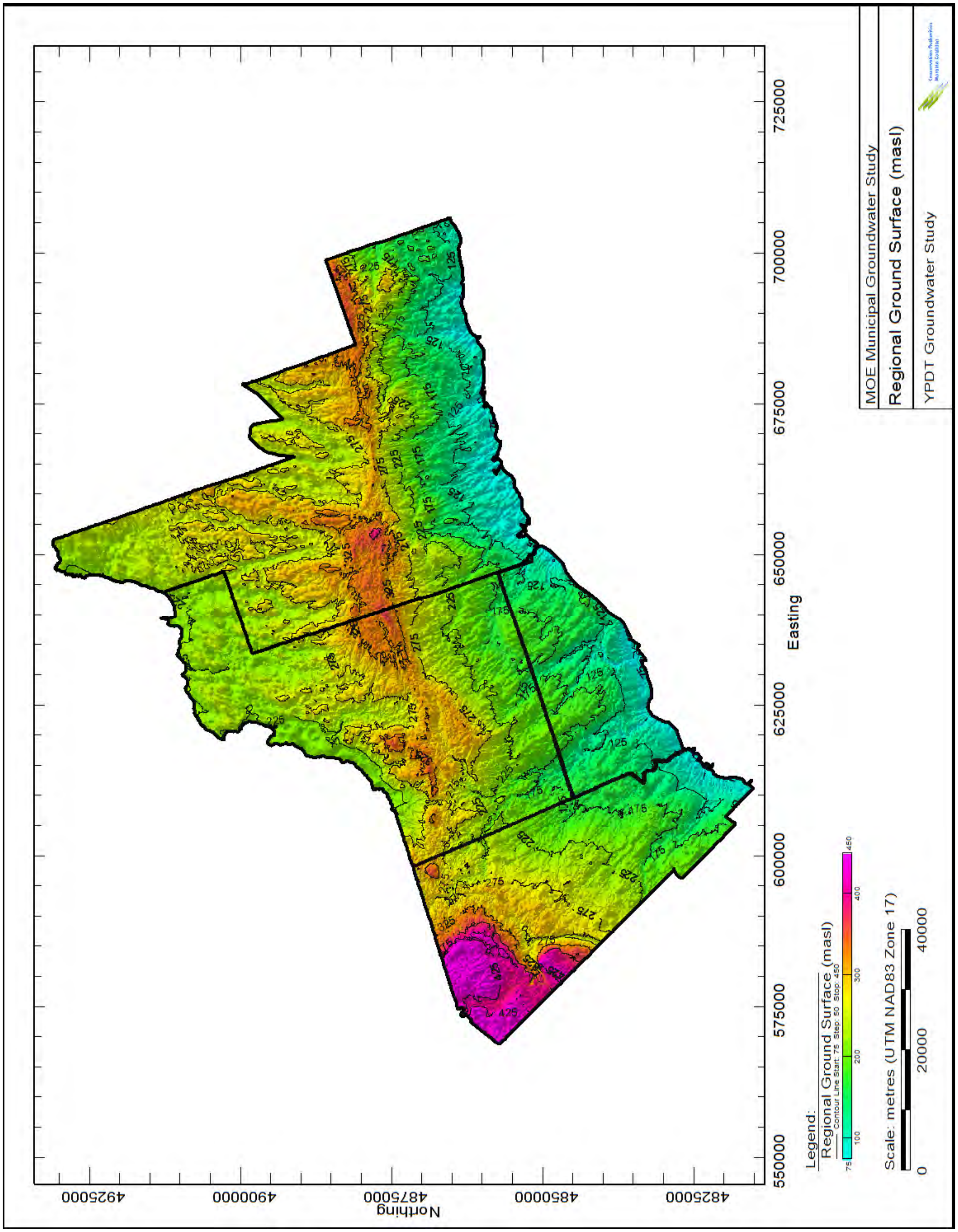
MOE Municipal Groundwater Studies - Maps

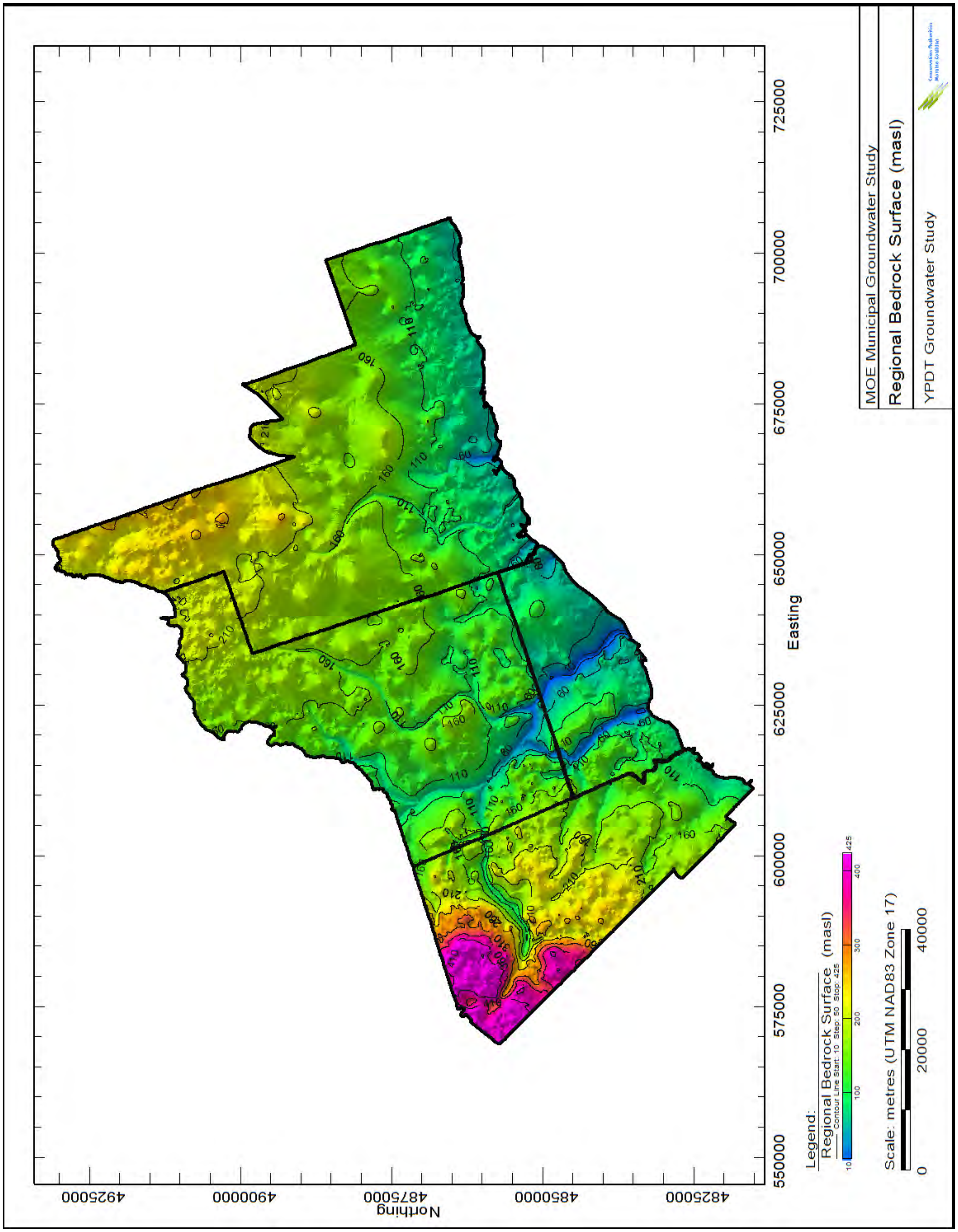
Appendix E: MOE Municipal Groundwater Studies - Maps

