APPENDIX B
Groundwater Flow Model Report

AquaResource
A Division of Matrix Solutions Inc.

CITY OF GUELPH TIER THREE WATER BUDGET AND LOCAL AREA RISK ASSESSMENT

APPENDIX B

GROUNDWATER FLOW MODEL REPORT

Report Prepared for:

Lake Erie Source Protection Region

Prepared by:

MATRIX SOLUTIONS INC.

July 2014
Breslau, Ontario

31 Beacon Point Court
Breslau, Ontario, Canada N0B 1M0

Phone: 519.772.3777 Fax: 519.648.3168
www.aquaresource.ca www.matrix-solutions.com

TABLE OF CONTENTS

FIGURES

LIST OF TABLES

APPENDICES

Appendix B1	Hydrological Model Update (GAWSER)
Appendix B2	Consumptive Groundwater Demand
Appendix B3	High Quality Calibration Targets
Appendix B4	Summer/Fall 2008 Baseflow Monitoring Program Summary Memo
Appendix B5	Transient Verification Results - Hydraulic Head - Municipal Wells

1.0 INTRODUCTION

This appendix describes the City of Guelph Groundwater Flow Model developed to support of the City of Guelph Tier Three Water Budget and Local Area Risk Assessment (Tier Three Assessment) presented in the main body of the report. The purpose of the Tier Three Assessment, as documented in the main body of the report, is to assess the ability for the City of Guelph's wells to meet their allocated pumping rates under average climate and drought conditions. The development of the City of Guelph's groundwater flow model relied on information provided in Appendix A – Conceptual Model Report (Golder Associates 2010).

The Study Area is illustrated on Figure 1-1 and was designed to encompass all areas that may contribute groundwater to the City of Guelph's municipal drinking water wells.

The City of Guelph is one of the largest cities in Canada to rely almost exclusively on groundwater for its potable water supply. The City of Guelph maintains a groundwater supply system that includes 23 groundwater wells that are distributed throughout the city (Figure 1-2). This report describes the development and calibration of a three-dimensional groundwater flow model for the City of Guelph.

In addition to the Tier Three Assessment, the groundwater flow model discussed in this report can be used to support numerous other drinking water management studies underway within the city. These additional studies include groundwater vulnerability assessments, modelling assessments completed in support of Environmental Assessments, and similar studies relating to the exploration for, and management of, drinking water supplies in the City of Guelph.

1.1 What is a Groundwater Flow Model?

Groundwater models are defined as simplified mathematical representations of the storage and flow of water through the subsurface. Groundwater models may be thought of as having two components; the first component is the representation of the physical structure of subsurface soils and rock, and the second is the numerical parameters that describe how water flows through the soil and rock. One of the most challenging aspects in the development of a groundwater flow model is determining the optimal set of numerical parameters that result in the groundwater flow model simulating groundwater flow conditions that reflect real-world conditions to the best extent possible.

Real-world hydrogeologic systems are very complex, and there are a number of simplifications and assumptions that must be introduced into a groundwater flow model to characterize and represent the geology and hydrogeology of a natural system. Geology is the science which studies soil (sediments) and rock, including how the sediments and rock were formed, how they were laid down, and how they have changed through time. Hydrogeology is the science that studies the flow of water through soil and rock.

The first step in the groundwater modelling process is the creation of a conceptual model, which consists of a set of assumptions that describe the system's geological units or layers using text, maps and figures. The assumptions that constitute a conceptual model relate to such items as:

- the spatial and vertical extent of the boundaries of geological and hydrogeological features being studied

- the type of solid matrix comprising the various geological and hydrogeological features (e.g., fractured limestone, sand, gravel, till)
- the conditions by which water enters (e.g., groundwater recharge) or leaves (e.g., pumping wells) the subsurface
- the extent to which groundwater flow conditions change over time (e.g., changes in pumping, drought conditions).

The specific types of simplifications and assumptions associated with the above elements of a conceptual model depend on the amount of data available, the degree to which that data can be used to describe the natural system, and the degree of complexity required in the groundwater flow model to address the goals and objectives of the modelling study.

The next step in the modelling process is to express the conceptual model in the form of a mathematical, or numerical, groundwater flow model. A mathematical model of a groundwater flow system begins with an assumption of the conservation of mass meaning that the difference between the amount of groundwater flowing into and out of a given volume must equal the change in storage of water within that volume. A numerical groundwater flow model represents the conceptual model using equations and parameters that represent hydrogeologic structure, the ability for water to flow through and be stored in geological materials, and boundary conditions that govern how water is transferred in and out of the groundwater flow model. The assumptions that constitute a numerical model relate to such items as:

- The hydraulic conductivity of geological materials. The term “hydraulic conductivity” is a parameter that reflects the ability of groundwater to flow through soil or rock. Hydraulic conductivity values can vary in the vertical and horizontal directions within the same geological unit reflecting the influence of the deposition of each geological unit.

- Groundwater recharge rates can vary spatially and temporally, and they represent the flux of water that moves from ground surface and shallow soils into the saturated groundwater system that lies below the water table.

- Formulation of boundary conditions. Various types of boundary conditions can be present in a groundwater flow model to represent the addition or removal of groundwater from the flow system. Groundwater can be removed from a model where it discharges to surface water features such as streams and wetlands on the land surface, or it can also be removed via groundwater pumping wells.

Ultimately, the numerical parameters assigned to a groundwater flow model are derived through a process called model calibration. The calibration process follows an iterative series of parameter adjustments to arrive at an endpoint where the model’s estimation of groundwater flow conditions suitably reflects measured real-world values.

1.2 Previous Groundwater Models in the City of Guelph

The City of Guelph has completed numerous hydrogeological studies that developed and used groundwater flow models as summarized in the following subsections. The recent history of groundwater model development in the City of Guelph is summarized below in Table 1-1.

Table 1-1 History of the Guelph Tier 3 Groundwater Flow Model

Date	Project	Description
2004-2006	Guelph-Puslinch Groundwater Protection Study (Golder 2006a)	Golder Associates developed a three-dimensional numerical groundwater flow using FEFLOW. The model spans 1,340 km^2 covering the entire City of Guelph, and a relatively large area surrounding the city.
2006-2007	City of Guelph Source Protection Project (AquaResource 2007a)	AquaResource (2007) delineated preliminary wellhead protection areas and groundwater vulnerability maps using the Golder (2006a) FEFLOW model. Minor modifications to the model were made including effective porosities used in determining of time-of-travel capture zones.
2008-2011	City of Guelph Tier Three Water Budget and Local Area Risk Assessment (current study)	The current study is initiated, with the scope of work including the refinement of the City of Guelph's conceptual hydrogeologic model and the development and calibration of a new groundwater flow model. • A preliminary version of the calibrated model was completed late in 2009 and presented to project peer reviewers. • A draft of the Model Calibration Report (this current report) was submitted for peer review in mid-2010. • The preliminary version of the model was used to delineate vulnerable areas as part of the City of Guelph Source Protection Project (AquaResource 2010). • After the 2010 peer review, additional model calibration efforts were undertaken including transient model verification and model calibration in the Arkell Springs area.
2008-2009	City of Guelph Source Protection Project (AquaResource 2010)	The second phase of the City of Guelph Source Protection Project (2010) used a preliminary version of the current Tier Three model to delineate capture zones and vulnerable areas.
2009-2010	Southwest Quadrant Class Environmental Assessment (SWQ-EA; Golder 2010)	This study explored ways to best use the existing groundwater aquifer by investigating the potential to increase the capacity of existing wells and install a new well(s) in the southwest quadrant. Golder (2010) refined the calibration of the preliminary version of the Tier Three model within the southwest quadrant/Hanlon Creek areas. Modifications to the model were fed back into the Tier Three model and are described in this report.

1.2.1 Early Studies

The City of Guelph began to conduct detailed hydrogeological investigations on a city-wide basis in the 1990s to better understand its groundwater resources. In 1991 it was recognized that the information on the City of Guelph's water supply system was incomplete and in some cases insufficient. As such, a comprehensive study was initiated to collect additional information to adequately define the water resources. This study included testing the municipal wells for extended periods of time, and thus only a portion of the system was evaluated in any given year to avoid interruption in water service. To ensure continuous service, the Study Area was divided in four quadrants with Gordon/Woolwich Streets and the Speed/Eramosa Rivers forming the quadrant boundaries. The study was completed on a quadrant-by-quadrant basis by Jagger Hims Limited (Jagger Hims 1998a; 1998b; 1998c; 1995;). The first quadrant evaluated was the northeast quadrant in 1993, followed by the northwest in 1994, the southwest in 1995, and the southeast in 1996/1997.

The quadrant studies involved the compilation and review of available geologic and hydrogeologic information for each quadrant area and detailed testing of each municipal well located in the subject quadrant to determine its capacity to yield water. The studies also included a review of the water quality at each municipal well.

A summary of the groundwater resources within the City of Guelph was prepared as part of the City of Guelph Water Supply System Study in 1999 (Gartner Lee, Jagger Hims and Braun 1999). As part of this study, a multi-layered MODFLOW groundwater flow model was developed and used to delineate 2-year, 5-year, 10-year, and steady-state capture zones based on the geologic and hydrogeologic understanding at that time. This study also provided recommendations relating to the management of municipal drinking water supplies.

1.2.2 Guelph-Eramosa Township Groundwater Study

The Guelph-Eramosa Township Groundwater Study was completed in 2003 by Gartner Lee Ltd. (Gartner Lee 2003a). The objective of the study was to assemble relevant data and information that could be used to develop a long-term plan to manage the quantity and quality of the groundwater resources within the Township. As part of the study, a finite-difference groundwater flow model was developed based on the quadrant studies for the City of Guelph and used to map wellhead protection areas for existing and proposed water supply wells within the Township. The study also characterized the susceptibility of the aquifer to potential surficial sources of contamination and included a potential contaminant sources inventory within the Township's wellhead protection areas based on land use information.

1.2.3 Arkell Spring Grounds Groundwater Supply Investigation

The City of Guelph's use of the Arkell Spring Grounds as a source of drinking water dates back to 1908. The spring source was supplemented with four high-capacity wells: three completed in bedrock and one in the overburden. The four wells were installed within the Arkell Spring Grounds between 1963 and 1966. In 1999, recognizing the need to locate additional water supply sources to meet the growing demands of the municipality, the City of Guelph retained Gartner Lee Ltd (2003b) to investigate the Arkell Spring Grounds and evaluate its potential as a source of additional groundwater supplies. This area was selected as it was believed there was potential for large groundwater yields from the bedrock aquifer.

The Arkell Spring Grounds Groundwater Supply Investigation included several long-term pumping tests with extensive groundwater and surface water monitoring. The groundwater flow model, developed by Gartner Lee (2003a), was used to predict aquifer drawdown under long term (steady-state) pumping conditions and assess potential changes in groundwater-surface water interactions, and to delineate capture zones for the wells.

1.2.4 Guelph- Puslinch Groundwater Protection Study

As part of the Guelph-Puslinch Groundwater Protection Study (Golder 2006a) a numerical groundwater flow model was developed to delineate capture zones for the municipal water supply wells. The study also included regional groundwater characterization, groundwater susceptibility (vulnerability) mapping, a regional contaminant source inventory (threats database), and a groundwater use assessment.

The groundwater flow model developed in that study covered 1,340 km^2 including the entire City of Guelph and a large area surrounding the city. The model was based on the finite-element method using FEFLOW (Diersch 2006) for the groundwater flow analysis.

1.2.5 County of Wellington Groundwater Protection Study

The County of Wellington Groundwater Protection Study (Golder 2006b) was initiated in 2003, and it refined the regional scale mapping completed for groundwater studies in 2001/2002. This study focused on areas susceptible to groundwater contamination from surficial sources, as well as wellhead protection areas using hydrogeological maps from across the County. This study would later form the basis of a groundwater protection strategy created for the County of Wellington.

A regional potential contaminant sources database was developed as part of this study. The database was prepared in a similar format to the threats database developed in the Guelph-Puslinch Groundwater Protection Study (Golder 2006a).

1.2.6 City of Guelph Source Protection Project

In 2006, the City of Guelph retained a team led by AquaResource and included Stantec Consultants (Stantec) and S. S. Papadopulos and Associates Inc. (SSPA), to conduct a groundwater protection study. With funding from the Province of Ontario under the Clean Water Act program, preliminary wellhead protection areas and groundwater vulnerability maps were developed for the City of Guelph. Wellhead protection areas delineated in this study were based on the groundwater model developed in the Guelph-Puslinch Groundwater Protection Study (Golder 2006a). A second phase of the study used a preliminary version of the Guelph Tier Three model to update capture zones and delineate vulnerable areas.

1.2.7 Southwest Quadrant Class Environmental Assessment

A study of the southwest quadrant is currently underway by Golder Associates and AECOM (Golder 2010). This study is investigating the potential to increase the capacity of existing wells and install new wells in the study area. The study will also develop a well testing and monitoring program to determine long-term well capacities for the municipal wells and assess potential environmental impacts. This project is subject to a Municipal Class Environmental Assessment under Ontario’s Environmental Assessment Act, and it is expected to be completed in 2011.

1.3 Objectives and Goals of the Groundwater Model

The City of Guelph Groundwater Flow Model described in this report was developed with the primary goal of completing the City of Guelph's Tier Three Water Budget and Local Area Risk Assessment. In addition to fulfilling the requirements of the Tier Three Assessment, the model may also be used in the future to help the City of Guelph with various groundwater related studies. Specifically, projects which may benefit from having a calibrated regional scale groundwater flow model include:

- groundwater vulnerability studies that require the delineation of capture zones for municipal wells
- environmental assessments that need to evaluate the sustainability of potential municipal supply wells and pumping scenarios, and the potential impact of municipal pumping on the environment
- other groundwater studies as required

An understanding of the groundwater flow system is gained by reviewing available information, developing a conceptual geological model, and constructing a three-dimensional groundwater flow model that represents the elements of the conceptual geological model. The groundwater flow model is used as a tool to further understand and simulate the groundwater flow system.

The following goals were defined for this project:

- Develop a spatially referenced database of hydrogeologic information for visualization and characterization of regional and local hydrogeologic information.

- Develop a watershed-scale, three-dimensional, conceptual geological model that builds upon the existing conceptualization and numerical models developed within the City of Guelph and surrounding area (this detailed conceptual geologic model is presented by Golder Associates (2011) in Appendix A of the main body of the Tier Three Assessment report).

- Develop a calibrated groundwater flow model that incorporates details from the conceptual model and is calibrated to available data, including the City of Guelph's groundwater monitoring data, other hydraulic head datasets, and estimates of the rates of groundwater discharge into watercourses.

- Apply the calibrated groundwater flow model to estimate water budget parameters within the Study Area.

- Use the calibrated groundwater flow model to evaluate scenarios as require by the Province as part of the Tier Three Assessment (as described in the main body of the report).

1.4 Report organization

This report is organized into the following sections:

Section 2.0: **Groundwater Flow Model Development** describes the set-up and input parameters applied within the FEFLOW groundwater flow model.

Section 3.0: **Model Calibration and Verification** describes the calibration targets and process used to calibrate and verify the groundwater flow model.

Section 4.0: References.

2.0 GROUNDWATER FLOW MODEL DEVELOPMENT

2.1 Introduction

This section describes the development of the City of Guelph Groundwater Flow Model based on a detailed geological conceptual model. The development of the detailed conceptual model is described in Appendix A – Conceptual Model Development provided in support of the main body of the City of Guelph Tier Three Assessment Report. The calibration and verification of the groundwater flow model is described in Section 3 below.

The approach used to develop the City of Guelph Groundwater Flow Model builds upon the approach followed in the Guelph-Puslinch Groundwater Flow Model (Golder 2006a). The key advancements made in developing this updated and refined City of Guelph Groundwater Flow Model are as follows:

- The geographic coverage of the City of Guelph Model was extended to include the Grand River to the west and the Niagara Escarpment to the east. Carrying the model westward to the Grand River provides a natural boundary condition for groundwater flow, and the Niagara Escarpment represents the physical location where the Gasport Formation bedrock aquifer, the main aquifer supplying the City of Guelph's water supplies, pinches out.

- The conceptual model developed for this study was based on detailed interpretation of geologic units at numerous high-quality boreholes located throughout the Study Area, whereas the bedrock conceptual model used in the Guelph-Puslinch Groundwater Flow Model was simplified and represented by layers of constant thickness.

- The City of Guelph has installed several groundwater monitoring wells screened in discrete hydrogeologic units within the city since the development of the Guelph-Puslinch Model. These wells measure groundwater elevations and vertical gradients throughout the city on a continuous basis and provide an improved and enhanced understanding of the bedrock flow system in the area.

- The City of Guelph Groundwater Model was refined to include additional surface water features that were not previously represented in the Guelph-Puslinch Groundwater Flow Model.

2.1.1 Modelling Process

The process followed to develop the City of Guelph Groundwater Flow Model consisted of the following four stages:

- **Conceptual Model Development.** A conceptual model describes an interpretation of the physical features represented in a model including surface water features, groundwater recharge, hydrostratigraphy (e.g., hydrogeologic units), and water use.

- **Model Selection.** The computer software FEFLOW (v. 5.4; Diersch 2006) was selected as the modelling code used to develop the City of Guelph Groundwater Flow Model.

- **Numerical Model Construction.** A groundwater flow model is constructed by representing the conceptual model using numerical parameters that represent interpreted hydrogeologic features, with depth, and the external interactions with groundwater (e.g., pumping wells and boundary conditions).

- **Model Calibration and Verification.** The next steps of the modelling process, calibration and verification, are discussed in Section 3 below.