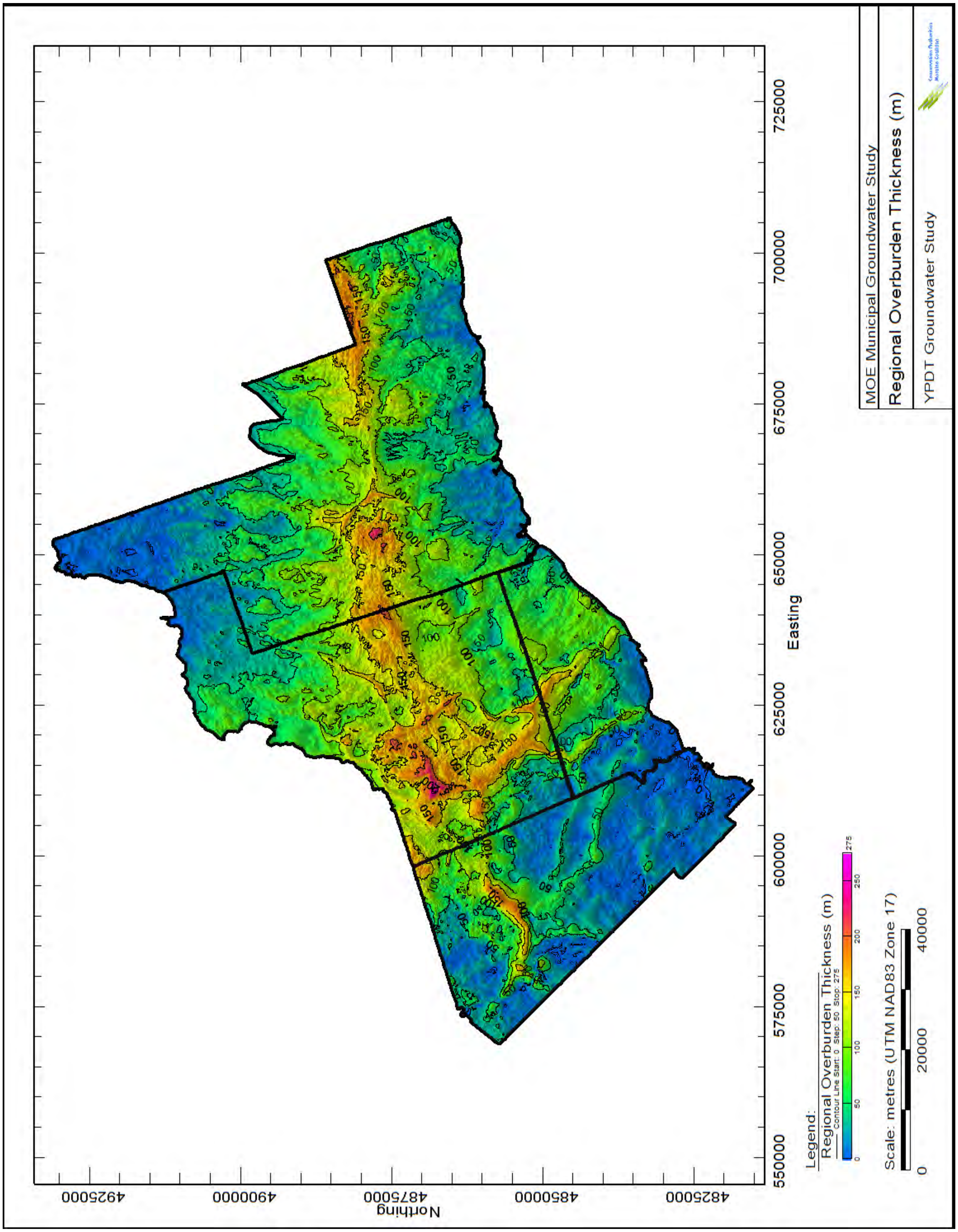
The project received funding under the Ministry of the Environment's Municipal Groundwater Studies program to carry out an Aquifer Characterization Study. To meet the requirements of the MOE's Aquifer Characterization Study, specific maps were requested. While much of the data has been presented in earlier sections of the report, selected maps, which cover the Regions of York, Peel, Durham and the City of Toronto in their entirety, are included in this appendix to meet the MOE requirements.

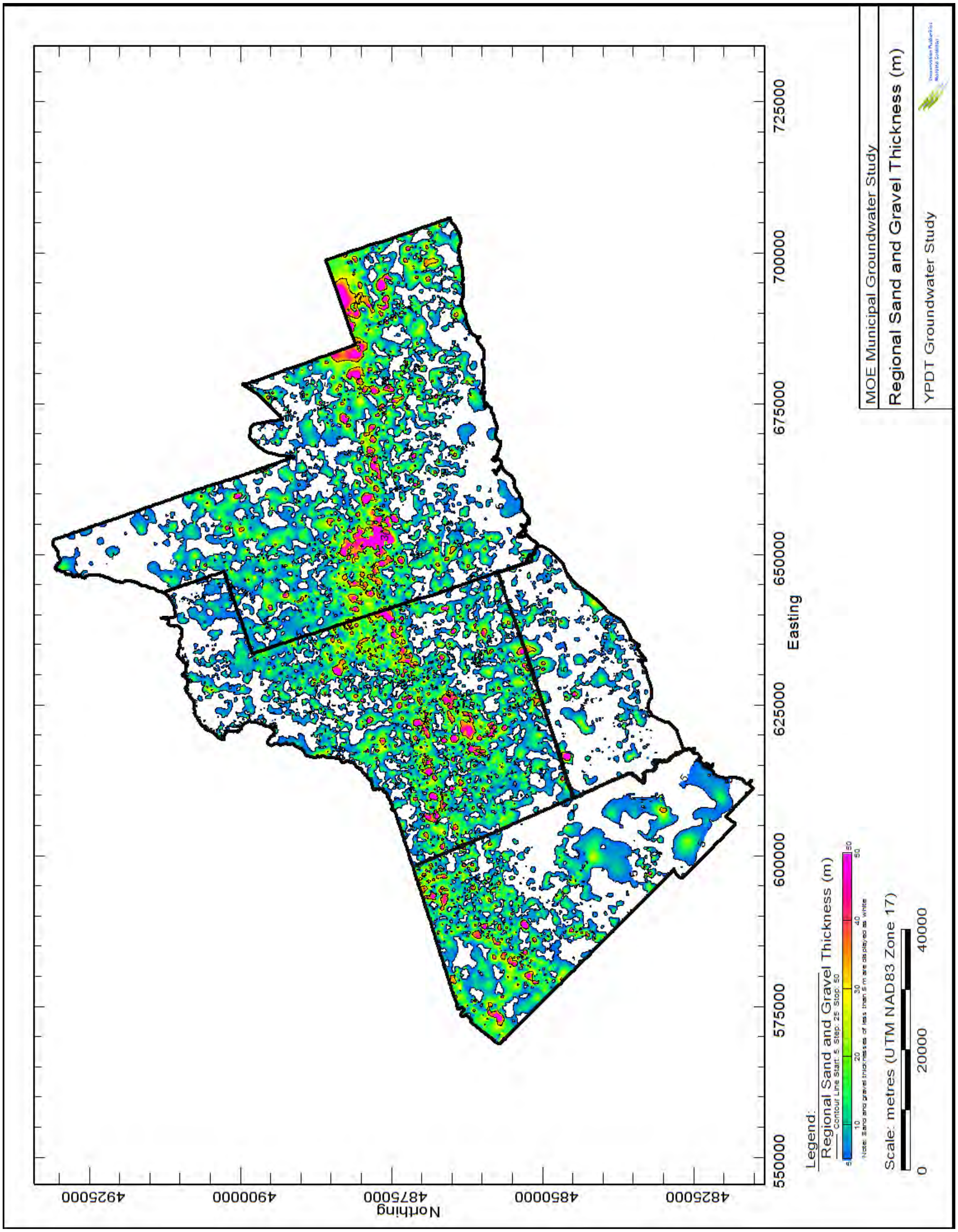
The following maps were prepared as outlined in the MOE's Terms of Reference document for the Municipal Groundwater Studies program:

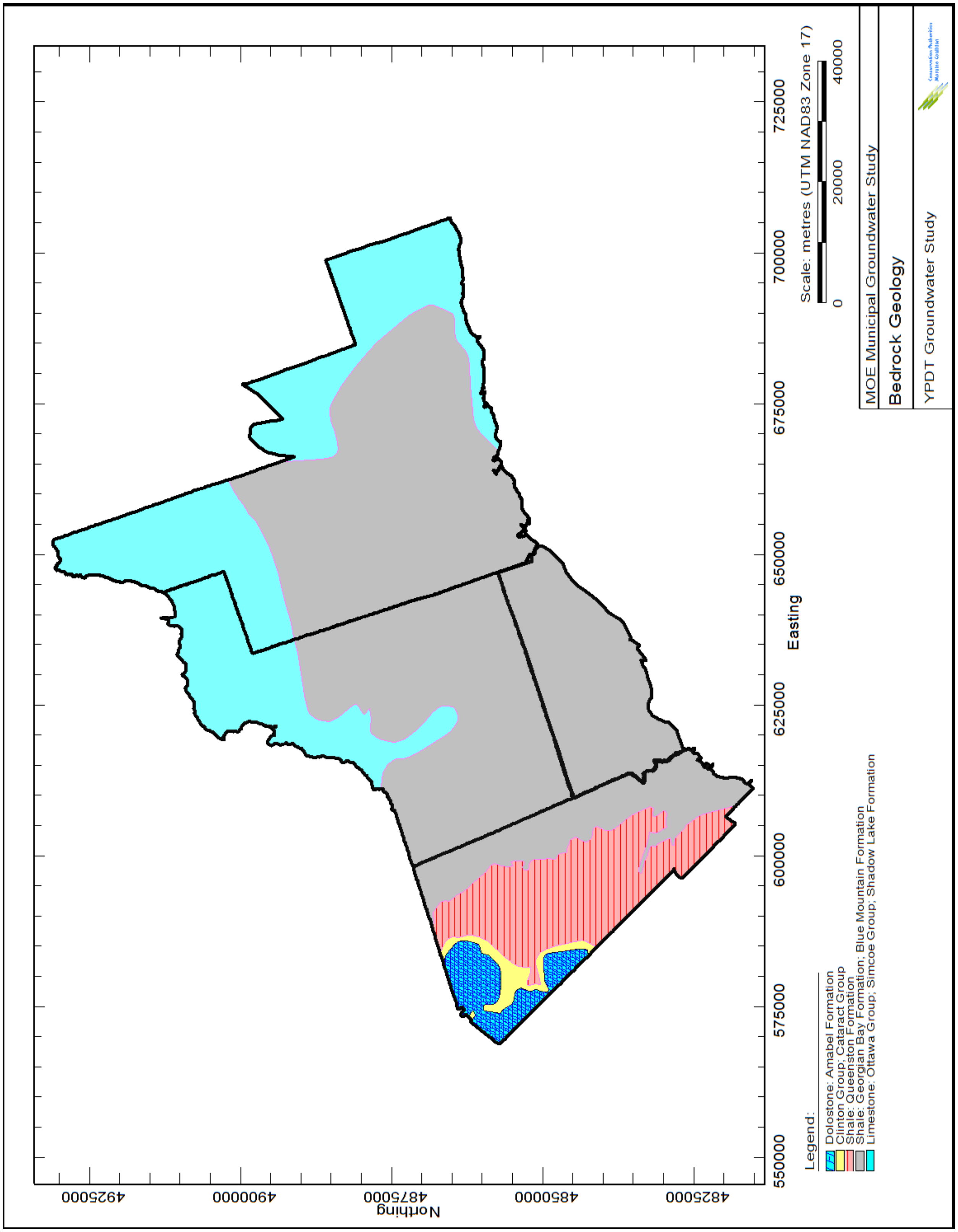
- Ground Surface
- Bedrock Surface
- Overburden Thickness
- Sand and Gravel Thickness
- Bedrock Geology
- Quaternary Geology
- Surface Drainage
- Water Table
- Potentiometric surface
- Specific Capacity (Bedrock & Overburden)
- Water Quality (Bedrock & Overburden)
- Intrinsic Susceptibility Mapping

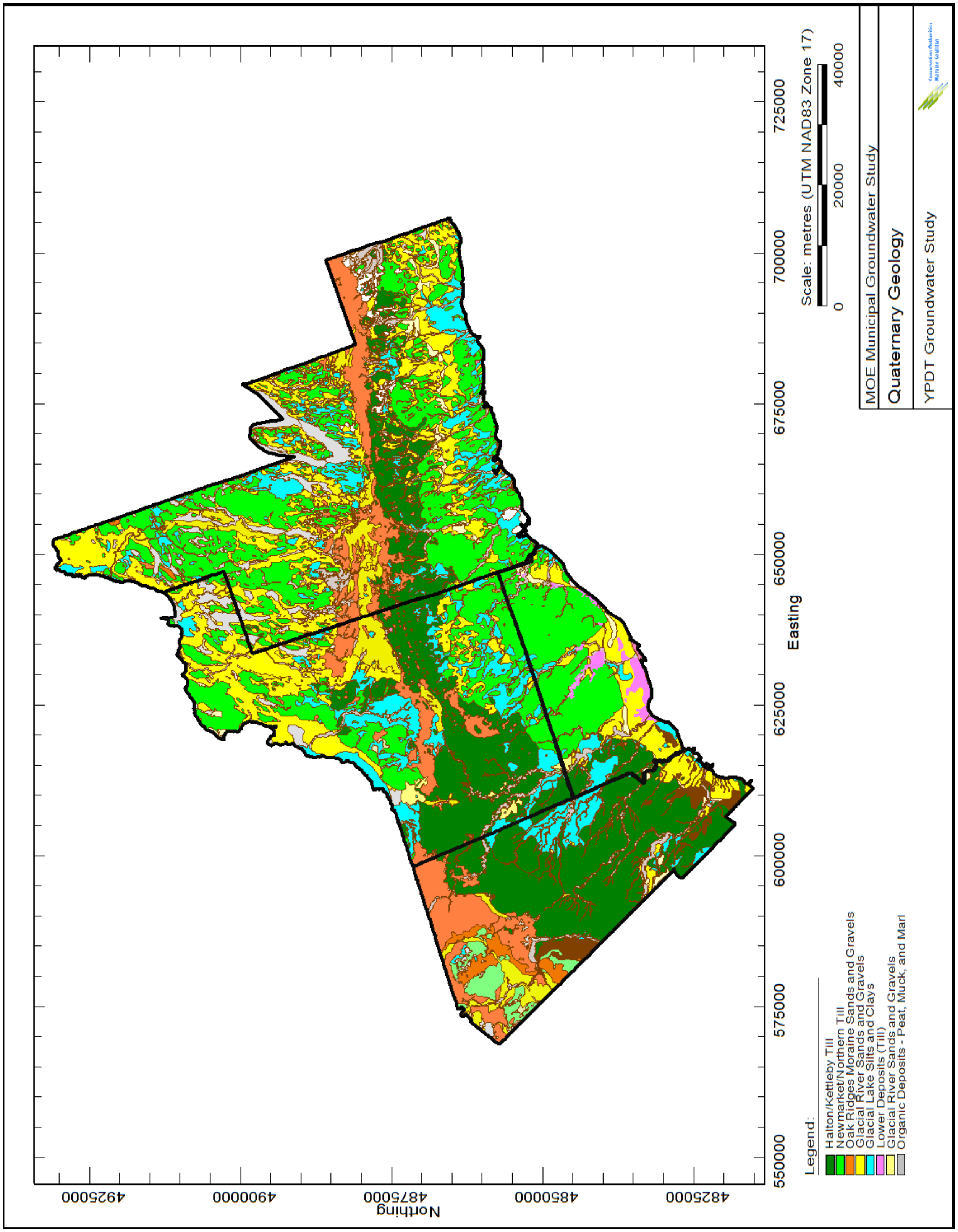

MOE Municipal Groundwater Study
Regional Ground Surface (masl)
YPDT Groundwater Study
Legend:
Regional Ground Surface (masl)
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
550000
575000
600000
625000
650000
675000
700000
725000
Northing
4825000
4850000
4875000
4900000
4925000

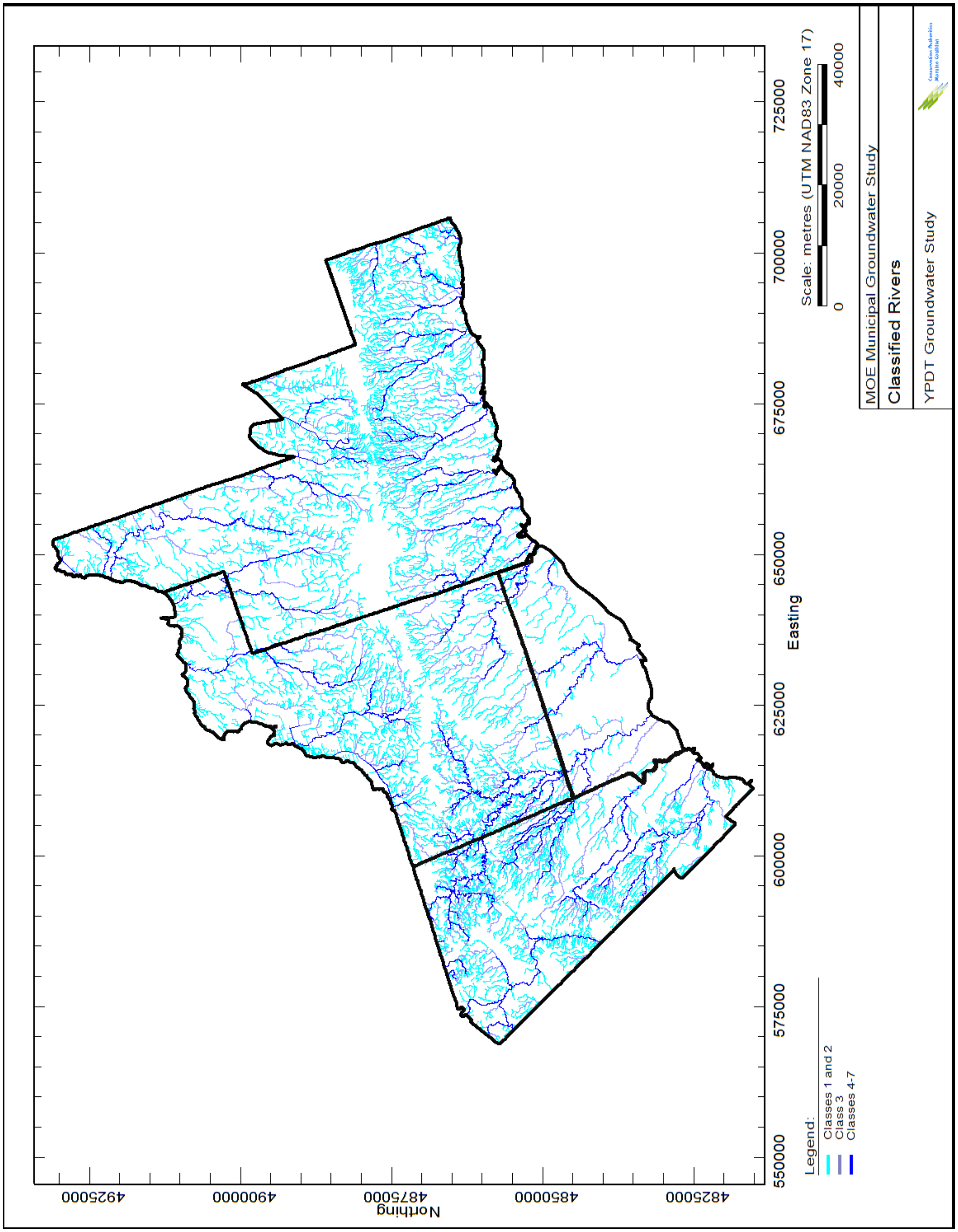

MOE Municipal Groundwater Study
Regional Bedrock Surface (masl)
YPDT Groundwater Study
Legend:
Regional Bedrock Surface (masl)
Contour Line Start: 10 Step: 50 Stop: 425
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
Northing
550000
575000
600000
625000
650000
675000
700000
725000
4825000
4850000
4875000
4900000
4925000