2.2 Conceptual Model

The first step in the development of a groundwater flow model is the creation of a conceptual model which describes the physical aspects of the Study Area, including the geology and hydrogeology, as well as the climate and land use. The conceptual model developed for the Tier Three Assessment is described in detail in Appendix A – Conceptual Model (Golder 2011) of the main body of the report and includes a discussion of the following:

- Study Area
- Physiography and Surface Water Features
- Land Use
- Geology
- Hydrogeology
- Groundwater/Surface Water Interactions

2.2.1 Surface Water Hydrology

The Study Area (Figure 2-1) for the City of Guelph Tier Three Assessment lies mainly within the Grand River watershed, but also includes portions of the Credit River Watershed to the east, Fletchers Creek to the south, and Bronte Creek in the southeast (Halton Region). The confluence of the Speed and Eramosa Rivers lies within the City of Guelph, and the Speed River eventually joins with the Grand River along the western boundary of the Study Area in Cambridge.

Other important Grand River tributaries within the Study Area include Mill and Irish Creeks located south of the City of Guelph; and Hanlon, Torrance and Clythe Creeks located within the city limits. Hopewell and Cox Creeks are located northwest of the City of Guelph. Blue Springs Creek is located east of the City of Guelph and is a major tributary to the Eramosa River. Flow in many of these tributaries is maintained by groundwater discharge, and many tributaries are associated with Provincially Significant Wetlands that are important in terms of groundwater/surface water interactions.

A number of artificial lakes and reservoirs, such as Guelph and Mountsberg Lakes, were constructed in the Guelph area for flood control, recreational use, and/or aesthetic purposes. In addition, a number of artificial ponds created by the extraction of aggregate (e.g., sand and gravel) below the water table also exist in the Study Area, and these are most common southwest of the City of Guelph within the Mill Creek subwatershed.

Kettle lakes are small, closed depression lakes that are often located in hummocky topography. Within the Study Area, several kettle lakes exist along the Paris and Galt Moraines; the largest being Puslinch Lake located west of Cambridge. This lake was formed in a depression left behind by melting ice that was buried at the time of the last glaciation approximately 10,000 years ago.

Refer to Appendix A of the main body of the report (Characterization Report) for additional details relating to the surface water features in the Study Area.

2.2.1.1 *GAWSER Streamflow Generation Model*

The Guelph All-Weather Sequential-Events Runoff (GAWSER) streamflow generation model is a physically-based, deterministic hydrologic model used to predict the total stream flow resulting from inputs of rainfall and/or snowmelt. It can operate in both continuous and event-based modes. It can be used to model recharge ponds and can predict pollutant accumulation, wash off, and transport. Climate input data required for continuous modelling includes daily maximum and minimum temperatures, daily total precipitation, and hourly rainfall.

The Grand River Conservation Authority (GRCA) developed and calibrated a continuous GAWSER model to simulate the hydrology of the Grand River watershed. The hydrologic model was originally constructed for flood forecasting purposes in the late 1980s, and the model has continually improved and evolved since that time as new information and updates in conceptualization have evolved. The event-based model was converted to a continuous model in the late 1990s when a substantial calibration and verification exercise was carried out.

More recently, the GAWSER model was revisited based on initial feedback from a three-dimensional groundwater flow model developed for the GRCA Watershed and applied as part of the Grand River Tier Two Water Budget and Subwatershed Stress Assessment (AquaResource 2009a). The GAWSER model was further refined as a joint effort between the City of Guelph and Regional Municipality of Waterloo Tier Three Assessments and is described in detail in Appendix B1 of this appendix. The overall objective of this modelling exercise was to provide refined recharge estimates for the Tier Three Assessments.

Specific updates to the GAWSER model are as follows:

1. The simulation time period was extended from 1961-1999 to 1961-2005 to allow the model to consider the entire late 1990s to early 2000s drought.

2. Additional climate stations within the central portion of the Grand River watershed were incorporated to better represent climate variability.

3. Additional stream gauges were considered to verify local response. Prior to this update, model performance was primarily evaluated within the larger river systems, whereas smaller watercourses were not investigated in detail.

4. Hydrologic response units within urban boundaries were refined. In previous models, the response units were based on 1992 land cover data, which was not reflective of current land use patterns.

5. The urban land area was subdivided into various urban land uses. Previously, all urban response units were modelled to have a similar imperviousness. Discretizing the urban response units by

specific land use better represents the spatial distribution of imperviousness and therefore recharge.

6. Recently developed lands designed to infiltrate the same volume of water as before they were developed were identified and characterized as having infiltration characteristics similar to undeveloped lands.

Within the Study Area, the GAWSER model refinements focused on improving the calibration of the Mill Creek Subwatershed, Upper Speed River Watershed, Eramosa River Watershed, and Blue Springs Creek Subwatershed. The land areas associated with these drainage areas represent a large proportion of the Study Area and the key groundwater recharge areas associated with the City of Guelph's drinking water supplies.

2.2.2 Hydrogeology

The conceptual understanding of the overburden and bedrock geology in the Study Area are described below, while Appendix A of the main body of the report describes the development of the conceptual geologic model in greater detail.

The City of Guelph Groundwater Flow Model was developed with more extensive local hydrogeologic data and characterization than was available for the Guelph-Puslinch Groundwater Protection Study (Golder 2006a). The previous conceptual hydrogeological model for the Study Area was updated and improved as part of the Tier Three Assessment. The revised conceptual model is described in this section including discussion of the modifications and advancements made with respect to the previous model. An update to the previous conceptual model was warranted based on the following key factors:

- Approximately 100 higher quality deep bedrock boreholes were drilled in the Cities of Guelph and Cambridge since the Guelph-Puslinch Study was completed. These boreholes have included continuous coring and/or high-quality geophysical logging to better understand the nature of the bedrock geology. These boreholes provided a sufficient density of high-quality information within the municipal well fields to explicitly define the contact elevations of the various bedrock geologic formations with a higher degree of confidence.

- The drilling program for the Tier Three Assessment provided high-quality deep bedrock geologic information outside the core areas of the municipal well fields. This high-quality data was used to interpret a regional hydrogeological conceptual model in these well field areas.

  The recent borehole data and associated geologic interpretations were made possible due to funding contributions and input from the Ontario Geologic Survey's (OGS) Bedrock Aquifer Mapping Program. The OGS is currently mapping the Silurian carbonate strata along the Niagara Escarpment and has proposed revisions to the Silurian Stratigraphy of this area. The updated stratigraphic framework described by the OGS (Brunton 2009) forms the basis for the re-interpretation and revisions to the Guelph area bedrock conceptual hydrogeological model. Table 2-1 compares the current updated stratigraphic framework and the previous conceptualization used in the Guelph-Puslinch Study.

Table 2-1 Updated Stratigraphic Framework (Brunton 2009)

<table>
<tr><th colspan="2">Revised Conceptualization
Formation/Member</th><th colspan="2">Previous Conceptualization
Formation/Member</th></tr>
<tr><td colspan="2">Overburden</td><td colspan="2">Overburden</td></tr>
<tr><td rowspan="2">Guelph Formation</td><td>Hanlon Member</td><td colspan="2" rowspan="2">Guelph Formation</td></tr>
<tr><td>Wellington Member</td></tr>
<tr><td rowspan="3">Eramosa Formation</td><td>Stone Road Member</td><td rowspan="6">Amabel Formation</td><td rowspan="3">Eramosa Member</td></tr>
<tr><td>Reformatory Quarry Member</td></tr>
<tr><td>Vinemount Member</td></tr>
<tr><td>Goat Island Formation</td><td>Ancaster / Niagara Falls Members</td><td rowspan="3">Wiarton / Colpoy / Lions Head Members</td></tr>
<tr><td>Gasport Formation</td><td>Gothic Hill Member</td></tr>
<tr><td colspan="2">Rochester /Irondequoit / Rockway / Merritton Formations</td></tr>
<tr><td colspan="2">Cabot Head Formation</td><td colspan="2">Cabot Head / Reynales Formation</td></tr>
</table>

The following key updates were made to the previous three-dimensional conceptual model as part of this Tier Three Assessment:

Definition of variable three-dimensional bedrock formation surface elevations based on current data and following the OGS revised stratigraphic framework.

Improved delineation and separation of bedrock units primarily including:

- Separation of the Eramosa Member into the Vinemount and Reformatory Quarry Members which have distinctly different hydraulic properties as described further below.
- Better definition of the top of the Gasport Formation (formerly Amabel Formation) including delineation of the Goat Island Formation as a separate unit.
- Integration of bedrock geology characterization derived from the concurrent Tier Three Water Budget and Local Area Risk Assessment work being carried out for the Region of Waterloo in the Cambridge Area (AquaResource In Progress).

The conceptual model revisions that were completed as part of this project focused on improving the delineation and characterization of the bedrock units as they have a significant influence on the groundwater flow in the municipal aquifer system. The overburden conceptual model layer structure developed as part of the Guelph-Puslinch Study was largely retained for this project. Key exceptions are in the Southwest Quadrant area of Guelph where a local-scale review and refinement of the Guelph-Puslinch model's overburden stratigraphy was completed in conjunction with the Southwest Quadrant Class Environmental Assessment (Golder 2010), as well as in the Arkell Spring Grounds.

The uppermost Paleozoic bedrock geology beneath the Study Area as delineated in the conceptual model is illustrated on Figure 2-2. The City of Guelph and the remainder of the Study Area are underlain by Silurian dolostones and shaley dolostones of the Guelph, Eramosa, Goat Island and Gasport Formations and various underlying bedrock units. Figure 2-3 illustrates the bedrock surface developed using Ministry of Environment (MOE) water well records, high-quality borehole data, bedrock outcrops, and previous hydrogeological studies. For additional information on the creation of this bedrock surface, refer to Appendix A (Golder 2011). The bedrock surface elevation ranges from a low of approximately 240 m asl in southwest Puslinch Township to a high of 470 m asl north of Guelph. The Speed and Eramosa Rivers have carved valleys into the bedrock surface. Other paleochannels were similarly eroded into the bedrock surface thousands of years ago and were subsequently infilled with sediment. These buried bedrock valleys extend from Rockwood in the north-eastern portion of Guelph towards the modern-day Eramosa River valley (Greenhouse and Karrow 1994).

Figure 2-4 illustrates the surficial geology mapped within the Study Area by the Ontario Geological Survey (2003). Figure 2-5 shows the thickness of overburden in the Study Area produced by subtracting the bedrock surface (discussed above) from the 10 m Digital Elevation Model (DEM) of the ground surface. Bedrock is exposed along the banks of the Speed and Eramosa Rivers; whereas, overburden thickness exceeds 70 m along the crests of the Galt and Paris Moraines. Areas where the thickness of overburden is greater than 30 m are generally restricted to the Galt and Paris Moraines and the buried bedrock valley that lies northeast of the City of Guelph. Appendix A provides additional description of the surficial geology of the Study Area.

The conceptual hydrogeological model applied in the Tier Three Assessment is illustrated on Figure 2-6. A brief description of each bedrock formation and conceptual hydrogeological unit is provided below in Table 2-2 and in the following sections (from oldest to youngest).

Figure 2-7 and Figure 2-8, reproduced from Appendix A of the main body of the report, illustrate the conceptual hydrostratigraphic units in north-south and east-west cross-sections. The following subsections further describe these units.

Table 2-2 Hydrostratigraphy and Ranges of Hydraulic Conductivity and Thicknesses

Hydrostratigraphic Unit Description	Estimated Horizontal Hydraulic Conductivity (m/s)	Estimated Vertical Hydraulic Conductivity (m/s)	Estimated Thickness Where Present (m)
Overburden A (Upper Sand and Gravel) Coarse-grained outwash gravel and sand deposits, Wentworth Till, Port Stanley Till, Fine grained sediments, and Bedrock outcrops *(Aquifer)*	5.0e-8 to 2.3e-3	1.0e-8 to 5.0e-4	1 – 70 m
Overburden B (Lower Till) Wentworth Till, Port Stanley Till, Catfish Creek Till, Bedrock outcrops *(Aquitard)*	5.0e-8 to 5.0e-4	5.0e-9 to 5.0e-4	2 – 70 m
Contact Zone Fractured bedrock and overlying basal unconsolidated deposits *(Aquifer)*	3.0e-5	3.0e-6	4 m
Guelph Formation (*Aquifer*)	1.0e-6 to 1.0e-4	1.8e-8 to 2.9e-5	10 – 40 m
Eramosa Formation - Reformatory Quarry Member (*Aquifer/Aquitard*)	5.0e-7 to 5.3e-6	1.0e-8 to 5.6e-7	5 – 50 m
Eramosa Formation - Vinemount Member (*Aquitard*)	1.0e-7 to 5.0e-6	1.0e-9 to 5.0e-8	2 – 10 m
Goat Island Formation (*Aquifer/Aquitard*)	1.0e-6 to 8.0e-5	8.3e-8 to 4.0e-5	5 – 40 m
Upper Gasport Formation (*Aquifer*)	1.0e-6 to 1.0e-5	2.0e-7 to 1.0e-5	3 – 40 m
Middle Gasport Formation (*High Permeability Aquifer*)	1.0e-6 to 3.6e-3	1.0e-6 to 3.6e-3	12 m
Lower Gasport Formation (*Aquifer*)	2.0e-6	2.0e-8	10 – 20 m
Cabot Head Formation (*Aquitard*)	1.0e-10	1.0e-12	10 – 39 m

Cabot Head Formation (Underlying Impermeable Bedrock)

The Cabot Head Formation, readily distinguished by its grey-green colour, is a noncalcareous (i.e., not containing calcium carbonate) shale with thin interbeds of sandstone and limestone. The formation ranges from 10 to 39 m thick (Johnson et al. 1992). As the hydraulic conductivity of the shale is several orders of magnitude lower than the overlying dolostone formations, for the purposes of this study, the Cabot Head Formation is assumed to form the lower boundary of the active groundwater flow system in the Study Area and it acts as a regional aquitard. As a highly stratified shale unit, the Cabot Head Formation is assumed to have a high horizontal to vertical anisotropic ratio (100 times). The interpretation of this unit has not changed significantly since the Guelph-Puslinch Groundwater Protection Study was completed, although considerably more borehole data became available since then to define the uppermost surface of this formation in the Study Area.

Rochester/Irondequoit/Rockway/Merritton Formations

The following four bedrock units have an estimated total thickness of approximately 3 to 5 m in the Study Area. These units were been described as lower or undifferentiated dolostone and have not been previously defined in any detail with the exception of the Rochester Formation, which was identified in the Cambridge area but is not present in Guelph. As further described in Appendix A of the main body of the report, although geologic picks for these formations were made as part of the Tier Three Assessment, these formations were grouped with the Lower Gasport hydrostratigraphic unit in a similar manner to that of the Guelph-Puslinch Groundwater Protection Study. These formations have similar hydraulic properties to the lower portion of the Gasport Formation and do not represent a significant hydrostratigraphic unit to be included separately in the regional model for this study.

- ***Merritton Formation (included with the Lower Gasport Hydrostratigraphic Unit)*** – The Merritton Formation consists of a pinkish-brown, finely crystalline dolostone unit with dark shaley partings (Brunton 2009). This unit, where present in the area, is generally less than 1 m thick.

- ***Rockway Formation (included with the Lower Gasport Hydrostratigraphic Unit)*** – The Rockway Formation is a greenish-grey fine crystalline argillaceous dolostone with shaley partings (Brunton 2009). The thickness of the formation is consistent and generally ranges from 1 to 2 m across the Study Area.

- ***Irondequoit Formation (included with the Lower Gasport Hydrostratigraphic Unit)*** – The Irondequoit Formation is a thickly to medium-bedded crinoidal grainstone (Brunton 2009). The unit has a fairly consistent thickness of approximately 3 m throughout the Study Area.

- ***Rochester Formation (included with the Lower Gasport Hydrostratigraphic Unit)*** – The Rochester Formation is a calcareous shale (i.e., containing calcium carbonate) with carbonate interbeds and, where present in the Cambridge area, it is a thin unit (typically about 1 m thick) located above the Irondequoit Formation (Brunton 2009). This formation is not present in the Guelph area.

Gasport Formation

The Gasport Formation was commonly referred to as the Amabel Formation in previous hydrogeological studies in the Study Area. The formation is a cross-bedded crinoidal grainstone-packstone with sequences of reef mound and coquina (shell bed) lithofacies (Brunton 2009). In the Study Area, the formation varies from approximately 25 m to greater than 70 m in thickness. Zones of increased primary and secondary porosity in the upper sections of the reef mounds, the crinoidal grainstones, and the coquina shell beds make this formation highly transmissive, where such zones are present. This formation has been divided into upper, middle, and lower hydrostratigraphic units to allow for a generalized representation of the vertical variations in hydraulic properties and vertical distribution of the more transmissive reef mound and coquina shell bed lithofacies. The three hydrostratigraphic units are as follows:

- **Lower Gasport Hydrostratigraphic Unit** - Across the Study Area, the lower 10 to 20 m of the Gasport Formation exhibits a lower permeability than the middle and upper portions of the formation, and does not usually contain highly transmissive reef mounds or coquina bed zones. As mentioned above, as part of this assessment the underlying bedrock formations (Rochester, Irondequoit, Rockway and Merritton Formations) were grouped with this lower permeability Lower Gasport Hydrostratigraphic Unit. The conceptualization, characterization, and simulation of this unit in this Tier Three Assessment is generally consistent with the previous Lower Amabel layer conceptualized and simulated in the Guelph-Puslinch Groundwater Protection Study (Golder 2006a). Similar to the underlying Cabot Head, the Lower Gasport unit is assumed to have a high horizontal to vertical anisotropic ratio with a horizontal hydraulic conductivity 100 times greater than the vertical.