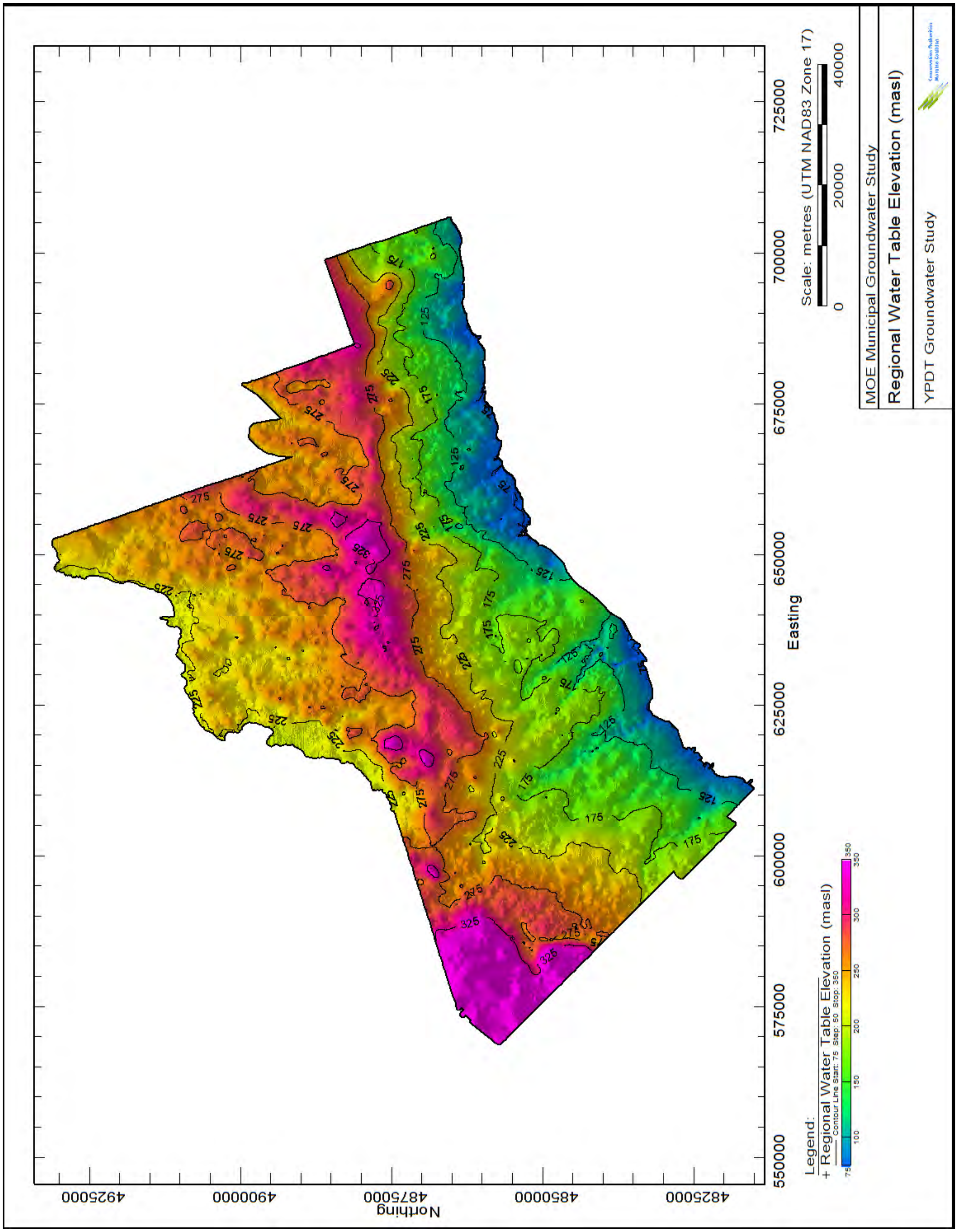

MOE Municipal Groundwater Study
Regional Overburden Thickness (m)
YPDT Groundwater Study
Legend:
Regional Overburden Thickness (m)
0
50
100
150
200
250
275
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
550000
575000
600000
625000
650000
675000
700000
725000
Northing
4825000
4850000
4875000
4900000
4925000

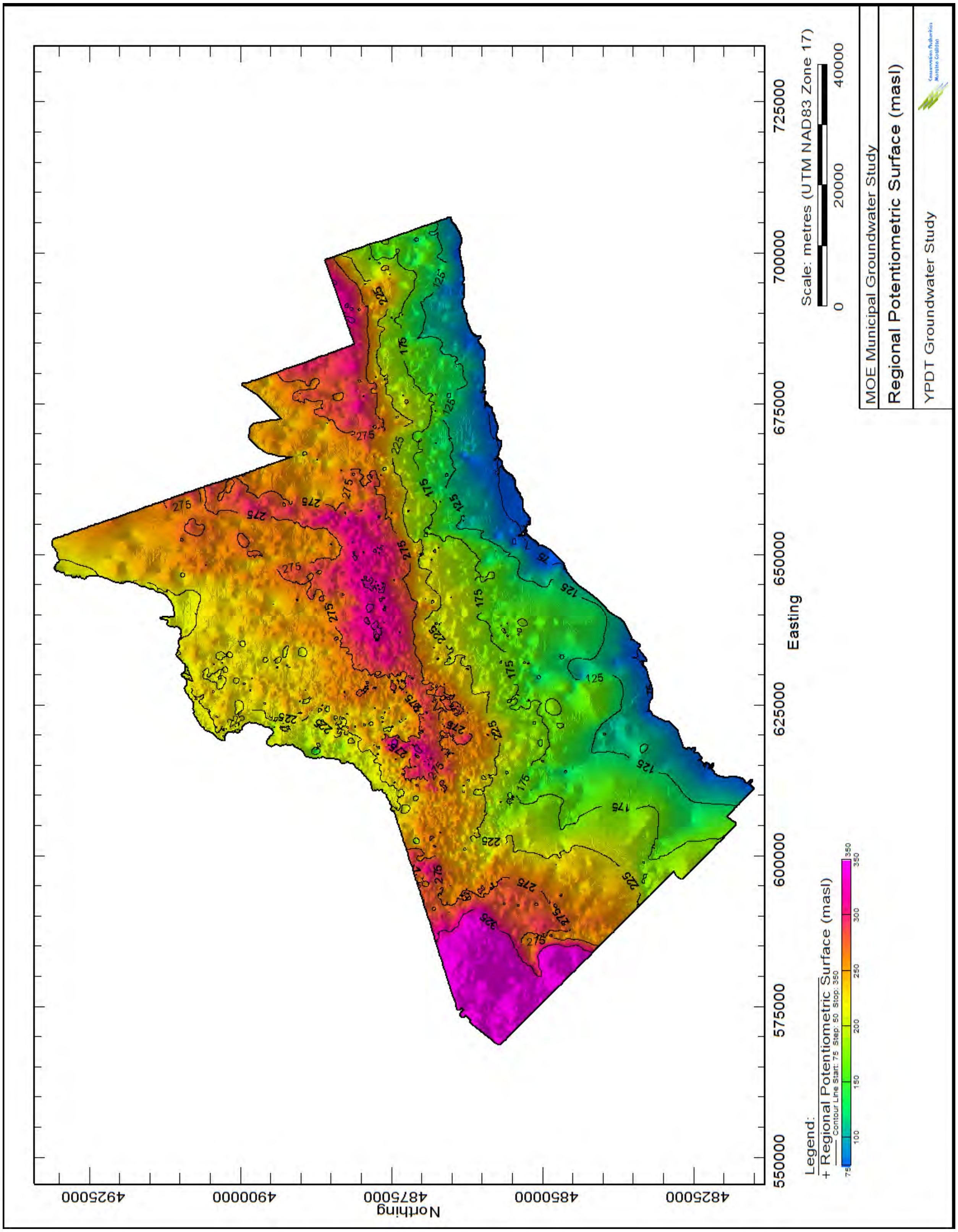

MOE Municipal Groundwater Study
Regional Sand and Gravel Thickness (m)
YPDT Groundwater Study
Legend:
Regional Sand and Gravel Thickness (m)
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
550000
575000
600000
625000
650000
675000
700000
725000
Northing
4825000
4850000
4875000
4900000
4925000