- **Middle Gasport Hydrostratigraphic Unit**- A highly transmissive layer within the Gasport Formation was identified and represented in the Guelph-Puslinch Groundwater Protection Study (Golder 2006a) as the Production Amabel layer (or Amabel Production zone). The Production Amabel layer in the Guelph-Puslinch Study was assigned a constant thickness of 12 m in the groundwater flow model based on the average thickness of a zone of cavities, vugs, and fracturing observed in geophysical logs and video surveys undertaken at 28 wells within the City of Guelph. The top and bottom surfaces of this layer were assumed to be planar in the Guelph-Puslinch Groundwater Protection Study with a constant dip to the southwest. These surfaces were used in the current Tier Three Assessment to delineate the top of the Middle Gasport and top of the Lower Gasport hydrostratigraphic units.

- Although high-quality data regarding vertical variations in transmissivity within the Gasport Formation (flow profiling, packer testing, Flute profiling, etc.) were available for some boreholes in the Study Area, the lack of high-quality data across the City of Guelph and beyond was not available. As such, a three-layer conceptual hydrostratigraphic representation of the Gasport Formation with a middle unit of constant slope and thickness was used in the Tier Three Assessment. The use of a constant thickness Middle Gasport unit was consistent with the Guelph-Puslinch model and was advantageous for numerical model calibration as insights gained in the previously model calibration could be directly applied to the Tier Three Assessment model calibration. In general the Middle Gasport is conceptualized to have close to isotropic hydraulic conductivity.

- **Upper Gasport Hydrostratigraphic Unit-** The base of the Upper Gasport Hydrostratigraphic Unit is consistent with the base of the Upper Amabel layer in the previous conceptual model. However, the top of the Upper Gasport Hydrostratigraphic unit differs from the previous top of the Upper Amabel. The Upper Amabel layer simulated in the Guelph-Puslinch Groundwater Study included the Goat Island Formation which was simulated in the Tier Three model as a separate unit (see below). The

Upper Gasport Hydrostratigraphic unit ranges from about 3 to 40 m thick and is typically of lower transmissivity relative to the underlying Middle Gasport Hydrostratigraphic unit with an anisotropic hydraulic conductivity ratio equal to 10.

Goat Island Formation

The Goat Island Formation consists of two members: the upper Ancaster Member and lower Niagara Falls Member (Brunton 2009). The Ancaster Member is a chert-rich, finely crystalline dolostone that is medium to ash-grey in colour. This member generally overlies the Niagara Falls Member, although in some cases in the Cambridge and Guelph areas these units are interbedded. The Niagara Falls Member is a finely crystalline and cross-laminated crinoidal grainstone with small reef mounds (Brunton 2009). The finely crystalline nature of these members typically results in a lower conductivity and transmissivity of this formation compared to the underlying Gasport Formation. In some areas the Ancaster Member contains low permeability shaley beds similar to the Vinemount Formation and acts as an aquitard. Conceptually, the two members of the Goat Island were grouped together and treated as a single hydrostratigraphic unit for the Tier Three Assessment. The Goat Island Formation was not distinguished in the previous conceptual model and was included as part of the Upper Amabel layer (Golder 2006a).

The Goat Island Formation is generally thin (< 5 m) or absent in areas of thick Gasport reef mounds. Thick sequences of Goat Island (up to 40 m) are found further west in Cambridge where the Gasport Formation is thinner.

Eramosa Formation – Vinemount Member

The Vinemount Member is described as a thinly bedded, fine crystalline dolostone with shaley beds that give off a distinctive petroliferous odour when broken (Brunton 2009). This dark grey to black dolostone unit was commonly identified in water well records as “black shale” and mapped in previous studies in the Study Area as the Eramosa Member. This unit represents an aquitard where present within the Study Area. Discretely modelling the Vinemount Member of the Eramosa Formation, separate from the Reformatory Quarry Member, is a key revision to the conceptual model as these units have different hydraulic properties. The Vinemount Member is not observed to the west of the thick Gasport reef mounds observed in the Hespeler and Pinebush areas of Cambridge and is not observed in Breslau to the west of Guelph. The Vinemount, where present in the Study Area, is less than 10 m thick and has a strong influence on vertical hydraulic connections and vertical gradients within the bedrock aquifer with a vertical hydraulic conductivity 100 times less than the horizontal conductivity.

Eramosa Formation – Reformatory Quarry Member

The Reformatory Quarry Member is described by Brunton (2009) as light brown to cream coloured, pseudonodular, thickly bedded and coarsely crystalline dolostone. This proposed member of the Eramosa Formation is generally represented as a poor aquifer or poor aquitard. This unit is susceptible to karstification due to uniform fine dolomite crystallinity (Brunton 2009). This unit also often contains mud-rich and microbial mat-bearing lithofacies that may act as aquitard materials reducing the vertical permeability across this unit. This unit was previously conceptualized as part of the Guelph Formation or the Eramosa Member of the Amabel Formation in previous investigations in the Study Area. More recently, the OGS defined a third member of the Eramosa Formation, named the Stone Road Member (Brunton 2009). The Stone Road Member has similar hydraulic properties to the Guelph Formation and as such, was not discretely represented as a separate conceptual model layer in this study. The thickness of the Reformatory Quarry Member is quite variable across the Study Area. In areas of thicker Gasport the Reformatory Quarry unit is thin or often absent. Thick sequences of Reformatory Quarry (up to 50 m) are observed in western Cambridge, Breslau and to the north of Guelph. These are assigned a vertical hydraulic conductivity that is 50 to 100 times lower than the horizontal conductivity.

Guelph Formation

The Guelph Formation consists of medium to thickly bedded crinoidal grainstones and wackestones and reefal complexes (Brunton 2009). The Guelph Formation is a cream coloured fossiliferous dolostone that represents an important aquifer in the Cambridge and Guelph area where it is most often the uppermost bedrock unit. As part of the Tier Three Assessment, large portions of the Guelph Formation were re-interpreted in borehole logs as the Reformatory Quarry Member of the Eramosa Formation. The thickness of the Guelph Formation in the Study Area is quite variable and in many boreholes the Guelph Formation is not present. Thick sequences of Guelph Formation of 25 to 40 m are observed in northwest Guelph and some areas of Cambridge. This unit conceptualized to be mildly anisotropic with a horizontal to vertical ratio of 10.

Bedrock Contact Zone

To account for the weathered and fractured uppermost portion of the bedrock (regardless of formation), a bedrock contact zone was included as a conceptual hydrostratigraphic unit. In some areas, the weathered uppermost bedrock is hydraulically connected to, and difficult to distinguish from, overlying coarse granular deposits. The upper weathered/fractured bedrock and overlying coarse-grained materials typically form a thin (assumed thickness of 4 m) aquifer that is able to support domestic water wells. This unit includes the coarse-grained overburden sediments that overlie bedrock in the Study Area. Horizontal hydraulic conductivity is assumed to be 10 times greater than vertical hydraulic conductivity.

Lower Overburden (Overburden B)

A Lower Overburden unit, consisting primarily of glacial till, was conceptualized to exist across the Study Area overlying the bedrock contact zone. This understanding is consistent with the Guelph-Puslinch Groundwater Protection Study model (Golder 2006a).

The Lower Overburden unit consists of a combination of glacial tills, including (from oldest to youngest) the Catfish Creek Till, Port Stanley Till, and Wentworth Till. The Catfish Creek Till is an overconsolidated glacial till that is frequently reported in drillers logs as “hardpan.” Overlying the Catfish Creek Till across much of the Study Area is the Port Stanley Till, a sandy-silt till that is considered a lower permeability aquitard, or a poor aquifer when interbedded with higher permeability sands and gravels. South and east of the Eramosa River, the Lower Overburden unit includes Wentworth Till and the Paris and Galt Moraines. In this area, the Wentworth Till is a sandy to sandy-silt till frequently interbedded with discontinuous lenses of coarse-grained sand and gravel - the cumulative thickness of which extends up to 15 m in some areas. Delineating individual till or sand and gravel units within the Paris or Galt Moraines in the Study Area is not possible given the low quality borehole data. This Lower Overburden unit is conceptualized to have a greater hydraulic conductivity within and surrounding the moraines where the coarser-grained Wentworth Till and interbedded coarse-grained sediments are prevalent.

The horizontal to vertical anisotropic ratio in hydraulic conductivity ranges from 1 up to 200 for the highly stratified moraine tills. As in the Guelph-Puslinch study, this unit was constrained to a minimum thickness of 2 m and assumed to cover the entire Study Area (Golder 2006a).

Upper Sand and Gravel (Overburden A)

An Upper Sand and Gravel (Overburden A) unit was inferred to be present as the uppermost surficial unit in portions of the model area where sand and gravel deposits are mapped at surface based on the Ontario Geological Survey's surficial geology map of Ontario (2003). The base of this Upper Sand and Gravel was delineated in detail in the Mill Creek area as part of the Guelph-Puslinch Groundwater Protection Study (Golder 2006a) through the generation and interpretation of cross-sections and well logs. Outside of the Mill Creek watershed, the thickness of the Upper Sand and Gravel was assumed to be 5 m or less where surficial sands and gravels were mapped at surface and zero thickness where tills or bedrock were mapped at surface. As mentioned previously, the base of the Upper Sand and Gravel was refined in the Southwest Quadrant area of Guelph where, in conjunction with the Southwest Quadrant Class EA, a local scale review and refinement of the Guelph-Puslinch model overburden stratigraphy was completed (Golder 2010). The horizontal to vertical anisotropic ratio in hydraulic conductivity ranges from 1 for the sands and gravels up to 200 for the highly stratified tills forming the cores of the moraines.

2.2.3 Groundwater Flow

The regional hydrogeology of the Study Area was described in the Guelph-Puslinch Groundwater Protection Study (Golder 2006a). Figure 2-9 illustrates the deep aquifer potentiometric surface as interpreted from the City of Guelph's monitoring wells in the Gasport Formation. The vertical head difference between the shallow (typically the Guelph Formation) and deep (Gasport Formation) bedrock groundwater flow systems within the City of Guelph area are shown in Figure 2-10. These maps were assembled using data specific to each of the bedrock units compiled as part of this project. Appendix A of the main body of the report (Golder 2011) provides additional details regarding the preparation of these maps and the following discussion relating to groundwater flow in the Gasport Formation.

Regionally, groundwater flow in the deeper Gasport Formation is south-southwest from highs in hydraulic head of about 430 m asl to the northeast of the City of Guelph to lows of about 270 m asl on the south-western boundary of the Study Area. Locally, flow directions are strongly modified by pumping at municipal wells in Guelph and Cambridge along with quarry dewatering immediately west of Guelph. Groundwater flow in the Gasport Formation converges on the main pumping centres in Guelph along an elongate zone extending south-southwest through the city as is shown on Figure 2-9. This narrow elongate zone is indicative of a higher transmissivity feature that is bounded laterally by lesser transmissive rock within the Gasport Formation. This higher transmissive zone supports pumping from many of the large-capacity municipal water wells that provide most of the City of Guelph's drinking water supplies. Dewatering at the Guelph Lime Quarry also draws groundwater from this more transmissive zone of the Gasport Formation. The effects of municipal pumping at the Arkell Springs Grounds to the southeast of Guelph are also evident from the localized area of flow convergence as shown on Figure 2-9.

Over much of the area influenced by pumping, groundwater levels in the Gasport Formation have been lowered below the elevation of the Speed River. As such, groundwater in the Gasport Formation does not discharge to the Speed River in this area.

South of the City of Guelph, the few monitoring locations available indicate an extensive area of low horizontal hydraulic gradients suggesting that the effects of pumping in the southwest section of Guelph extend into the Township of Puslinch. This area of low horizontal gradients may also indicate an extension of the highly transmissive zone in the Gasport Formation south into Puslinch and towards Cambridge. Further downgradient, groundwater flow in the Gasport Formation is more south-westerly in response to municipal pumping on the east side of the City of Cambridge.

Groundwater flow directions in the overlying Guelph Formation are controlled by local topography with flow converging on the main rivers: the Eramosa and Speed Rivers and Blue Springs Creek. The effects of municipal groundwater pumping and quarry dewatering are not evident. Groundwater flow directions in the Guelph Formation are described in the Guelph-Puslinch Report (Golder, 2006a).

Groundwater pumping from the Gasport Formation has strongly influenced flow directions and vertical hydraulic head differences in the vicinity of the pumping centres (Figure 2-10). Where controlled by pumping, groundwater levels in the Gasport are as much as 20 to 30 m below those in the overlying Guelph Formation with groundwater elevations below the base of the Speed River. Locally, in areas of higher elevation such as on the Paris Moraine, strongly downward vertical gradients are observed beyond the areas of municipal pumping with groundwater levels in the Guelph Formation as much as 10 m above those in the Gasport Formation. Elsewhere, observed vertical gradients are generally weakly downward or essentially non-existent.

2.3 Model Selection

The software code FEFLOW (v5.4; Diersch, 2006) was selected to develop the numerical groundwater flow model for the Tier Three Water Budget and Local Area Risk Assessment. FEFLOW has been, or is currently being, used in a number of groundwater modelling studies within or adjacent to the Study Area including:

- The Guelph-Puslinch Groundwater Protection Study (Golder, 2006a);
- The Regional Municipality of Waterloo Water Budget Model (Waterloo Hydrogeologic, 2008);
- The Regional Municipality of Waterloo Tier Three Water Budget and Local Area Risk Assessment (AquaResource, in progress);
- The Tier Two Water Budget and Subwatershed Stress Assessment for the Grand River Watershed (AquaResource, 2009a); and
- The Tier Two Water Budget and Subwatershed Stress Assessment for the Credit River Watershed (AquaResource, 2009b).

FEFLOW is a commercially available, three-dimensional, variably saturated, finite element groundwater modelling code. It has the capability for simulating groundwater flow, and thermal energy and solute transport. FEFLOW was selected as the preferred modelling code because of its capabilities that include:

- An ability to discretize the mesh around specific areas of interest such as pumping wells or rivers to more precisely simulate observed physical features and follow naturally complex boundary conditions such as the steep slope of the Niagara Escarpment;
- An efficiency of localized mesh discretization that require far fewer calculation points to achieve the

same level of precision as with finite difference grids (e.g., MODFLOW) which are forced to carry refinements to the model boundaries;

- The ability of the elements to conform to the pronounced vertical variation of aquifer / aquitard layers;
- Advanced boundary conditions to avoid potential impacts of non-physical boundary conditions on the simulation results; and
- Stable water table simulations that facilitates more accurate modelling of the shallow subsurface and allows the modeller to focus on conceptual rather than numerical issues.

Given these considerations, FEFLOW was selected to develop the City of Guelph Tier Three Groundwater Flow Model.

2.4 Numerical Model construction

2.4.1 Model Domain

The Study Area numerical model domain is illustrated on Figure 1-1 and was designed to encompass the entire hydrogeological system that influences the City of Guelph's municipal water supply wells. The model domain encompasses the City of Guelph and the Townships of Puslinch and Guelph-Eramosa, as well as portions of Wellington County, Dufferin County, the Regional Municipality of Waterloo, the Regional Municipality of Halton, and the City of Hamilton. The model domain has a maximum width of approximately 45 km (west-east) and maximum length of 55 km (north-south) and an area of 1,925 km^2.

From a hydrologic perspective, the model domain encompasses the entire Speed River and Eramosa River watersheds (Figure 2-1). The model domain is bounded to the west by the Grand River, a natural groundwater flow boundary condition, and to the east by the Niagara Escarpment. The carbonate aquifers that supply a significant portion of the City of Guelph's water supply system pinch out at the Escarpment (Figure 2-2) and, as such, represent a natural boundary condition. No natural or physical flow boundaries exist south of the model area so a boundary condition was applied that followed constant groundwater elevations based on interpreted groundwater elevation contours.

The boundaries of the model are located at a sufficient distance from the City of Guelph municipal water supply wells that the boundaries do not influence the simulated groundwater flow conditions associated with the City of Guelph's existing and planned drinking water wells.

2.4.2 Finite Element Mesh

FEFLOW is a finite element groundwater flow modelling software package that simulates groundwater flow by solving mathematical equations governing groundwater flow at discrete points or locations within the model domain. The first step in solving a groundwater flow problem using the finite element method is to discretize the study domain into discrete elements. The domain is replaced by a collection of nodes and elements collectively referred to as the finite element mesh. Elements consist of three or more nodes joined together by line segments. Elements can be of any size, and the size and shape of each element can be different. Typically, the spacing between finite element nodes, and therefore the size of the elements, is smallest within areas of the model where groundwater levels are expected to change significantly or where a high resolution of model output is desired (e.g., near pumping wells). Numerical properties used to represent hydrostratigraphic units (e.g., hydraulic conductivity) are assigned to each element. Boundary conditions representing known conditions are assigned to finite element nodes (e.g., wells, lakes, streams, groundwater recharge, etc.).

The finite element mesh developed for the model domain contains 355,582 triangular prismatic elements in each of the 14 model layers, equating to a total of 4.98 million elements (Figure 2-11). "Slices" define the top and bottom of each model layer and each slice in the model has 179,318 nodes for a total of 2.69 million nodes within the model.

The mesh was refined in areas where it was important to have an enhanced definition of groundwater flow and the potentiometric surface (Figure 2-11 inset detail). The mesh was refined in portions of the City of Guelph, along rivers and streams within the model domain, and around municipal and non-municipal pumping wells that extract large volumes of groundwater. The mesh in the central portion of the model domain was refined to a nodal spacing of approximately 200 m. A nodal spacing of 25 to 50 m was applied along rivers and streams as well as municipal pumping wells. Outside of the central portion of the model domain, the nodal spacing was approximately 400 m.

The resultant finite element mesh was designed to meet the requirements of the Tier Three Assessment in consideration of the City of Guelph's existing and planned municipal wells, other water users, and groundwater/surface water interaction. The model mesh may be refined in the future to examine new points of interest within the model domain. This type of refinement can easily be completed without negatively impacting the integrity of the model and the predictions presented in this study.

2.4.3 Vertical Discretization - Hydrostratigraphic Layer Structure

In addition to the mesh discretization horizontally, the model domain is also discretized vertically into layers to represent the changing hydrogeologic conditions with depth. A detailed discussion of the development of the hydrostratigraphic layer structure across the model domain was previously summarized in Section 2.2 of this appendix and provided in Appendix A of the main body of the report.

As discussed above, 11 hydrostratigraphic units were characterized over the model domain. These 11 units were represented in the numerical model using 14 discrete model layers (Table 2-3). The shallow subsurface, or Overburden A, was subdivided into two layers to provide more detailed calculations at the groundwater/surface water interface. Similarly, the primary regional bedrock aquitard, the Vinemount Member of the Eramosa Formation, was subdivided into three layers to account for steep vertical changes in flow directions between the Vinemount Member and the adjacent aquifers. This is important when using a groundwater flow model for particle-tracking to ensure the direction of the groundwater velocities calculated in the aquifer and aquitard are properly reflected.

Table 2-3 Model Representation of Hydrostratigraphic Units

Model Layer	Hydrostratigraphic Unit Description
1-2	Overburden A. Coarse-grained outwash gravel and sand deposits, Wentworth Till, Port Stanley Till, Fine grained sediments, and Bedrock outcrops
3	Overburden B. Wentworth Till, Port Stanley Till, Catfish Creek Till, Bedrock outcrops
4	Contact Zone. Fractured bedrock and overlying basal unconsolidated deposits
5	Guelph Formation (*Aquifer*)
6	Eramosa Formation - Reformatory Quarry Member (*Poor Aquifer/Poor Aquitard*)
7-9	Eramosa Formation - Vinemount Member (*Aquitard*)

Model Layer	Hydrostratigraphic Unit Description
10	Goat Island Formation (*Poor Aquifer*)
11	Upper Gasport Formation (*Aquifer*)
12	Middle Gasport Formation (*High Permeability Aquifer*)
13	Lower Gasport Formation (*Aquifer*)
14	Cabot Head Formation (*Aquitard*)

As described in detail in Appendix A of the main report, a number of the hydrostratigraphic units do not exist across the entire model domain. Figure 2-12 and Figure 2-13 are regional cross-sections through the groundwater flow model that illustrate the hydrostratigraphic units and model layers listed above. These cross-sections are the FEFLOW model representations of the conceptual model cross-sections shown in Figure 2-7 and Figure 2-8 that are reproduced from Appendix A of the main report.

It is important to note that, given the nature of finite element models, numerical model layers must be continuous across a model domain. As shown in Figure 2-14, a detail of cross-section A-A' through the northwest portion of the City of Guelph, the Reformatory Quarry, Vinemount, and Goat Island layers do not exist is some areas and they 'pinch out' (Model Layers 6 to 10), as does the Lower Gasport (Model Layer 13). To accommodate this situation, the thicknesses of these Model Layers are set to a minimum thickness of 0.5 m, and the hydraulic properties of the underlying unit are applied. In the cases where multiple layers are 'pinched out', the hydraulic properties of the closest underlying unit that exists are applied to the overlying minimum thickness layers so the numerical model closely resembles the conceptual model.

As previously discussed, the Contact Zone was conceptualized as a four metre thick unit that consists of weathered (fractured) bedrock and overlying unconsolidated coarse-grained sediments. To represent this in the model, the top and bottom of the Contact Zone were specified at two metres above and two metres below the top of bedrock surface. This conceptualization and numerical representation is consistent with the model developed for the Guelph-Puslinch Groundwater Protection Study (Golder 2006a). On the cross-sections, the Contact Zone is coloured the same as the underlying bedrock unit that exists, but the hydraulic properties of the Contact Zone are treated separately from the corresponding bedrock unit.

The base of the model was specified 100 m below the top of the Cabot Head Formation throughout the model to allow for the simulation of potential groundwater flow into and out of the deeply incised bedrock channels. Due to the extremely low hydraulic conductivity of the Cabot Head Formation, no vertical leakage was simulated into or out of the base of the model.

2.4.4 Hydrogeologic Properties

Hydrogeologic properties assigned within the finite element model included hydraulic conductivity, storage parameters (specific storage and specific yield), and porosity. These properties are assigned to zones that encompass multiple elements in each layer throughout the model domain.

2.4.4.1 *Hydraulic Conductivity*

Hydraulic conductivity represents the ability for a hydrostratigraphic unit to transmit water. A geologic material that is highly permeable to water (e.g., gravel) has a high hydraulic conductivity value, while geologic materials that are not very permeable to water (e.g., clay) have low hydraulic conductivity values. Hydraulic conductivities tend to be anisotropic, meaning groundwater travels more easily in one direction than another. Quite often the hydraulic conductivity in the vertical direction is lower than the horizontal direction as a result horizontal bedding or layering.

Prior to model calibration, reasonable estimates of hydraulic conductivity values, and their likely ranges, were assigned to the various hydrostratigraphic units based on the results of the field program, professional judgement and previous modelling undertaken in the Study Area (see Table 5.0 in Appendix A: Characterization Report [Golder 2011]). Additionally, local knowledge and conceptualization, information from previous modelling efforts, field-based studies, and literature values (Freeze and Cherry 1979; Anderson and Woosner 2002) were consulted to ensure the calibrated hydraulic conductivity values were reasonable. Hydraulic conductivity values for each geologic unit were adjusted through the calibration process before arriving at a set of values for all units that produced the best overall simulation of groundwater levels as compared to the observed field data.

Layers 1 to 3 - Overburden Model Layers

Hydraulic conductivity zones for the three overburden layers were assigned following a method used in the development of the Guelph-Puslinch Groundwater Model (Golder 2006a). The conductivity zones of the two upper overburden layers (Overburden A; Figure 2-15), were derived from the surficial geology mapping of the area, and correspond to various surficial tills, fine-grained clays/silts, and coarse-grained outwash sands and gravels.

The major hydraulic conductivity zones associated with the upper overburden Model Layers 1 and 2 (Overburden A) are described as follows:

- The orange and yellow areas (Zones c, h, and j) correspond primarily to outwash sands and gravels (high hydraulic conductivity).
- The green zones to the south and east (Zones r, u and v) correspond to the moderate hydraulic conductivities of the Wentworth Till.
- The green zones to the north and northwest (Zones f and g) correspond to the low hydraulic conductivities of the Port Stanley Till.
- The pink areas (Zone a) corresponds to bedrock exposed at ground surface and hydraulic properties match those of the contact zone.

Figure 2-16 illustrates the hydraulic conductivity zones for the Lower Overburden (Model Layer 3; Overburden B). The hydraulic conductivity zones associated with this layer represent broad geologic features:

- The green zones to the north and northwest (Zones f and g) correspond to low hydraulic conductivities of the Port Stanley Till.
- The green zones to the south and east (Zones r, s and t) correspond to moderate hydraulic

conductivities of the Wentworth Till.

- The yellow and brown zones within the City of Guelph (Zones i and k) correspond to sand and gravel areas delineated as part of local calibration efforts in the Hanlon Creek area.

- The pink areas (Zone a) correspond to bedrock outcrop locations, and these were delineated along the Eramosa River where the river valley is incised into bedrock, and along the eastern boundary where bedrock outcrops at surface and is conceptualized to have hydraulic properties comparable to those of the Contact Zone.

Layer 4 – Contact Zone Model Layer

Figure 2-17 illustrates hydraulic conductivity zones applied to Layer 4 (Contact Zone) which are delineated as follows:

- The pink zone (Zone 1) corresponds to a regionally extensive hydraulic conductivity for the Contact Zone.

- The purple area on the west side of the City of Guelph (Zone 2), represent a lower conductivity zone that was delineated as part of local calibration efforts in the Hanlon Creek area.

- The purple area on the east side of the City of Guelph (Zone 3) corresponds to high hydraulic conductivity zone supporting the shallow Carter and Burke wells.

- The areas in the southwest (Zones 5 to 8) represent higher conductivity zones surrounding several municipal water supply wells in the Cambridge area delineated in the calibrated groundwater flow model of the East Cambridge area as part of the Region of Waterloo Tier Three Study.

Layer 5 – Guelph Model Layer

Figure 2-18 illustrates hydraulic conductivity zones applied to Layer 5 (Guelph Formation) which are delineated as follows:

- The blue area in the western portion of the Study Area (Zone 9) corresponds to the Guelph Formation. This unit pinches out towards the center of the Study Area and is absent in areas east of the City of Guelph.

- The light blue areas (Zone 21) represent the area where the Reformatory Quarry Member of the Eramosa Formation is the uppermost bedrock unit (subcrop) in the subsurface.

- The green areas (Zone 37) represent the higher conductivity Upper Gasport Unit that subcrops east of the City of Guelph and in buried bedrock channels located north and east of the City of Guelph.

- The lighter purple area on the east side of the City of Guelph (Zone 4) corresponds to higher hydraulic conductivity zone supporting the shallow Carter and Burke wells. This zone is carried down into Layer 6 (as shown on Figure 2-19)

- The pink area (Zone 1) delineated along the Eramosa River is where the river valley is incised into the Upper Gasport Unit, and the hydraulic properties of the Contact Zone are applied from ground surface down through all layers until the Upper Gasport unit (Figure 2-18 to 2-21).

- The shales of the Cabot Head Formation underlying the Study Area are illustrated in orange (Zone 68; Figure 2-18) and subcrop along the eastern model boundary, and along a buried valley in the north-east portion of the Study Area.

- Zones 11 to 20 correspond to conductivity zones in the Guelph Formation that were delineated during calibration of the East Cambridge model as part of the Region of Waterloo Tier Three Study.

Layer 6 – Reformatory Quarry Model Layer

Figure 2-19 illustrates hydraulic conductivity zones applied to Layer 6 (Reformatory Quarry) which are delineated as follows:

- The extensive blue area in the west (Zone 21) represent the Reformatory Quarry Member of the Eramosa Formation which pinches out and is absent to the east of the Study Area.

- The green areas (Zone 37) represent the higher conductivity Upper Gasport Unit that subcrops east of the city and in the base of buried channels located north and east of the City of Guelph.

- The purple area on the east side of the City of Guelph (Zone 4) corresponds to higher hydraulic conductivity zone supporting the shallow Carter and Burke wells as described above.

- The pink area (Zone 1) delineated along the Eramosa River corresponds to the incised river valley described above.

- An example of an area which represents a small "window" in the Reformatory Quarry Member is seen in the northwest corner of the City of Guelph. This is illustrated by isolated zones (Zones 27, 31 and/or 37), surrounded by the (blue) Reformatory Quarry zone (Zone 21). Reformatory Quarry is absent in this location and the layer is given the properties of the underlying units (Vinemount, Goat Island, and Upper Gasport – Zones 27, 31, and 37). Similarly in the south-west corner of the Study Area, the East Cambridge study delineated Zone 23 which has the hydraulic properties of the underlying Vinemount Formation, and Zone 24 which represents the Upper Gasport.

- As above, the hydraulic conductivity representative of the Cabot Head Formation is illustrated in orange (Zone 68; Figure 2-19) and interpreted to exist along the eastern model boundary and along a buried valley located in the north-eastern reaches of the Study Area.

Layers 7, 8, 9 – Vinemount Model Layer

Figure 2-20 illustrates hydraulic conductivity zones applied to Layers 7, 8 and 9 for the Vinemount, which are delineated as follows:

- The blue areas (Zone 25, 26 and 27) in the central portion of the Study Area correspond to the Vinemount Member. The Vinemount Member is absent in the western and eastern portions of the

Study Area, and as such the properties of the underlying units are applied. The area where the Vinemount is present was divided into three zones: a central portion surrounding the City of Guelph where subsurface characterization is greater, and eastern and western portions where the characterization is more uncertain. The western and eastern zones were divided roughly along a line that grouped the deeply incised bedrock channels into the eastern zone.

- The light green area (Zone 31) in the western portion of the Study Area represents the Goat Island Formation.
- The green areas (Zone 37) represent the higher conductivity Upper Gasport Unit that subcrops east of the City of Guelph and in buried channels located north and east of the City of Guelph.
- The pink area (Zone 1) delineated along the Eramosa River corresponds to the incised river valley described above.
- A small "window" through the Vinemount Member is interpreted in the northwest corner of the City of Guelph. This window is represented by applying the hydraulic conductivity of the Goat Island and Upper Gasport zones (Zones 31 and 37) within the Vinemount model layer (blue; Zone 25 on Figure 2-20).
- The hydraulic conductivity value representative of the Cabot Head Formation (orange zone; Zone 68) was applied in the Vinemount model layer in places along the eastern boundary and along a buried valley in the north-east of the Study Area.
- The East Cambridge model provided Zones 28 to 30 in the southeast with Zone 28 representing the Goat Island Formation where the Vinemount Member is absent, Zone 29 representing the Vinemount Formation, and Zone 30 representing thinner margins of the Vinemount unit.

Layer 10 – Goat Island Model Layer

Figure 2-21 illustrates hydraulic conductivity zones applied to Layer 10 (Goat Island) which are delineated as follows:

- The light green area (Zone 31) in the central portion of the Study Area represents the Goat Island Formation.
- The dark green areas (Zone 37) east of the City of Guelph represent the Upper Gasport Formation.
- The green area on the western side of the Study Area (Zone 48) represents a higher conductivity zone in the Goat Island Formation, which has properties similar to the underlying Middle Gasport Formation (Zone 48 in Figure 2-22).
- The light green area in the south portion of the City of Guelph (Zone 32) represents a slightly lower conductivity zone in the Goat Island Formation that was delineated as part of local calibration efforts in the South West Quadrant and Hanlon Creek Area.
- The pink area (Zone 1) delineated along the Eramosa River corresponds to the incised river valley

described above.

- A small "window" exists in the Goat Island Formation in the northwest corner of the City of Guelph. This window is illustrated as a dark green zone of Upper Gasport Unit (Zone 37) within the green Goat Island zone (Zone 14).

- The Cabot Head Formation illustrated in orange (Zone 53) is applied to the Goat Island model layer in areas along the eastern boundary and along a buried valley located northeast of the Study Area.

- The East Cambridge Zones 33 to 36 have properties similar to Goat Island and the underlying Upper Gasport unit.

Layer 11 – Upper Gasport Model Layer

Figure 2-22 illustrates hydraulic conductivity zones applied to Layer 11 (Upper Gasport) which are delineated as follows:

- The large green area (Zone 37) covers the majority of the Study Area, and represents the regionally extensive Upper Gasport Formation.

- The light green area in the west of the Study Area (Zone 48) represents a higher conductivity zone with properties of the underlying Middle Gasport Formation. Additionally, small areas of this unit appear on the east side of the study area in this layer.

- The multiple zones in the south west of the Study Area (Zones 40 to 47) represent conductivity zones within the Upper Gasport Formation. The conductivity zones were obtained from a calibrated groundwater flow model of the East Cambridge area as part of a Region of Waterloo Integrated Urban Systems study.

- The dark green area in the south portion of the City of Guelph (Zone 39) represents a conductivity zone in the Upper Gasport Unit that was delineated as part of local calibration efforts in the South West Quadrant and Hanlon Creek Area.

- The Lower Gasport zone (Zone 66), and the Cabot Head Formation zone (Zone 68), both illustrated in orange, were carried through the Upper Gasport (Zone 37) in places along the eastern boundary and along a buried valley in the northeast of the Study Area.

Layer 12 – Middle Gasport Model Layer

Figure 2-23 illustrates hydraulic conductivity zones applied to Layer 12 (Middle Gasport) which are delineated as follows:

- The green area (Zone 48) that extends across the majority of the Study Area represents the regionally extensive Middle Gasport Unit.

- Multiple conductivity zones exist in the central portion of the City of Guelph (Zones 49 to 62) that were initially delineated based on the Guelph-Puslinch Groundwater Protection Study (Golder

2006a) and the Arkell Spring Grounds Groundwater Supply Investigation (Gartner Lee 2003). These zones were further refined and additional zones were added based on calibration efforts for this current study.

- As above, the variable hydraulic conductivity zones in the southwest portion of the Study Area (Zones 63 to 65) represent the conductivity zones that were obtained from the calibrated groundwater flow model of the East Cambridge area as part of the Region of Waterloo Tier Three Study.

- The Lower Gasport Formation (Zone 66) and the Cabot Head Formation (Zone 68), both illustrated in orange, were applied in areas where the Middle Gasport Formation is absent. These areas include portions of the eastern boundary and areas along a buried valley in the northeast portion of the Study Area.

Layer 13 – Lower Gasport Model Layer

Figure 2-24 illustrates hydraulic conductivity zones applied to Layer 13 (Lower Gasport) which are delineated as follows:

- The orange area (Zone 66) covering a majority of the Study Area represents the regionally extensive Lower Gasport Formation.

- As above, the Cabot Head Formation illustrated in orange (Zone 68) is where the Lower Gasport Formation is absent along the eastern boundary and along a buried valley northeast of the Study Area.