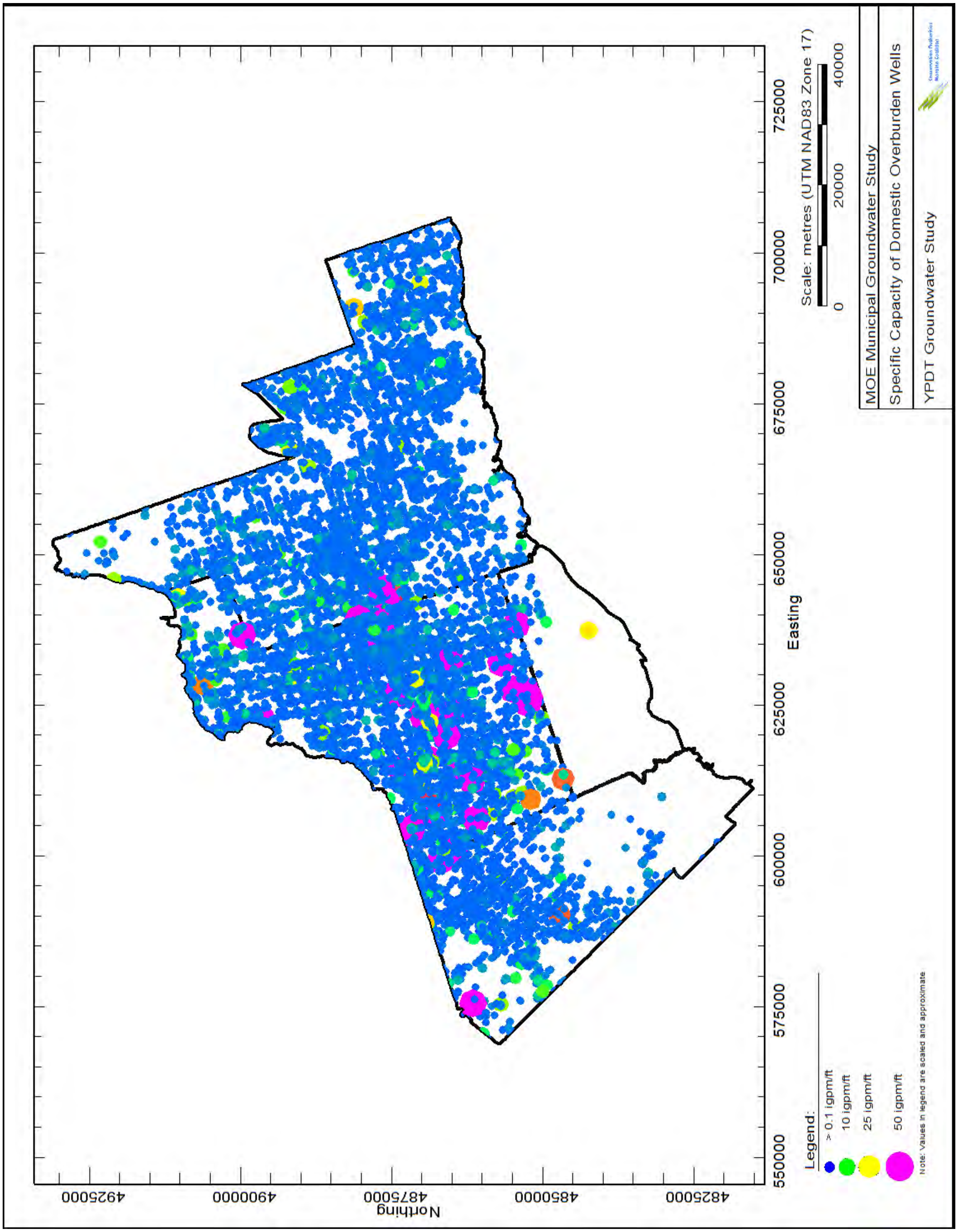

MOE Municipal Groundwater Study
Bedrock Geology
YPDT Groundwater Study
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
Northing
550000
575000
600000
625000
650000
675000
700000
725000
4825000
4850000
4875000
4900000
4925000
Legend:
Dolostone: Amabel Formation
Clinton Group; Cataract Group
Shale: Queenston Formation
Shale: Georgian Bay Formation; Blue Mountain Formation
Limestone: Ottawa Group; Simcoe Group; Shadow Lake Formation

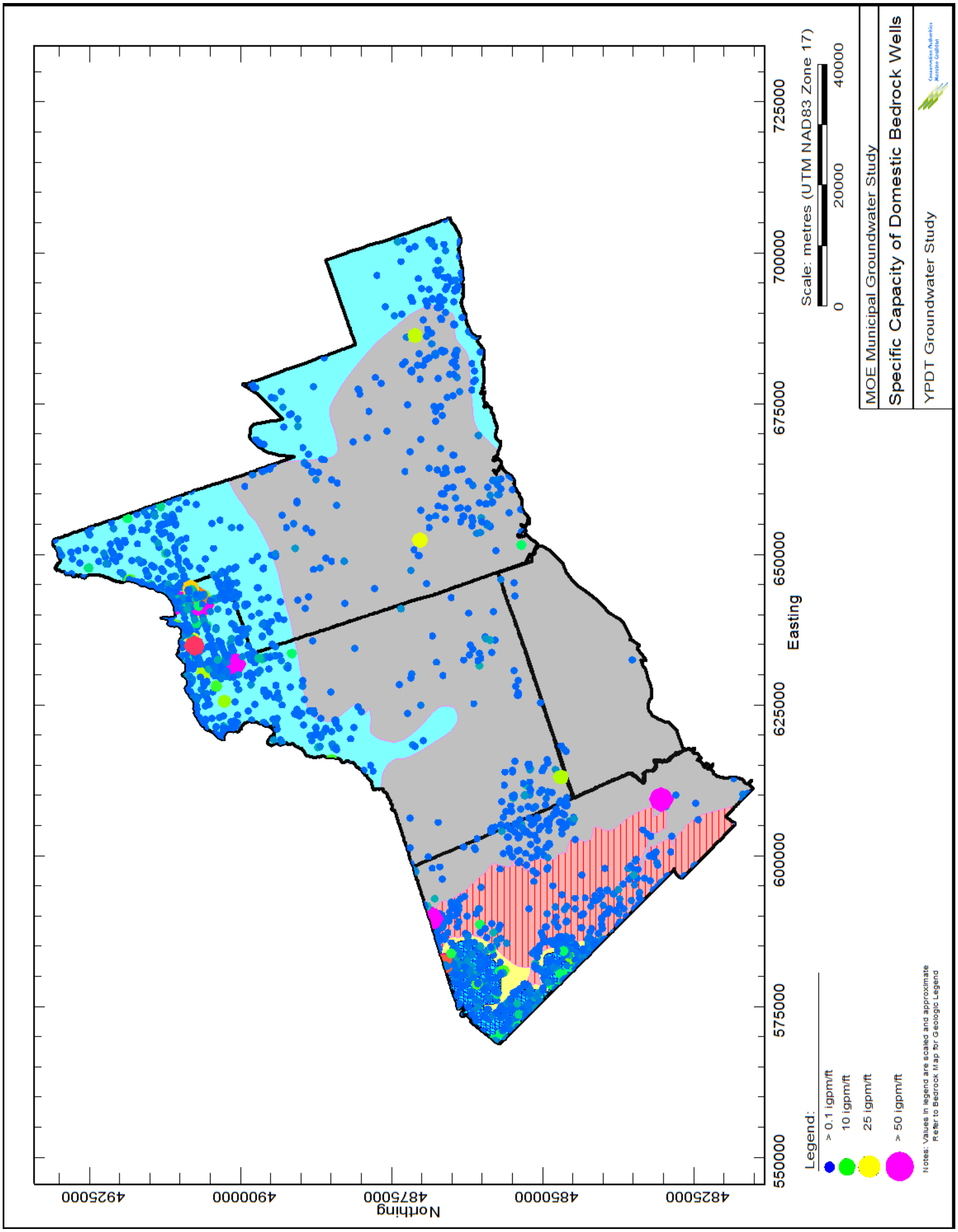

Northing
4925000
4900000
4875000
4850000
4825000
Easting
550000
575000
600000
625000
650000
675000
700000
725000
Legend:
Halton/Kettleby Till
Newmarket/Northern Till
Oak Ridges Moraine Sands and Gravels
Glacial River Sands and Gravels
Glacial Lake Silts and Clays
Lower Deposits (Till)
Glacial River Sands and Gravels
Organic Deposits - Peat, Muck, and Marl
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
MOE Municipal Groundwater Study
Quaternary Geology
YPDT Groundwater Study