Layer 14 – Cabot Head Formation

The Cabot Head Formation is a regionally extensive unit that completely underlies the Study Area. Insufficient hydraulic or hydrogeologic data exists to refine the understanding of the spatial variability within the unit so a uniform hydraulic conductivity was applied across all elements within Layer 14.

2.4.4.2 *Storage Parameters*

Groundwater storage is defined as the quantity of water released from an aquifer system due to a unit change in hydraulic head. The magnitude of the FEFLOW storage coefficient is dependent on whether the aquifer is unconfined or confined. If an aquifer is confined, the storage coefficient is referred to as Specific Storage (S_s). In a confined aquifer, when there is a reduction of hydraulic head or pressure, water is derived from storage through the expansion of water and the compression of the rock or sediment. In a confined aquifer setting, the load on top of an aquifer is supported by the solid rock skeleton, and the hydraulic pressure exerted by water (the hydraulic pressure acts as a support mechanism). Specific Storage for consolidated bedrock aquifer materials ranges from $1x10^{-8}$ to $1x10^{-6}$/m.

In an unconfined aquifer, the storage is referred to as Specific Yield (S_y) and the predominant source of water is from gravity drainage from the pores. Water released from storage from the compaction of rock (or sediment) is negligible. Specific Yield values are comparable to estimates of porosity and range from 0.1 to 0.3 for overburden aquifers.

In FEFLOW, estimates of storage and porosity are applied in zones similar to hydraulic conductivity values. Storage parameters are not used in steady-state flow solutions, but become important parameters in calibrating transient groundwater flow models (see Section 3 of this Appendix).

2.4.4.3 *Effective Porosity*

Groundwater flow models provide estimates of the Darcy flux, or flow rate, of groundwater per unit cross-sectional area through porous media (i.e., overburden or rock). To estimate the linear groundwater velocity, representing the speed at which a particle of water might travel, this flux is divided by the effective porosity of the porous media. Effective porosity differs from the total porosity of a porous media and is typically smaller than the total porosity. While a porous media may have a high proportion of pore space, many of those pores may not be connected, particularly in the case of fractured bedrock aquifers, and as a result, those unconnected pores do not act as pathways for groundwater to travel. The effective porosity is meant to represent the fraction of pore space that is connected providing a path for groundwater to travel from one point to another.

In the saturated zone, effective porosity does not affect the simulated groundwater heads or the flux of water computed to move through an aquifer or discharging to a boundary condition. Linear groundwater velocities are required for particle tracking or contaminant migration modelling. The Tier Three Water Budget and Local Area Risk Assessment does not require the computation of time-dependent pathlines; however, it is recognized that the model will be used for future studies and the following discussion is provided for reference purposes.

Within the groundwater flow model, hydraulic conductivity is assigned to hydrostratigraphic units independent of effective porosity. The estimated effective bedrock porosity has a significant impact on the size of delineated time-of-travel capture zones (e.g., the 2-year, 5-year, and 25-year time-of-travel) because the calculated linear velocity is inversely proportional to the specified “effective” porosity value. Effective porosity cannot be measured directly in the field and can only be estimated indirectly based on observations of the movement of dissolved chemicals in similar hydrogeological environments. Estimates of effective porosity for the Guelph area are derived from field observations in Cambridge, Ontario in addition to estimates made by other professionals practicing in the Guelph area.

Flow and porosity data were collected as part of a bedrock hydrogeological study in the limestone aquifer in Cambridge, Ontario. These studies included the use of televiewer logs, flow profiles, tracer tests and packer tests to identify flow horizons and estimate porosity in the Guelph and Gasport Formations. The studies concluded that fractures are the most important features contributing to the overall transmissivity of the bedrock aquifer, but areas with higher concentrations of vuggy or secondary porosity also provide localized higher transmissivity zones. Four tracer tests were conducted in Cambridge, Ontario (Beak Consultants 1995; Lotowater 1997), and analysis of the tracer test results estimated the effective porosity range for use in a groundwater flow was 0.07% to 11% (Duke 1998). From these results, however, the most realistic estimate of porosity for capture zone delineation is 3.9%, based on a tracer test that is completed over a relatively long distance (i.e., 250 m). Other tests were completed over shorter distances (i.e., 10 m) where volumes of fractured bedrock are not large enough to constitute a reasonably sized sample of the aquifer. Duke Engineering and Services Inc. (1998) also conducted numerical and analytical modelling using a dual porosity code (SWIFT-II) to show that effective porosity of 3% provides a reasonable approximation of dual porosity at the spatial and temporal scale of typical capture zones.

Various other estimates of effective porosity have been used for capture zone delineation in the Guelph Area. The Guelph-Puslinch Study (Golder 2006a) used an estimate of 5% effective porosity for the contact zone and production zone and 1% effective porosity in other bedrock units. The Arkell Spring Grounds Groundwater Supply Investigation (Gartner Lee 2003b) used the same estimates. Finally, the Wellington County Groundwater Study (Golder Associates 2006b) assumed porosity for all bedrock units to be 5%.

Table 2-4 summarizes the porosity values applied in this model. These values were selected in consultation with the City of Guelph staff and are considered to be low estimates which will result in capture zones that are conservatively larger.

Table 2-4 Specified Porosities Applied in the Groundwater Model

Geologic Unit	Effective Porosity
Bedrock (Except Middle Gasport)	1%
Middle Gasport Unit	3%
Overburden/Bedrock Contact Zone	3%
Overburden	20%

2.4.4.4 *Unsaturated Zone Representation*

With the current model, FEFLOW is run in a variably-saturated mode and is used to simulate both the saturated and unsaturated zones simultaneously. It is noted, however, that although the FEFLOW model is simulated in variably saturated mode, only the numerical results pertaining to the saturated zone are evaluated. The solution for both saturated and unsaturated flow is prescribed solely for the purpose of model stability, and the numerical solution relating to the unsaturated zone is not relevant to this study.

Flow through the unsaturated zone is modelled using the Richard's equation and Van Genuchten relationships that describe the pore water pressure-saturation and relative hydraulic conductivity-saturation relationships. These constitutive relationships define the ability of water to move through the unsaturated zone (conductivity) and the ability of that water to be released from storage due to a decline in the water table position (pressure-saturation). In order to increase numerical stability of the model and to reduce non-linearities within the unsaturated zone, the relationship between the relative hydraulic conductivity and saturation has been simplified from an exponential relationship to a linear function. The effects of hysteresis (i.e., saturation's dependence on the previous wetting/drying history of the material) have also been ignored. These simplifications are appropriate for this regional-scale variably-saturated model where detailed delineation of flow within the unsaturated zone is not required.

2.4.5 Model Boundary Conditions

Boundary conditions represent the interaction between the groundwater within the model domain and the surrounding areas outside the model domain. Boundary conditions included in the model are described below:

- *Specified Flux* boundary conditions are assigned to represent a known flux across a surface, into or out of the model domain. These types of boundaries are often used to simulate recharge entering the model through the uppermost layer of the model. Groundwater pumping wells are also a special type of specified flux boundary.

- *Specified Head* boundary conditions are assigned in a model where the head value at a particular location is known. Specified head boundary conditions are often used to simulate flow along the perimeter of a model, or in the simulation of lakes, rivers, or similar surface water features.

2.4.5.1 *Recharge*

Groundwater recharge refers to the amount of water that infiltrates through the unsaturated zone and ultimately reaches the underlying water table. The rate of groundwater recharge is dependent on a number of factors, including land use and vegetation, surficial soil type (geology), physiography, and ground surface topography. Recharge is enhanced in areas where the ground surface is hummocky as overland flow to nearby creeks and rivers is reduced.

Recharge rates are commonly derived using surface water modelling techniques that are often undertaken on a watershed or subwatershed basis. A surface water model that simulates the entire Study Area does not exist, and, as such, recharge for the Study Area was estimated based on a combination of the available data from various surface water models undertaken within the Study Area. The recharge rates applied in the FEFLOW model, as specified flux boundary conditions are illustrated on Figure 2-25 and discussed below. In general, the estimated recharge rates ranged from a low of 0 mm/yr, where groundwater discharges to some wetlands, to a high of 533 mm/yr on hummocky regions associated with the Paris and Galt Moraines that are underlain by sand and gravel.

Grand River Watershed

The Grand River Watershed GAWSER continuous streamflow-generation model was used to estimate groundwater recharge rates within the Grand River Watershed portion of the Study Area. The existing GAWSER continuous streamflow-generation model was revised as part of this study as discussed in Appendix B1 of this document. The GAWSER model reflects approximately 15 years of continuous improvement and advancement. Originally created for flood flow estimation, the investment in the model has been leveraged to provide flood forecasting capability as well as continuous water budget modelling. Details on the GAWSER model and how it was calibrated are presented in the Grand River Conservation Authority's Tier Two Integrated Water Budget Report (AquaResource 2009a).

The GAWSER continuous streamflow-generation model utilizes Quaternary geology, land cover, and topography to subdivide the model area into hydrologic response units that predict how that land unit will respond to a precipitation event. Precipitation, estimated using input from historic and current climate records, is partitioned into three major hydrologic components: evapotranspiration, runoff, and recharge. The model is calibrated by comparing the GAWSER model simulated hydrographs to observed streamflow at various gauge locations within the Study Area.

Within the Grand River Watershed, the highest groundwater recharge rates are simulated in the hummocky outwash areas that exist along the Paris and Galt Moraines east and northeast of the City of Guelph. High groundwater recharge rates are also simulated in the northern area of the Speed River and

Eramosa River watersheds where coarse-grained outwash sediments are mapped at surface. Relatively low groundwater recharge rates are simulated on the fine-grained till plains located north and northwest of the City of Guelph.

Credit River Watershed

Credit Valley Conservation (CVC) has published average annual groundwater recharge rates for the Credit River Watershed as part of its Integrated Water Budget Report (AquaResource 2009b). These recharge rates, derived using the CVC's HSP-F surface water flow model, were used in the Credit River Watershed portion of the Study Area. HSP-F is a comprehensive modelling package capable of simulating hydrologic processes as well as pollutant generation and transport processes within drainage catchments and along watercourse networks. The HSP-F software has been developed over a number of decades and is currently maintained and supported by the U.S. Environmental Protection Agency. Similar to the Grand River Watershed, the recharge rates for the Credit River Watershed were derived based on the results of the hydrologic response units that reflect soil type, land use, slope, and vegetation across the landscape.

Halton Region and Hamilton Region Conservation Authorities

The remaining portion of the Study Area that lies outside the Credit and Grand River Watersheds is part of the Halton and Hamilton Region Conservation Authorities. The USGS Precipitation-Runoff Modelling System (PRMS) code has been used in those areas to model surface water hydrology as part of the Source Water Protection – Wellhead Protection Area Study for Halton Region. The PRMS recharge predictions have been used in a number of studies, including a "Simulation of Groundwater Flow in the Vicinity of the Cedarvale Wellfield, Georgetown, Ontario" (EarthFx 2009). Similar to GAWSER and HSP-F, PRMS uses hydrologic response units to divide the domain into subunits for which water and energy balances are calculated daily.

2.4.5.2 *Surface Water Boundary Conditions*

The interaction between groundwater and surface water is simulated in the model using boundary conditions. Based on the model simulated groundwater level, and the water level in the surface water feature, groundwater may discharge into the surface water body, or water may discharge from the surface water feature into the underlying aquifer.

Several large lakes located within the Study Area were modelled using specified head (Type I) boundary conditions. The water level elevations of these lakes were assigned in consultation with the GRCA Reservoir elevation data (2007) where available or the 10 m Digital Elevation Model (DEM) of the ground surface. Table 2-5 outlines the lakes simulated in the model and the reference elevations applied.

Table 2-5 Model Simulated Lake Stage Elevations

Lake	Simulated Lake Stage Elevation (masl)
Belwood Lake	418.0
Guelph Lake	346.0
Puslinch Lake	302.5

Lake	Simulated Lake Stage Elevation (masl)
Guelph Lime Quarry Pond	290.0
Mountsberg Reservoir	299.0
Shade's Mills Reservoir	284.0

Due to computational limitations, it was impractical to assign boundary conditions for every water course in the Study Area. Figure 2-26 illustrates the rivers and creeks that were simulated as boundary conditions in the model. In general, creeks with a Strahler Order equal to 2 or more were simulated in the model, as well as some additional headwaters streams that were added to supplement the coverage in areas where surface water features were lacking. Headwater stream reaches with a length less than 1,000 m were not simulated in the model.

When developing the finite element mesh, the selected streams were 'simplified' in a Geographic Information System (GIS) so the streams had segments that were a minimum of 50 m along their reach. Finite element nodes were then assigned at the end of each segment along each surface water reach with a buffer row of elements assigned around each reach.

The surface water boundary condition was represented in the model by assigning a specified head (Type I) boundary to each node along each river reach. The specified head for each boundary was equal to the estimated surface water elevation at that location, and this was estimated using the 10 m Ground Surface DEM for the Study Area. In some cases, the elevation estimated using the DEM was inconsistent with the centreline of the modelled stream channel. To overcome this, the stream network was closely inspected in the GIS, and the river stage specified in the model was assigned to ensure the river stage decreased monotonically in the downstream direction.

2.4.5.3 *Perimeter Boundaries*

The model domain extends from the Grand River in the west to the Niagara Escarpment to the east. Aside from these natural boundaries, additional boundary conditions were applied to simulate the influx or out-flux of water at these outer boundaries (Figure 2-27).

Specified head boundary conditions were assigned along the Grand River in the overburden at an elevation corresponding to the elevation of the Grand River. Specified head boundary conditions were also assigned on the perimeter of all three Gasport layers to allow water to enter or leave the model across the Formation.

Along the eastern boundary (Niagara Escarpment), a specified head boundary condition was assigned along the bottom of the Lower Gasport Formation to allow water to flow out of the model at the Escarpment. The elevation of this boundary was based on mapping of static water elevations interpreted from local domestic water wells. At the regional scale, this boundary is physically reasonable, as groundwater seeps are common along the face of the Escarpment at many locations. While the boundary has uncertainty associated with the representation of local hydrogeologic processes at the Escarpment, this uncertainty is acceptable considering the distance of the Escarpment from the City of Guelph's municipal water supply wells investigated in this study.

2.4.5.4 *Pumping Wells*

Figure 2-28 illustrates municipal and non-municipal water takings that were considered for inclusion as pumping wells. Those included were simulated as specified flux boundary conditions within the groundwater flow model. Table 2-6 lists the municipal wells simulated in the model. In FEFLOW, wells are simulated using one-dimensional vertical line elements superimposed on the three-dimensional finite element mesh. The pumping rate is applied to the layer(s) where the well is screened, and if the well is extracting water from more than one layer, the pumping rate is partitioned automatically along the well screen (or open hole) according to the transmissivity of the model layers.

Table 2-6 Municipal Pumping Wells

Town/ Township	Well Name	Easting (NAD83)	Northing (NAD83)	Formation Screened	Permitted Rate (m^3/day)	Model Calibration Rate (m^3/day)
City of Guelph[1]	Arkell 1	567944	4822434	Contact Zone	3,273	730
	Arkell 14	568096	4823126	Upper to Middle Gasport	n/a	0
	Arkell 15	567440	4822878	Upper to Lower Gasport	n/a	0
	Arkell 6	567934	4823061	Upper to Middle Gasport	6,546	3,774
	Arkell 7	567993	4822436	Upper to Middle Gasport	6,547	3,689
	Arkell 8	568055	4822971	Upper to Middle Gasport	6,546	3,694
	Burke	565157	4818701	Guelph to Middle Gasport	6,546	5,385
	Calico	554602	4819900	Upper Gasport	5,237	748
	Carter Wells	564870	4820808	Guelph	7,655	2,004
	Clythe Creek	564031	4823927	Reformatory Quarry to Lower Gasport	5,237	0
	Dean Ave.	560997	4819805	Upper to Middle Gasport	2,300	1,215
	Downey Rd.	561798	4817015	Upper to Middle Gasport	5,237	3,940
	Emma	559931	4823351	Upper to Middle Gasport	3,100	2,273
	Helmar	560357	4825777	Upper to Middle Gasport	3,273	500
	Membro	560293	4819861	Upper to Middle Gasport	6,050	3,036
	Paisley	558126	4819636	Upper to Middle Gasport	3,200	762
	Park 1 and 2	560430	4823231	Upper to Middle Gasport	10,300	5,897
	Queensdale	558482	4818297	Guelph to Upper Gasport	5,237	702
	Sacco	556416	4821929	Guelph to Middle Gasport	n/a	0
	Smallfield	556748	4820866	Guelph to Lower Gasport	n/a	0
	University	561613	4819168	Upper Gasport	3,300	1,648
	Water Street	560773	4820356	Upper to Middle Gasport	3,400	1,184
Puslinch[2]	Irish Creek	559037	4807868	Guelph to Upper Gasport	327	20
Guelph/ Eramosa[2]	Rockwood 1 & 2	568785	4830026	Middle Gasport	1,964	751
	Blue Forest	557563	4825915	Upper to Middle Gasport	294	63
	Cross Creek	558038	4825840	Upper to Middle Gasport	812	94
	Huntington	558405	4826512	Upper to Middle Gasport	916	104
Erin[3]	Erin #7	573556	4847599	Gasport	2,160	1,031
	Erin #8	573466	4846759	Gasport	1,964	780
	Hillsburgh #2	568676	4849209	Gasport	982	780
	Hillsburgh #3	568233	4849607	Gasport	655	1,344
Region of Halton[3]	4th Line Well A	577038	4835290	Gasport	1,309	734
	Davidson #1	577011	4833241	Gasport	1,250	648

Town/ Township	Well Name	Easting (NAD83)	Northing (NAD83)	Formation Screened	Permitted Rate (m^3/day)	Model Calibration Rate (m^3/day)
	Davidson #2	577011	4833241	Gasport	1,250	216
	Prospect Park Wells	576804	4830877	Gasport	4,546	216
Region of Waterloo[4]	C2	540782	4821527	Overburden		4
	C5	540828	4821478	Overburden		111
	G16	558336	4804721	Guelph to Upper Gasport		1,636
	G17	556271	4804365	Contact Zone to Middle Gasport		1,364
	G39	557324	4802665	Contact Zone to Guelph		2,814
	MH1	549457	4820230	Guelph		18
	MH2	549454	4820234	Overburden		22
	P16	550338	4807753	Contact Zone		217
	P9	555792	4806582	Contact Zone to Upper Gasport		1,157
	H3	555314	4808183	Contact Zone to Upper Gasport		281
	P10	556951	4806839	Overburden to Guelph		2,085
	P11	557140	4806113	Contact Zone to Upper Gasport		1,106
	P17	557128	4806110	Contact Zone to Lower Gasport		832
	G7	558050	4802493	Overburden to Guelph		2,199
	G8	558339	4802613	Contact Zone	2,292	1,042
	G6	556355	4805062	Contact Zone to Upper Gasport		1,237
	G18	557327	4804287	Guelph to Upper Gasport		1,347
	P15	555754	4806616	Contact Zone to Upper Gasport	1,638	468
	G5	555084	4806561	Contact Zone to Guelph		1,225
	G9	557175	4800261	Guelph		2,475
	P6	554159	4804014	Guelph to Middle Gasport		1,386
	H4	556693	4808882	Contact Zone to Guelph		284
	H5	555327	4810826	Guelph		1

1 City of Guelph pumping rates are calculated average annual pumping rates from 2008
2 Township of Puslinch and Guelph/ Eramosa pumping rates were obtained from the Guelph-Puslinch Groundwater Protection Study (Golder 2006a) and the Wellington County Groundwater Protection Study (Golder 2006b)
3 Town of Erin and Region of Halton pumping rates were obtained from the Credit River Watershed Tier Two Integrated Water Budget Report (AquaResource 2009b)
4 Region of Waterloo pumping rates were obtained from ROW Calibration Report (Waterloo Hydrogeologic 2008)

In addition to municipal water demands, many non-municipal permitted water takers also rely on groundwater supplies within the Study Area (Figure 2-28). Appendix B2 describes the methodology followed to estimate consumptive water demands for the non-municipal permitted water takers within the Study Area. These consumptive demands could be considerably less than the permitted water use rates and thus are vital to estimate for inclusion in the model.

Figure 2-29 illustrates permitted groundwater takings in the vicinity of the City of Guelph, highlighting the category of water use and the permit number. This information is summarized in Table 2-7 below. The average annual consumptive demand for each user is estimated as described in Appendix B2. The aquifer source for each permit is inferred from the screened interval determined as described in Appendix B2.

Table 2-7 Non-Municipal Permitted Water Demand near City of Guelph

Permit No.	Easting (NAD83)	Northing (NAD83)	Category and Specific Purpose	Water Source	Permitted Rate (m^3/d)	Average Annual Consumptive Demand (m^3/d)	In Model as Flux Boundary (Well)
0147-6K9RKS	562971	4822422	Remediation - Other	Guelph	23	10	Y
0147-6K9RKS	562968	4822422	Remediation - Other	Contact Zone	13	0	N
0147-6K9RKS	562971	4822424	Remediation - Other	Guelph	13	7	Y
0147-6K9RKS	562963	4822429	Remediation - Other	Contact Zone	10	0	N
0147-6K9RKS	563000	4821986	Remediation - Other	Guelph	7	7	Y
0147-6K9RKS	563024	4821986	Remediation - Other	Guelph	7	7	Y
01-P-2004	557025	4823001	Remediation - Groundwater	Guelph	328	152	Y
01-P-2245	570784	4815980	Miscellaneous - Irrigation	Guelph	60	32	Y
01-P-2245	570901	4815964	Miscellaneous - Heat Pumps	Overburden	69	5	Y
03-P-2003	561056	4814413	Industrial - Aggregate Washing	Contact Zone	490	0	N
0882-6FTHMA	566388	4816161	Water Supply - Other	Guelph	656	10	Y
0882-6FTHMA	566425	4815893	Water Supply - Other	Guelph to Upper Gasport	65	0	Y
0882-6FTHMA	566318	4816054	Water Supply - Other	Guelph	130	9	Y
1204-62XKAF	562403	4822865	Industrial - Cooling Water	Guelph to Lower Gasport	110	53	Y
1216-6SCL4W	571022	4812087	Industrial - Food Processing	Guelph	110	16	Y
1528-6GTN6M	557917	4822988	Remediation - Other	Guelph	299	88	Y
1528-6GTN6M	557809	4823006	Remediation - Other	Guelph to Lower Gasport	15	0	N
1528-6GTN6M	557836	4822990	Remediation - Other	Guelph	15	0	N
1787-6C8RLU	562478	4820358	Agricultural - Other	Guelph	737	126	Y
1787-6C8RLU	562551	4820377	Agricultural - Other	Guelph	525	26	Y
1787-6C8RLU	561928	4819232	Agricultural - Other	Guelph	1,309	0	N
2540-6PLKFX	553898	4812349	Commercial - Golf Course Irrigation	Overburden	1,637	189	Y
2540-6PLKFX	553771	4812203	Commercial - Golf Course Irrigation	Overburden	655	1	Y
2768-6QXRCC	557427	4815114	Industrial - Manufacturing	Guelph	79	79	Y

Permit No.	Easting (NAD83)	Northing (NAD83)	Category and Specific Purpose	Water Source	Permitted Rate (m^3/d)	Average Annual Consumptive Demand (m^3/d)	In Model as Flux Boundary (Well)
3024-6CQJZ5	565174	4820242	Commercial - Golf Course Irrigation	Guelph	882	77	Y
3036-6QPKHE	560000	4823000	Institutional - Other - Institutional	Guelph to Lower Gasport	137	137	Y
3331-73RKYV	569534	4814390	Water Supply - Communal	Guelph	132	20	Y
3331-73RKYV	569537	4814528	Water Supply - Communal	Upper Gasport	185	33	Y
3331-73RKYV	569499	4814701	Water Supply - Communal	Guelph	323	74	Y
3331-73RKYV	569080	4814310	Water Supply - Communal	Guelph	333	2	Y
3830-6W6JHW	569250	4811950	Industrial - Aggregate Washing	Overburden	23,568	993	Y
4366-6BTRUX	563512	4821997	Miscellaneous - Heat Pumps	Contact Zone to Lower Gasport	816	816	Y
5081-6GEPMB	560760	4827800	Water Supply - Other	Contact Zone	130	2	Y
5081-6GEPMB	560520	4828020	Water Supply - Other	Guelph	130	2	Y
5170-6X9H33	568312	4816988	Commercial - Golf Course Irrigation	Guelph	657	186	Y
5201-6B7HDA	567598	4812203	Industrial - Other	Middle Gasport	115	2	Y
5201-6B7HDA	567476	4812030	Industrial - Other	Upper Gasport	516	12	Y
5201-6B7HDA	567608	4811999	Industrial - Other - Industrial	Upper Gasport	802	16	Y
5336-6C8R2N	563398	4821157	Agricultural - Field and Pasture Crops	Overburden to Middle Gasport	110	16	Y
5336-6C8R2N	563010	4820588	Agricultural - Field and Pasture Crops	Contact Zone to Middle Gasport	175	25	Y
5336-6C8R2N	563036	4821307	Agricultural - Field and Pasture Crops	Guelph to Middle Gasport	252	35	Y
6560-6DYPGH	570188	4811581	Industrial - Manufacturing	Guelph	250	250	Y
6560-6DYPGH	569847	4811446	Industrial - Manufacturing	Guelph	200	200	Y
6800-72CLQH	558858	4823140	Industrial - Other - Industrial	Guelph to Lower Gasport	1,635	105	Y
7043-74BL3K	568935	4812721	Commercial - Bottled Water	Contact Zone to Lower Gasport	3,600	2,396	Y
7240-65YKTN	559873	4819122	Dewatering - Pits and Quarries	Gasport	13,750	7,888	N*
72-P-0453	568922	4812609	Industrial - Aggregate Washing	Overburden	8183	396	Y
5626-7WLQ3W	569616	4813435	Water Supply - Communal	Contact Zone	137	0	N
5626-7WLQ3W	569536	4813137	Water Supply - Communal	Guelph	67	0	N

Permit No.	Easting (NAD83)	Northing (NAD83)	Category and Specific Purpose	Water Source	Permitted Rate (m^3/d)	Average Annual Consumptive Demand (m^3/d)	In Model as Flux Boundary (Well)
5626-7WLQ3W	569384	4813245	Water Supply - Communal	Guelph	785	8	Y
5626-7WLQ3W	569389	4813250	Water Supply - Communal	Middle Gasport to Lower Gasport	785	10	Y
88-P-2069	558681	4816893	Industrial - Other	Guelph to Upper Gasport	655	655	Y
89-P-2014	569462	4812611	Industrial - Other	Guelph	73	5	Y
93-P-2103	565004	4819478	Commercial - Golf Course Irrigation	Middle Gasport	540	8	Y
98-P-2064	569203	4814403	Water Supply - Campgrounds	Upper Gasport	393	164	Y
99-P-2070	561092	4820909	Remediation - Groundwater	Lower Gasport	46	6	Y
99-P-2070	561018	4820862	Remediation - Groundwater	Lower Gasport	46	11	Y
99-P-2070	560985	4820923	Remediation - Groundwater	Lower Gasport	46	6	Y
99-P-2070	560982	4820975	Remediation – Groundwater	Lower Gasport	46	8	Y

* The two sources permitted for the Guelph Lime Quarry were modelled as specified head boundary conditions and thus not included as specified flux boundary conditions (wells).

After the consumptive water demand was estimated for each permitted well, the data was further analyzed to select those wells for inclusion into the groundwater flow model. Those with zero average annual consumptive demands and sources marked as springs were not included in the model as specified flux boundaries (i.e., wells). The Guelph Dolime Quarry was explicitly modelled by specified head boundaries, and thus was excluded as a specified flux boundary. Additionally, some water takers located close to the model boundaries were excluded (or partially account for through recharge reductions (i.e., quarries on the crest of the Escarpment [see Section 3.3.1.2]) as they caused numerical instabilities due to the proximity with the model boundary. The impact of excluding these water takers on the regional model results is negligible as the boundaries are located at sufficient distance from the City of Guelph's municipal water supply wells do not influence model predictions.

2.4.5.5 *Glen Collector and Arkell Recharge System*

In addition to the 23 groundwater production wells, the City of Guelph operates the groundwater collection system located at the Arkell Spring Grounds. The Glen Collector System collects shallow groundwater from the overburden through a series of perforated pipes. A similar system, the Lower Road Collection System, was taken offline in 2001 due to water quality concerns. The yield from the Glen Collector System varies seasonally according to fluctuations in the water table elevation. To enhance the supply of water into the collection system, the City of Guelph operates an Eramosa River surface water intake and an Artificial Recharge System at the Spring Grounds. Between April 15 and November 15 of each year water is pumped out of the Eramosa River and discharged into an infiltration pit and trench where the water recharges the shallow overburden aquifer supplying the Glen Collector. Figure 2-30 illustrates the local details of the collection system configuration with respect to the

Eramosa River Intake and the Spring Grounds.

The Glen Collector System is represented in the groundwater flow model using specified head boundaries with elevations set to the invert elevations of the collectors as reported in the City of Guelph's Southeast Quadrant Groundwater Study (Jagger Hims Limited 1998c). The Artificial Recharge System is represented in the model using specified flux boundaries with a total injection rate of 3,000 m^3/d. This rate is equal to the average daily volume pumped from the Eramosa River and discharged into the recharge pit and infiltration trench.

Figure 2-31 illustrates how the Glen Collector System, recharge pit, and infiltration trench are represented within the finite element model using specified head and flux boundary conditions.

2.5 Assumptions of Model Design

The hydrogeologic conditions that control the movement of groundwater in the subsurface are complex and, as such, assumptions and simplifications must be made during the construction of numerical models that are used to simulate groundwater flow. The following simplifying assumptions were made in the design of the City of Guelph Groundwater Flow Model and should be considered when assessing any model predictions in the future:

- Groundwater / Surface Water Interactions. The City of Guelph Groundwater Flow Model was designed to simulate detailed local groundwater flow conditions within and near the city, and regional scale flow conditions outside the city. As a result, some streams and wetlands outside of the City of Guelph were not represented as boundary conditions in the model. This assumption should be considered when analyzing shallow groundwater flow predictions at the local scale outside of the City of Guelph. The finite element model has the flexibility to be updated or modified in the future to represent additional local-scale features.

- Bedrock Conceptual Model. The bedrock conceptual model implemented in the groundwater flow model is based on the interpretation completed to date within the City of Guelph. However, groundwater flow conditions within the fractured bedrock system are complex and the certainty of local conditions may be limited to the characterization information available in those areas.

- Overburden Conceptual Model. The conceptual model for the model domain simplifies the overburden into two units – the Upper and Lower Overburden Units. While this assumption is appropriate on a regional-scale, and may be appropriate locally in many areas, areas exist within the model domain where the overburden hydrostratigraphy is more complex. For example, additional buried bedrock valleys may exist within the Study Area but there is insufficient data available to characterize these features (if they exist) using the available data.

- Groundwater Recharge. The modelled groundwater recharge rates were derived from surface water flow models calibrated in the Grand River and Credit River watersheds. While the regional trends in groundwater recharge rates are similar, some differences exist in local predictions between the models.

- Niagara Escarpment. The Niagara Escarpment is represented in the model as a specified head boundary condition in the Gasport Formation. While this assumption is appropriate on a regional basis, it may not accurately represent groundwater flow in local areas near the Escarpment. This boundary condition is located at sufficient distance from the City of Guelph's municipal water supply wells, and as such, it is not expected to influence model predictions.

- Other Municipal Systems. Hydrogeologic conditions in the vicinity of other municipal systems (e.g., Cambridge, Rockwood, Acton, Erin, and Hillsburgh) are not represented in detail in the model; therefore simulation results in those areas should be considered to have a higher level of uncertainty than predictions made within the City of Guelph.

3.0 MODEL CALIBRATION AND VERIFICATION

3.1 Introduction

The purpose of calibration is to establish that the groundwater flow model can reproduce field-measured heads and flows. The model calibration process identifies a set of values for aquifer parameters and boundary conditions that are reasonable based on the conceptual model. Numerical groundwater flow models are typically calibrated by systematically and iteratively adjusting the model input parameters and boundary conditions to determine the optimum match (within an acceptable margin of error) between the model-predicted results and field observations. The model's ability to represent observed conditions is analyzed qualitatively to assess trends in water levels and distribution of groundwater discharge, and quantitatively to determine statistical measures of calibration. Parameter estimation software programs are sometimes used to automate the process of varying the model parameters, running the model, and computing and assessing statistics which measure the degree to which the model can be considered calibrated.

This section summarizes the calibration carried out for the City of Guelph Groundwater Flow Model. The approach adopted included a combination of manual and software-assisted calibration for steady-state conditions, and a calibration to transient conditions that simulated a long-term pumping test. A transient model verification step was undertaken to confirm the performance of the model under transient conditions.

3.1.1 Calibration Approach

The groundwater flow model was calibrated using a combination of iterative manual calibration techniques and a parameter estimation analysis tool, PEST (Parameter ESTimation; Doherty 2010). PEST is a model-independent parameter estimation and uncertainty analysis software tool that uses non-linear parameter estimation techniques to identify the set of model input parameters that provide the best-fit to observed field head and flow data.

Overall, the model calibration undertaken in the Tier Three Assessment involved the following main tasks:

1. Initial Manual Calibration. A preliminary version of the groundwater flow model was calibrated at an early stage to arrive at rough estimates of parameters values that resulted in a reasonable prediction of hydraulic heads and flows.

2. Model Refinement. The conceptual model was refined in some areas in response to the results of the initial manual calibration. Refinements included adjustments to stream boundary conditions in a

few areas and additional hydraulic conductivity zones added to enhance the representation of some processes that were not considered in the initial conceptual model.

3. Initial PEST Assisted Steady-State Calibration. Following the model refinement, PEST was used to guide the refinement of model input parameter values to achieve an optimal calibration that fit the conceptual understanding of the hydrology and hydrogeology of the Study Area.

4. Transient Calibration and Model Refinement. The transient calibration stage of the project evaluated the results of a long-term pumping test carried out at the Ironwood and Steffler wells in the Southwest Quadrant. This task included the refinement of hydraulic conductivity zones in the Middle Gasport Formation model layer. In addition, refinements were made to the model in the vicinity of the Hanlon Creek Subwatershed to bring the model predicted groundwater discharge rates into the range of field estimated values within that subwatershed.

5. Final PEST Assisted Steady-State Calibration. PEST was used to optimize the final calibration based on the results of the transient calibration and the final local-scale refinements.

6. Model Verification. To verify the performance of the model under longer-term variable climatic and municipal pumping conditions, a transient model simulation was conducted that covered the 1997 – 2005 period.

3.1.2 Introduction to PEST

The steady-state model calibration for the groundwater flow model was assisted through the use of PEST v.12 (Doherty 2010). PEST was used to help optimize the hydraulic conductivity parameters in the model through conducting a series of model runs where each model parameter is adjusted one at a time to determine the sensitivity of each of the parameters within the model. The sensitivity of a parameter (such as hydraulic conductivity) refers to how sensitive the model calibration is to a change in the parameter value. The change in model calibration due to the change in a single parameter can also be correlated with changes in other parameters. PEST uses the sensitivity and correlation information to identify a set of parameter values that best fit the model-predicted data to the observed field data.