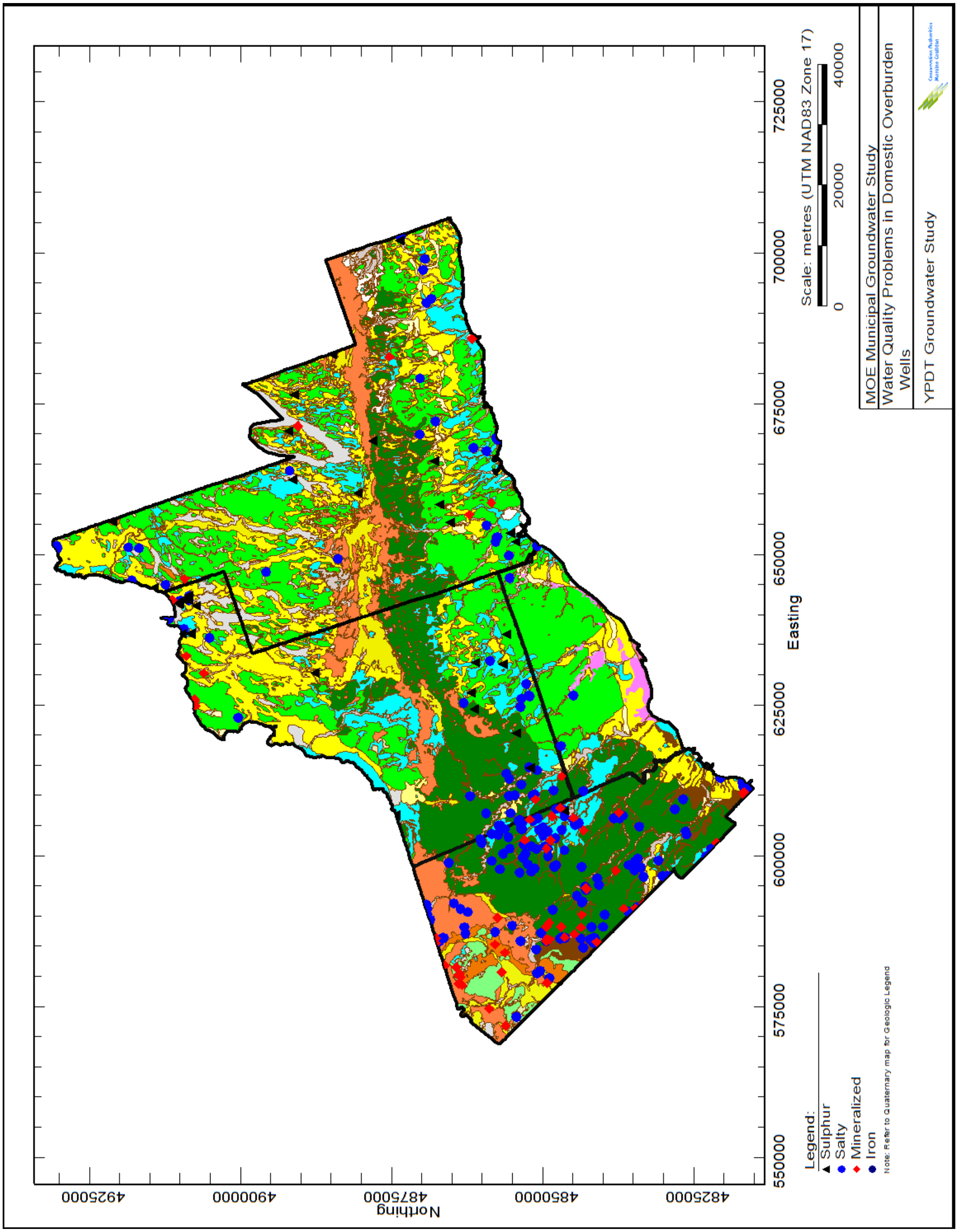

MOE Municipal Groundwater Study
Classified Rivers
YPDT Groundwater Study
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Legend:
Classes 1 and 2
Class 3
Classes 4-7
Easting
Northing
550000
575000
600000
625000
650000
675000
700000
725000
4825000
4850000
4875000
4900000
4925000