Groundwater flow model calibration typically produces a single set of model parameters that results in the best estimate and fit to observed data. However, there is no unique solution to a groundwater flow problem and several parameter sets may result in acceptable and equivalent measures of model calibration. PEST is used to identify other plausible alternative parameter sets through the use of an uncertainty assessment. When used correctly, PEST also provides information on: 1) parameter sensitivity, correlation and uncertainty; and 2) observation sensitivity. This information is not readily determined through manual calibration alone, and it can be used to provide insight on the conceptual model and where data gaps may be present in the dataset.

The optimization to identify the best-fit parameter set is guided both by field data and the conceptual model. Observations are weighted based on confidence in the measured value, and preferred values (or ranges) of parameter values are specified and maintained throughout the parameter estimation process. During optimization, the upper and lower bounds for each parameter can be set as hard constraints to ensure PEST does not adjust the values beyond conceptually acceptable limits.

3.2 Calibration Targets

Calibration targets are measurements or estimates of hydraulic heads or flows that are compared to the model-predicted values during the model calibration process. The steady-state groundwater flow model was calibrated to hydraulic head measurements reported in the MOE domestic water wells, as well as high-quality monitoring wells that are currently monitored, or were monitored in the past, by the City of Guelph. The model was also calibrated to a range of spot flow measurements collected by the GRCA and others at a number of stream reaches within the Study Area, and to baseflow measurements calculated at continuous stream gauges scattered across the Study Area.

3.2.1 Hydraulic Heads – MOE Water Well Records

Water well records are submitted to the Ontario Ministry of Environment for all drinking water wells and monitoring wells completed in the Province of Ontario. The MOE maintains a database of information contained in each of the records including a record of the lithology observed when drilling and the static water level elevation observed in the well after completion. The database also contains information on the reliability of the geographic location and the topographic elevation of the well. Table 3-1 lists the total number of water well records used to support model calibration in the model domain.

Table 3-1 Summary of Water Well Records in Model Domain

Area of Model	Total Number of Water Well Records	Number of Static Water Level Observations used for Calibration		
		Total	Overburden	Bedrock
Grand River Watershed	8,152	7,041	1,314	5,727
Credit River Watershed	2,212	1,994	245	1749
Hamilton/Halton Conservation Authorities	2,701	2,480	315	2,165
Total	13,065	11,515	1,874	9,641

A total of 11,515 hydraulic head measurements reported in the MOE Water Well Information System (WWIS) were used to calibrate the steady-state model (Figure 3-1). Of these 11,515 wells, 1,874 are completed in overburden and 9,641 are completed in bedrock. Only wells in the WWIS database with a reported location reliability code of 5 or less (better than 50 m location reliability) and with a reported static water level were used. Furthermore, 872 water well records were removed from within the area of influence of the City of Guelph's municipal pumping wells, as many of these domestic wells were completed long ago and cannot be assumed to provide a reasonable estimate of water levels in the vicinity of the City of Guelph's pumping wells.

The remaining MOE water well records were not filtered for a particular time period and they are considered representative only of the time in which the water level was collected. These static water level observations offer the significant benefit of having a high number of model calibration targets that extend across the entire model domain; however, there can be uncertainty associated with individual observations. Uncertainties arise due to errors in the reported location of the wells, measurement techniques that were not designed to provide reliable scientific information, and variability in water levels over time at individual well locations. The MOE water well records were used to calibrate the model and identify regional trends in observations; however, they were not considered to be accurate indicators of an exact water level at a specific location.

3.2.2 City of Guelph Active Monitoring Wells

The City of Guelph currently maintains a groundwater monitoring network of wells installed in both the Arkell Springs Grounds and throughout the city. A total of 177 of the City of Guelph's monitoring wells were used as calibration targets and are shown as purple points on Figure 3-2. Details of these well within the Guelph area are shown on Figure 3-3. Appendix B3 summarizes these monitoring wells, including the hydrostratigraphic unit that the well is completed in, the range of water levels measured at the well, and the specific steady-state target estimated for the well.

3.2.3 Other High-Quality Wells

In addition to the City of Guelph active monitoring wells, there are a total of 221 monitoring wells identified within the Study Area classified as high-quality monitoring wells shown as orange points on Figure 3-2. These wells include older City of Guelph monitoring wells and other monitoring wells reported as part of consultants' reports, geotechnical reports, and other studies. In contrast to the MOE water well data, these higher quality monitoring wells are typically designed to measure groundwater level in a specific hydrostratigraphic unit. They are also monitored by qualified technicians and may have continuous monitoring data recorded for some duration. Appendix B3 summarizes these monitoring wells, including the hydrostratigraphic unit that the well is completed in and the specific steady-state target estimated for the well.

3.2.4 Baseflow Calibration Targets

In addition to calibrating against hydraulic head targets, baseflow calibration targets are compared with the model's prediction of groundwater discharge as an assessment of the regional and local water budget simulated by the model. Baseflow corresponds to the release of water from storage in a watershed or subwatershed. In some watersheds, most of this storage is associated with groundwater; however, storage could also be associated with wetlands, lakes, ponds, and reservoirs. Other anthropogenic impacts such as sewage treatment plant discharges or water diversions may constitute a portion of baseflow as well. The association of baseflow to groundwater discharge is not absolute. A key assumption when calibrating against baseflow targets is that the baseflow estimate in the creek or river is a reflection of groundwater discharge and not due to other factors.

Two broad sets of baseflow calibration targets were developed including those estimated from continuous stream gauges and those estimated from spotflow measurements. Figure 3-4 illustrates the locations of all baseflow calibration targets and the subwatersheds associated with the estimates. These targets are listed in Table 3-2 below.

Table 3-2 Summary of Baseflow Calibration Targets

Surface Water Course	ID	Description	Drainage Area (km^2)	Target Type	Baseflow Estimate (L/s)	
					Min	Max
Blue Springs Creek	BSC_30	At Camp Edgewood 1+2	76	Spotflow	146	1,735
	SW4	At 2nd Line	46	Spotflow	164	997
	2GA031	Near Eden Mills	42	WSC Gauge	361	445
	BSC-99a	Near Crewson's Corners	42	Spotflow	118	1,701

Surface Water Course	ID	Description	Drainage Area (km²)	Target Type	Baseflow Estimate (L/s)	
					Min	Max
	BSC_10	At 5th Line	31	Spotflow	65	1,231
	BSC_20	At 28th SDRD	17	Spotflow	25	59
Chilligo/Ellis Creek	ASF-5	At Maple Grove Rd	54	Spotflow	10	215
	CGC_10	At Kossuth Rd	40	Spotflow	18	114
	EC_10	At Wellington Rd 32	12	Spotflow	2	15
Cox Creek	CCT_20	Cox Ck S Trib at 6th Line E	19	Spotflow	6	44
Eramosa River	2GA029	Above Guelph	230	WSC Gauge	1,333	2,454
	ER-4	Above Guelph	230	Spotflow	525	3,500
	ER_40	At Wellington Rd 29	219	Spotflow	210	2,416
	ER-99b	At Rockwood	127	Spotflow	139	2,349
	ER_30	At Everton	105	Spotflow	188	1,383
	ER_20	At Wellington Rd 125	85	Spotflow	372	392
	ER_10	At 3rd Line	50	Spotflow	319	399
Guelph Lake Tributary	GLT_10	Cold Trib. At 3rd Line	19	Spotflow	33	51
	GLT_20	Trib. At Jones Baseline	18	Spotflow	17	25
Hanlon Creek	HC_10	At Hwy 6	18	Spotflow	33	68
	HCT_20	South Trib. At Hwy 6	5	Spotflow	0	0
Hopewell Creek	ASF-8	At Breslau Dam	76	Spotflow	13	187
	HWC_50	Below Hwy 7	73	Spotflow	92	163
	HP-1	At Greenhouse Rd	51	Spotflow	45	83
	HWC_10	At Wellington Rd 32	33	Spotflow	19	55
Irish Creek	IC_20	At Townline Rd	38	Spotflow	62	107
	IC_10	At Wellington Rd 32	18	Spotflow	8	31
Lutteral Creek	2GA033	Near Oustic	67	WSC Gauge	356	547
	LC_30	At 3rd Line	67	Spotflow	194	525
	LCT_20	Trib. At 6th Line	5	Spotflow	9	38
Marden Creek	MDC_10	At Wellington Rd 30	14	Spotflow	22	67
Mill Creek	2GAC19	At SR #10	82	GRCA Gauge	589	733
	MC-99a	At Paddock's Corners	71	Spotflow	241	605
	3AQ131	Aberfoyle Ck at Twp Rd 7	43	GRCA Gauge	198	255
	MC_10	At Victoria Rd	13	Spotflow	16	22
Moffat Creek	MOFC_20	At Hwy 24	18	Spotflow	88	121
	MOFC_10	At Franklin Blvd	14	Spotflow	26	30
Speed River	2GA015	Below Guelph	581	WSC Gauge	2,302	3,392
	2GA040	Near Armstrong Mills	174	WSC Gauge	808	1,291
	SR_40	Above Lutteral Creek	100	Spotflow	127	612
	SR_30	At 3rd Line	90	Spotflow	141	676
	SR_20	At 6th Line	48	Spotflow	83	325
	SR_10	At Wellington Rd 26	38	Spotflow	61	296
Swan Creek	ASF-13	At Sideroad 4	43	Spotflow	20	233
West Credit River	02HB02	At 8th Line	35	WSC Gauge	300	360

Spotflow measurements refer to instantaneous measurements of streamflow that are generally made during baseflow conditions. Spotflow measurements were compiled from three sources:

1. Raw historical spotflow measurements were obtained from the GRCA for 1995-2002. These measurements were recorded in a database with the date of measurement. As these measurements were taken throughout the year, only measurements taken during baseflow or low flow conditions

were used as calibration targets.

2. Spotflow measurements were collected by AquaResource, Inc. and Golder Associates in the summer and fall of 2008 as part of this study. Details on the field procedures employed within the baseflow monitoring program are documented in a memorandum to the City of Guelph (Appendix B4).

3. Spotflow measurements taken during a recent study of Blue Springs Creek were also included (AECOM Canada 2009).

These three sources of spotflow measurements were combined into one database of spotflow measurements.

Streamflow records for the 1980-2005 time period were used from eight gauges operated by either the Water Survey of Canada (WSC) or the GRCA. A baseflow separation calculation was performed on the continuous streamflow data to obtain baseflow estimates. The baseflow separation routine used in this analysis is the Baseflow Separation Program (BFLOW) included with the Soil and Water Assessment Tool (SWAT) hydrologic model. This routine employs a digital filtering technique designed to replicate manual hydrograph separation. This program has been selected as an acceptable baseflow separation technique by several conservation authorities in Southern Ontario including Ausable Bayfield, Maitland Valley and the Grand River. A review of common baseflow separation techniques was carried out by the GRCA and found BFLOW to be the most appropriate (Bellamy, et. al 2003).

Daily streamflow for each of the WSC and GRCA gauging stations was inputted into BFLOW to perform the baseflow separation. The program outputs a range (i.e., minimum and maximum) of daily estimated baseflow rates. The high and low baseflow estimates from the baseflow separation analysis were used as a target range for model calibration expressed as average annual baseflow estimates over the 1980-2005 period.

3.3 Model Refinements

As described in Section 3.1, refinements to the regional conceptual model were made during the model calibration process. Previously completed studies and reports were referenced to ensure that local modifications to the conceptual model were consistent with local characterizations.

3.3.1 Adjustments to Groundwater Recharge

3.3.1.1 *Grand River Conservation Authority - GAWSER*

As previously discussed, the Guelph All-Weather Sequential-Events Runoff (GAWSER) streamflow-generation model was used to predict the recharge to the groundwater system and total stream flow resulting from inputs of rainfall and/or snowmelt. The GAWSER groundwater recharge estimates were adjusted locally in some areas to achieve a better model calibration. GAWSER does not physically represent hydrogeologic processes and therefore its results have greatest uncertainty in areas where the hydrogeology may influence actual groundwater recharge. In addition, some of the assumptions made with respect to the hydrological response units (HRUs) may not be valid in local areas. Areas within the model where the GAWSER recharge rates were adjusted are described as follows:

- Some recharge adjustments were made in local areas where initial model results indicated that the conceptual model was inconsistent with the estimated groundwater recharge rates in that area. These situations often result in water levels being simulated above ground surface and are often caused by higher recharge rates being applied to a small area with lower hydraulic conductivities. For example, a small sand deposit only a few elements in size might be assigned high recharge because it is a sand, but if it was surrounded and underlain by a till with a low hydraulic conductivity, that recharge might be unrealistically high and instabilities in the model would occur. The till would not be able to receive the recharge and would cause unrealistically high hydraulic heads.

- Early model calibration results suggested that the recharge in Hopewell, Cox and Swan Creeks catchments was too high resulting in high groundwater discharge estimates as compared to the baseflow range. High groundwater recharge rates in those areas were predicted by GAWSER for a number of surficial sand deposits. These surficial deposits, however, are deposited on top of a much less permeable Port Stanley Till and it was therefore concluded that the actual amount of recharge entering the groundwater system would be less than predicted by GAWSER. The recharge rates on those for sand and gravel deposits was reduced from 320 mm/year to 120 mm/year to represent thin sand and gravel deposits with increasing silt and clay content overlying Port Stanley Till. These changes produced better calibration results for hydraulic heads and baseflow.

- Groundwater recharge rates were increased by 20% within the Eramosa River Watershed to predict groundwater discharge that was within the estimated baseflow range in the Eramosa River.

- Groundwater recharge rates were redistributed within the Hanlon Creek Subwatershed as part of the detailed calibration work completed in the Southwest Quadrant (Golder Associates 2011).

- Calibration was improved in the area east of Eden Mills on the Moffat Moraine by increasing recharge from an average of 156 mm/yr to 230 mm/yr.

3.3.1.2 *Halton and Hamilton Conservation Authorities - PRMS*

In the southeast of the study area, from Guelph over to the escarpment, PRMS estimates the recharge on exposed bedrock to be 400 to 450 mm/year which contributes to the overestimation of the stream flow in the associated catchment areas. For areas near the Paris moraine at the border between the GRCA and the Halton CA, where the PRMS model under-predicts flow, the Wentworth Till on the GRCA side of the model has an average recharge rate of ~220 mm/year, while on the Halton and Hamilton side, the average recharge from PRMS is ~170 mm/year. This contributes to an underestimation of total stream flow for Blue Springs Creek and, to some extent, Mill Creek.

The following changes were made during the calibration process:

- Recharge for exposed bedrock in the Halton-Hamilton area (the southeast of the study area) was adjusted based on depth to the bedrock piezometric surface in order to represent dry (upland) conditions (higher recharge), intermediate conditions, and wet (saturated or near saturated) low-lying segments (zero recharge). For areas where the observed bedrock piezometric surface was greater than 6 m below ground surface (mbgs) 100% of the PRMS recharge distribution for those bedrock areas was used. Where the bedrock piezometric surface was between 2 mbgs and 6 mbgs 50% of the PRMS recharge estimated for those bedrock areas was used. Recharge was set to 0 mm/year in bedrock areas where the piezometric surface was less than 2 mbgs. Recharge on the bedrock ranges from 120 to 400 mm/year.

- The recharge rate of the Wentworth Till on the Halton-Hamilton side of the Paris Moraine was increased by 100 mm/year to 220 mm/year matching the GAWSER-predicted recharge rates on the Grand River Watershed side of the boundary.

- The quarry water takings located adjacent to the eastern model boundary caused numerical instabilities when modelled as specified flux boundary conditions (i.e., wells) due to their proximity to the model boundary. To increase stability, these specified flux boundaries were removed and a portion of the reported water takings from the quarry sumps were incorporated into the calibrated model through the adjustment of the recharge rate to 0 mm/year in those areas. The location of the quarries is shown in Figure 3-5 and the final recharge distribution is shown in Figure 2-25. Although this solution changes the predicted shape of the piezometric surface in close proximity to the quarries, the impact of this adjustment on the regional model results is negligible as the boundaries are located at sufficient distance from the City of Guelph's municipal water supply wells do not influence model predictions.

  - The portion of the quarry water takings that is accounted for by reducing the groundwater recharge rate to zero is shown in Table 3-3. For the Acton Quarry, 47% of the reported water taking is accounted for by the areal recharge adjustment at the quarry, while 61% of the Milton Quarry water taking is represented. For the Halton Crushed Stone Quarry, 20% of the reported water taking is accounted for. The source of the water for the remainder of the water taking volumes is assumed to come from direct precipitation (minus evapo-transpiration) and run-off to the quarry which was estimated at 570 mm/year in a recent study conducted in support of an application for expansion of the Acton Quarry (CRA 2008). As the proportion of the quarry water takings coming from the groundwater system (recharge reduction) versus surface water (e.g., direct precipitation, run-off) is not known precisely (the reported takings are volumes pumping from quarry sumps), this estimation of recharge reduction is reasonable.