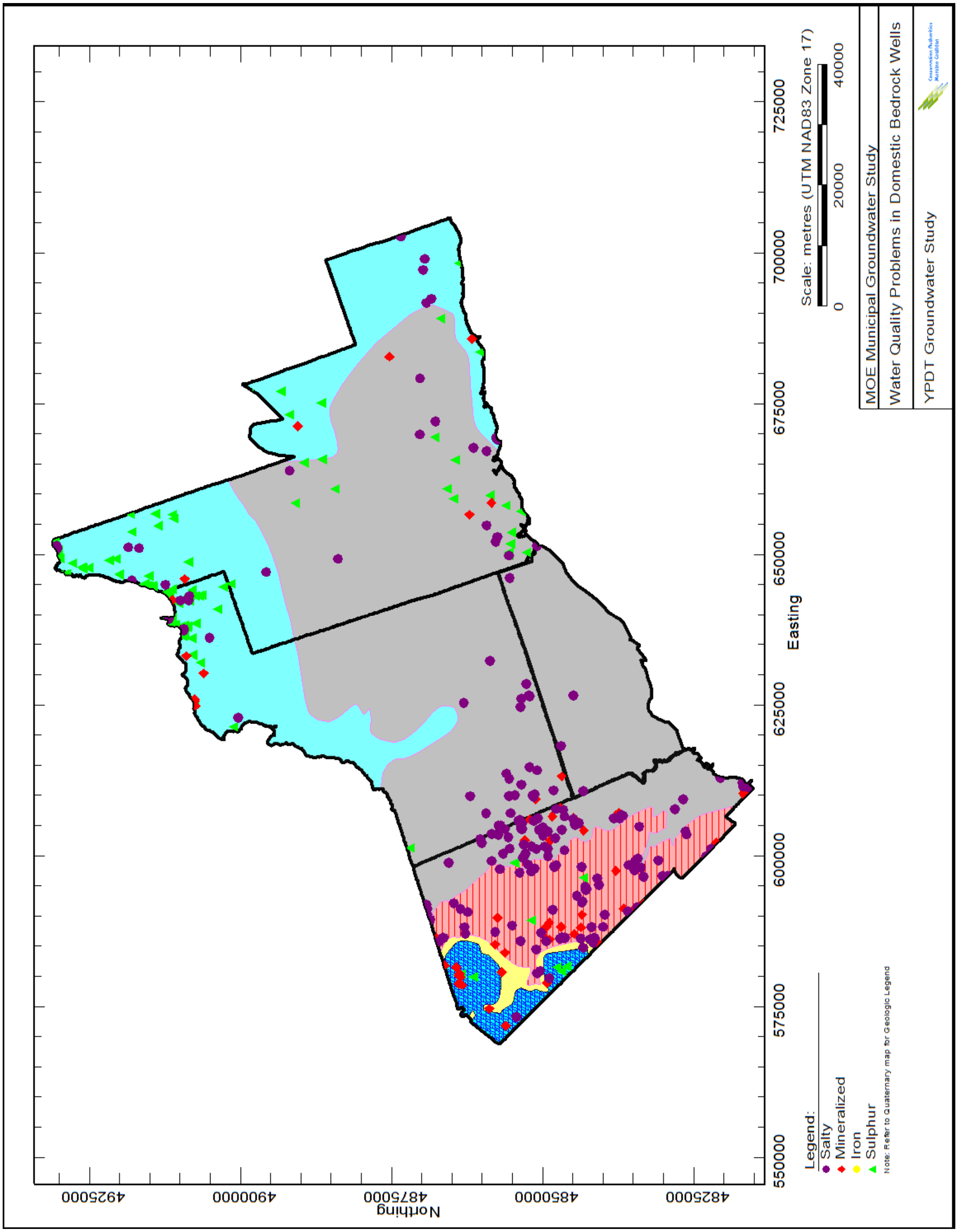

MOE Municipal Groundwater Study
Regional Water Table Elevation (masl)
YPDT Groundwater Study
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
Northing
550000
575000
600000
625000
650000
675000
700000
725000
4825000
4850000
4875000
4900000
4925000
Legend:
Regional Water Table Elevation (masl)
Contour Line Start: 75 Step: 50 Stop: 350
75
100
150
200
250
300
350

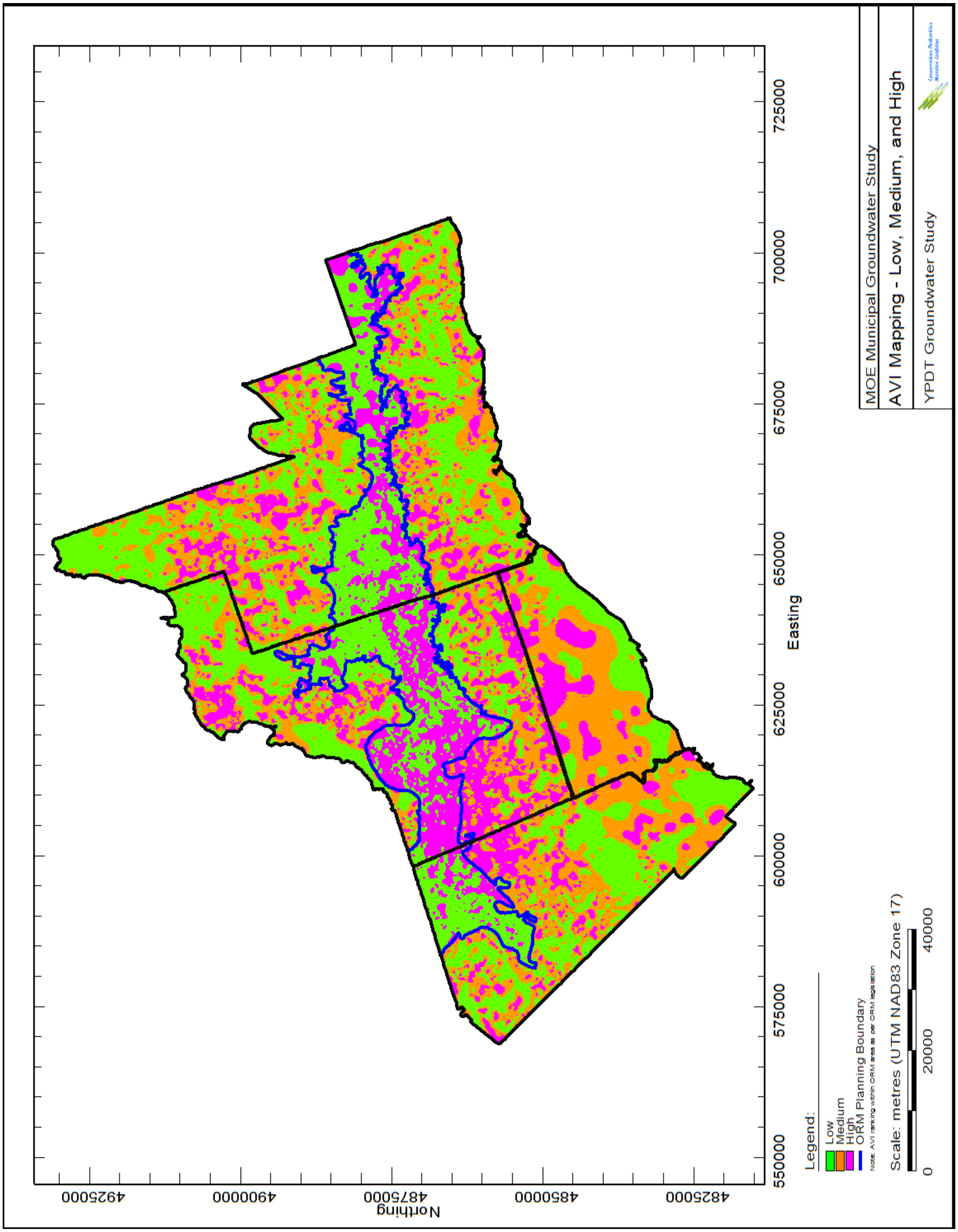

MOE Municipal Groundwater Study
Regional Potentiometric Surface (masl)
YPDT Groundwater Study
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
Northing
550000
575000
600000
625000
650000
675000
700000
725000
4825000
4850000
4875000
4900000
4925000
Legend:
Regional Potentiometric Surface (masl)
Contour Line Start: 75 Step: 50 Stop: 350


MOE Municipal Groundwater Study
Specific Capacity of Domestic Overburden Wells
YPDT Groundwater Study
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
Northing
550000
575000
600000
625000
650000
675000
700000
725000
4825000
4850000
4875000
4900000
4925000
Legend:
> 0.1 igpm/ft
10 igpm/ft
25 igpm/ft
50 igpm/ft
Note: Values in legend are scaled and approximate


MOE Municipal Groundwater Study
Specific Capacity of Domestic Bedrock Wells
YPDT Groundwater Study
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
Northing
550000
575000
600000
625000
650000
675000
700000
725000
4825000
4850000
4875000
4900000
4925000
Legend:
> 0.1 igpm/ft
10 igpm/ft
25 igpm/ft
> 50 igpm/ft
Notes: Values in legend are scaled and approximate
Refer to Bedrock Map for Geologic Legend


MOE Municipal Groundwater Study
Water Quality Problems in Domestic Overburden Wells
YPDT Groundwater Study
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
550000
575000
600000
625000
650000
675000
700000
725000
Northing
4825000
4850000
4875000
4900000
4925000
Legend:
Sulphur
Salty
Mineralized
Iron
Note: Refer to Quaternary map for Geologic Legend


MOE Municipal Groundwater Study
Water Quality Problems in Domestic Bedrock Wells
YPDT Groundwater Study
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
Northing
550000
575000
600000
625000
650000
675000
700000
725000
4825000
4850000
4875000
4900000
4925000
Legend:
Salty
Mineralized
Iron
Sulphur
Note: Refer to Quaternary map for Geologic Legend


MOE Municipal Groundwater Study
AVI Mapping - Low, Medium, and High
YPDT Groundwater Study
Legend:
Low
Medium
High
ORM Planning Boundary
Note: AVI ranking within ORM area as per ORM legislation
Scale: metres (UTM NAD83 Zone 17)
0
20000
40000
Easting
550000
575000
600000
625000
650000
675000
700000
725000
Northing
4825000
4850000
4875000
4900000
4925000