Table 3-3 Quarry Recharge Expressed as Percentage of Water Takings

	Avg. Recharge mm/year	Area (m^2)	Total Recharge m^3/d	Reported 2008 Taking m^3/d	Total Recharge as % of Reported Taking
Acton Quarry 1	227	1,116,621	694	1987	
Acton Quarry 2	22	374,429	23	518	
Acton Quarry 3	212	788,663	459	0	
Total Acton Quarry			1,176	2,505	47%
Milton Quarry 1	209	652,177	374	1,272	
Milton Quarry 2	355	987,283	961	2,435	
Milton Quarry 3	337	1,377,594	1,272	888	
Milton Quarry 4	133	550,937	201	0	
Total Milton Quarry			2,808	4,594	61%
Halton Crushed Stone Quarry	360	1,093,695	1,079	5,369	20%

3.3.2 Arkell Springs / Glen Collector

Local hydrogeologic conditions associated with the operation of the Arkell Springs Ground and the Glen Collector System were adjusted to reflect observed conditions. Groundwater recharge and discharge rates vary significantly throughout the year and calibration to steady-state conditions is considered as an approximation only.

The Glen Collector System (Figure 2-31) is represented by a series of specified head (Type 1) boundary conditions placed on finite element nodes on slice 3 along the collector footprint at elevations corresponding to the measured invert elevations. The Arkell Recharge System is represented in the model by specified flux (injection wells) placed near the recharge pit and trenches.

The locations of the injection well (recharge) nodes representing the Arkell Recharge System were modified during calibration. It was found that concentrating the injection nodes closer to the upstream end of the recharge trench and pit gave more flow to the collector system. The final configuration of boundary conditions is shown on Figure 2-31.

3.3.3 Carter / Burke Wells

The Carter and Burke Wells pump water primarily from the Guelph Formation in shallow bedrock. Hydraulic conductivities in the Guelph Formation during initial calibration were not high enough to support local flows to the Carter and Burke Wells. Furthermore, inspection of hydraulic gradients in the regional calibration simulations revealed too much hydraulic connection between the overburden and the bedrock layers. Detailed examination of previous studies, well logs, and hydraulic testing in the area revealed the presence of a buried valley in-filled with sediments ranging from a stony till to sand and gravel extending southeast to the base of the Paris Moraine. This feature was added to the model in the Contact Zone (Layer 4) and extended downwards through the Guelph and Reformatory Quarry Layers (Layers 5 and 6). The buried valley can be seen on Figure 2-17 to Figure 2-19 as Hydraulic Conductivity Zones 3 and 4.

Additionally, small, higher hydraulic conductivity zones representative of the Wentworth Till in Overburden B (Layer 3) in the vicinity of the Burke and Carter wells were adjusted to reflect the regionally extensive, lower permeability, Port Stanley Till. This change resulted in a desired hydraulic gradient between the overburden and bedrock layers matching observed data.

3.3.4 Northwest Quadrant

In the Northwest Quadrant of the City of Guelph (e.g., Smallfield and Sacco Wells), the model-simulated hydraulic heads in all the bedrock units are approximately 10 m lower that the observed heads. There is limited high-quality calibration data within this area and Jagger Hims (Northwest Quadrant Aquifer Performance Study 1998a) reported that this area has limited characterization information and it is particularly challenging to distinguish the bedrock units from each other. In particular, the contacts between the Guelph, Vinemount and Gasport (previously the Guelph, Eramosa, and Unsubdivided Amabel Members) were reported as indistinguishable in well logs. During the calibration effort for this model, adjusting hydraulic conductivities was unsuccessful at improving the model's calibration to observed high-quality data.

Groundwater recharge in the area was also adjusted during calibration. It was found that raising the average recharge over the north-west portion of the Quadrant from 58 mm/yr to 180 mm/yr was necessary to obtain a good fit to the observed data. Given that much of the land cover in the area is impermeable due to large commercial and industrial properties this recharge increase was deemed unrealistic.

From the current calibration effort, it is concluded that the conceptualization of a higher permeability Middle Gasport Unit does not suit hydrogeologic conditions in the Northwest Quadrant area, and that further characterization work is needed to better represent groundwater flow in that area. Jagger Hims reported that groundwater flow through the bedrock depends highly on the distribution and geometry of fractures, solution channels, and reefal structures (Jagger Hims 1998a). In general, these types of features are not incorporated in the current characterization and would need to be better understood and characterized, even on a conceptual level, to achieve a better calibration. Thus the residual error in hydraulic heads that remains in this area was deemed acceptable for this study as the City of Guelph is not pursuing increased water supply capacity in the Northwest Quadrant.

3.3.5 Northeast Quadrant

The hydraulic conductivity of the till in the Northeast Quadrant was varied in an effort to improve the calibration results. Overburden in the area is characterized as Port Stanley Till with a regional calibrated vertical hydraulic conductivity of $5x10^{-7}$ m/s. These areas in the vicinity of Clythe Creek and the Eastview Landfill are shown on Figure 2-15 and Figure 2-16 as Conductivity Zones “p” and “q” respectively. A vertical hydraulic conductivity of $5x10^{-8}$ m/s in these zones is consistent with existing characterizations and resulted in better simulations of observed water levels.

3.3.6 Eastern Study Area

The Eramosa River Valley is incised into the Gasport Formation along the Eramosa River north of Arkell through Eden Mills and Rockwood up to Everton and this appears to influence groundwater/surface water interactions and the match between calibrated and observed water levels. Adjustments in bedrock hydraulic conductivity were made along this reach to represent the incised nature of the river and to hydraulically connect it directly to the Gasport Formation. This was achieved by setting the properties of Layers 5 to10 in that area to those of the Contact Zone or weathered bedrock (Kx,y = $3x10^{-5}$ m/s; Kz = $3x10^{-6}$ m/s). Conceptually this represents extending the weathered bedrock from the Contact Zone down to the Gasport Formation. These adjustments are shown on Figure 2-18 to Figure 2-21 as Conductivity Zone 1.

Calibration was improved in the area east of Eden Mills on the Moffat Moraine by lowering the hydraulic conductivity of the till and increasing recharge. Shown as Conductivity Zone “r” on Figure 2-15 and Figure 2-16, this area was originally assigned the properties of the Wentworth Till, a sandy till with hydraulic conductivity of $5x10^{-5}$ m/s. Through calibration the conductivity was lowered to match that of a silty till with clayey-silt interbeds (Kx,y = $5x10^{-6}$ and Kz = $2.5x10^{-8}$ m/s). Recharge was increased from an average of 156 mm/yr to 230 mm/yr to represent more hummocky conditions.

The Paris moraine is a large area to the east of the City of Guelph mainly represented on surficial geology maps as Wentworth Till. Early calibration efforts identified contrasting calibration error trends in the north and south portions of the moraine and therefore this area was subdivided into north and south portions shown as Zones “u” and ”v” on Figure 2-15 and Zones “s” and “t” on Figure 2-16. Through calibration, the upper portion (Overburden A – Model Layers 1 and 2) of the southern region was adjusted to have a higher hydraulic conductivity of Kx,y = $1x10^{-4}$ m/s and Kz = $5x10^{-5}$ m/s possibly representing a more weathered till (shown in Figure 2-15 as Zone “v”). The hydraulic conductivity of the surface of the northern portion was reduced to Kx,y = $1x10^{-5}$ m/s with Kz = $5x10^{-6}$ m/s (shown in Figure 2-15 as Zone “u”). While there is limited characterization data to support subdividing the north and south areas, the final calibrated hydraulic conductivities improve model calibration and are acceptably within the range expected for these geological materials.

3.3.7 South-Western Study Area - East Cambridge

The south-western portion of the Study Area encompasses portions of East Cambridge and a number of water supply wells operated by The Regional Municipality of Waterloo. The Gasport Formation has been previously studied by Duke Engineering (Duke 1998) and a calibrated groundwater flow model was produced as part of that study. Concurrent to this present study, the Tier Three Assessment for the Regional Municipality of Waterloo (AquaResource in progress) has resulted in a new conceptualization for the Cambridge area. From that conceptualization, a detailed, calibrated groundwater flow model of the East Cambridge area has been developed. The hydraulic conductivity distribution in the bedrock units from that model have been incorporated into the City of Guelph Groundwater Flow Model and can be seen on Figure 2-17 to Figure 2-23 and have been described in Section 2.4.4.1.

3.3.8 Southwest Quadrant – Transient Calibration

As part of the City of Guelph’s concurrent Southwest Quadrant Class Environmental Assessment (Golder 2010), the model was calibrated to a pumping test carried out at the Ironwood and Steffler test well locations. This assessment refined the parameterization of the model in the SW Quadrant area of the City of Guelph. Reference should be made to the supporting documentation for the City of Guelph’s SW Quadrant EA for a detailed discussion of the FEFLOW model refinements, transient calibration details, and the resulting parameterization in this area of the model (Golder 2010). A brief summary of the findings and resulting adjustments to the groundwater flow model are provided below.

A long-term (32-day) pumping test was completed in the SW Quadrant of Guelph in July 2008 at the Ironwood and Steffler test well locations (see Figure 3-6 for the location of these test wells and the approximate influence area within the SW Quadrant of the city). These wells are completed in the Gasport Formation and are isolated from the shallower bedrock units above the Vinemount aquitard. During the 32-day period of the test, the combined groundwater takings from these wells reached a maximum of 10,400 m^3/day, and the response from pumping was monitored at a relatively large number of monitoring wells installed in this area of the City of Guelph from recent hydrogeological investigation programs, including locations in the Gasport Formation, locations in the shallower bedrock above the Vinemount Formation, and locations in the overburden. Specific monitoring above and below the Vinemount Formation provided a unique opportunity to assess the vertical hydraulic conductivity within the bedrock in addition to the horizontal distribution of hydraulic conductivity within the Gasport Formation. An early version of the groundwater flow model provided the initial platform for the transient calibration efforts to this long-term pumping test. With this model as the starting point, the following additional (local) refinements were made by Golder as part of the SW Quadrant EA:

- The FEFLOW finite element mesh was refined to provide more detailed representation of the

Guelph Lime quarry, located to the north of the Ironwood and Steffler test wells. This included increasing the number of elements around the quarry, and refining the boundary condition assignments to reflect the inferred water level in the quarry at the time of the test (290 masl) and seepage face conditions for the hydrostratigraphic units which subcrop along the walls of the quarry.

- The surface water courses in the SW Quadrant area of the city were adjusted to reflect local-scale mapping, in particular the drainages within the Hanlon Creek watershed. The boundary conditions for these features were also constrained such that groundwater could only discharge to these drainage features. This included drainages in Hanlon Creek, Irish Creek and the upper reaches of Mill Creek.

- The finite element mesh was locally refined to include specific nodes at the Ironwood and Steffler test wells. The pumping rates at these wells during the test, as well as the City of Guelph's existing supplies in the SW Quadrant of the city, were assigned based on information on actual takings immediately prior to and during the 32-day test.

- Recharge rates were adjusted locally to reflect the wetland areas within Hanlon Creek as areas of zero recharge. The recharge to the upland areas within the watershed were subsequently adjusted, such that the total recharge in this area remained consistent with that derived from regional scale surface water calibration efforts (i.e., GASWER model).

- The overburden characterization in the area of the Hanlon Creek subwatershed was refined based on a review of the available borehole logs and stratigraphic information. This primarily involved reflecting the distribution of overburden materials in accordance with surficial geological maps, as well as an interpretation of the areas where the surficial sands and gravels are in direct hydraulic connection with the underlying bedrock.

Following the above adjustments, transient calibrations were then completed with the model to approximate the observed response in the field, both above and below the low permeability Vinemount Unit. The following summarizes the main adjustments made as part of the SW Quadrant Class EA, which were subsequently incorporated back into the regional scale Tier Three model.

- The grid adjustments made prior to initial transient calibration, and the local scale updates to the boundary conditions (recharge, and quarry discharge boundaries) and overburden characterization were adopted in the regional model.

- The vertical hydraulic conductivity of the Vinemount Layer was established at $1x10^{-9}$ m/s. The transient calibration was found to be sensitive to the vertical hydraulic conductivity of the Vinemount Member, and this value was considered to represent a reasonable vertical hydraulic conductivity of this unit in the SW Quadrant of the city.

- The hydraulic conductivity of the Middle Gasport Layer in the immediate vicinity of the Ironwood and Steffler test wells was established at $2.2x10^{-3}$ m/s. Several additional modifications were made to the spatial distribution of the hydraulic conductivity zones within the Middle Gasport Layer generally indicative of increased hydraulic conductivity in a north-south trending zone through the SW Quadrant area with lower hydraulic conductivity on the shoulders of this more transmissive zone. The resulting hydraulic conductivity distribution from this process is illustrated on Figure 3-7. Within some of the Conductivity Zones in the Middle Gasport Layer, a north-south vs. east-west anisotropy in horizontal hydraulic conductivity was also introduced.

- The specific storage of the bedrock derived from the transient calibration process was $1x10^{-6}$ /m.

3.3.9 Middle Gasport Hydraulic Conductivity Zones

The initial configuration and parameterization of the Middle Gasport Hydraulic Conductivity Zones was taken from the previously calibrated Guelph-Puslinch model (Golder 2006a). That model built on hydraulic conductivity distributions and parameters from a number of previous studies including the Arkell Spring Grounds Groundwater Supply Investigation (Gartner Lee, 2003). During calibration of the current model, these zones were adjusted to improve the match between the model-predicted heads and the observed values, particularly with the higher quality City of Guelph calibration targets. The SW Quadrant EA transient calibration further assisted in the delineation and parameterization of the zones in the south of the City of Guelph.

3.4 Transient Model Verification

After final calibration of the model, further transient model simulations were conducted to examine the model's ability to simulate the groundwater system's response to: 1) two long-term aquifer response tests conducted as part of other studies in the area, and 2) to longer-term variable climatic and municipal pumping conditions covering the 1997 – 2005 period.

3.4.1 Integrated Wellfield Transient Verification

The two long-term aquifer response tests that were simulated during the first model verification step are those conducted as part of the Arkell Spring Grounds Groundwater Supply Investigation Report (Gartner Lee 2003) and the previously described Southwest Quadrant Class EA (Golder 2010). These two tests are described in detail in Section 5.4 (Summary of Aquifer Response Tests) of Appendix A of the main body of the Tier Three Assessment report.

Table 3-4 summarizes the results from the transient verification simulations at key observation wells. There is good agreement between the observed and model predicted drawdown for a majority of the wells examined in the calibration. For the Arkell pumping test, the simulated drawdown at the pumping wells (the wells with "Arkell" in the name) is reasonably close with the maximum difference between the observed and simulated drawdown of 1.5 m at Arkell 6. For the monitoring wells, model-predicted drawdown has good agreement with the observed drawdown with the larger deviations occurring in observation wells that are further from the pumping centre (e.g., OW16/00).

Table 3-4 Summary of Wellfield Transient Verification Results

Test (Date)	Observation Point	Observed Drawdown (m)	Simulated Drawdown (m)	Distance from Pumping Centre (m)	Formation Screened
Arkell 2001 Pumping Test (July-Sept 2001)	Arkell15-PW15A/00	4.6	5.6	400	Gasport
	Arkell6-PW6/63	6.8	5.3	270	Gasport
	Arkell7-PW7/63	5.8	5.5	400	Gasport

Test (Date)	Observation Point	Observed Drawdown (m)	Simulated Drawdown (m)	Distance from Pumping Centre (m)	Formation Screened
	Arkell8-PW8/63	5.1	5.2	270	Gasport
	OW11/00-D	3.8	4.8	940	Gasport
	OW11/00-S	0.3	0.5	940	Contact Zone
	OW12/00	4.4	4.8	1300	Gasport
	OW13/00	0.0	0.2	1100	Guelph Fm.
	OW14/00-D	5.1	5.0	420	Gasport
	OW14/00-S	0.3	0.4	420	Guelph Fm.
	OW15/00	4.6	5.5	410	Gasport
	OW16/00	1.9	4.7	1,200	Gasport
	OW18/00	4.6	4.9	750	Gasport
	OW19A/00	4.4	4.8	800	Gasport
	OW19B/00	0.2	0.1	800	Guelph Fm.
Southwest Quadrant 32-day Pumping Test (July, 2008)	MW04-01A	6.7	5.5	1,200	Gasport
	MW08-01A	6.7	5.9	1,250	Gasport
	TW08-01A	12.8	10.2	400	Gasport
	TW08-02A	13.6	14.7	600	Gasport
	TW04-01A	11.2	7.4	700	Gasport
	TW04-02A	2.1	4.1	1,800	Gasport

The Southwest Quadrant EA pumping test also displays good agreement between the observed and model-predicted drawdown in the monitoring wells. In this case, the largest deviations occur at TW08-01A and TW04-01A where the model under predicts drawdown. These two wells are closer to the centre of pumping and could, in reality, be more connected to the pumping wells through a discrete fracture network and/or secondary porosity that are not simulated explicitly in the model. Groundwater flow in the Gasport aquifer has been characterized as occurring mainly in the secondary porosity and permeability of the rock (fractures, solution channels and reefal structures) which is only incorporated into the groundwater flow model as bulk parameters using an equivalent porous media approach (EPM). This EPM approach is considered valid at the scale of the regional model and at the well field scale, but care must be taken when examining the model at the scale of a single observation well.

The results of the transient simulation of both the pumping tests demonstrate that, at the scale of the well field and larger, the model is able to simulate the observed response of the groundwater system in that those areas.

3.4.2 Long-Term Transient Verification (1997-2005)

The second model verification step consisted of a long-term transient simulation covering the nine-year period from 1997 to 2005 with the goal to compare the simulated head response in the municipal wells and the predicted groundwater discharge to the Arkell Glen Collectors with the observed data from that time period. The model was simulated with the following parameters:

- Monthly average groundwater recharge rates as predicted by GAWSER from 1997 to 2005 (Section 2.2.1.1);
- Monthly average historical pumping rates for the Guelph municipal wells; and
- Monthly average pumping to the Arkell Recharge System-according to the Eramosa River Intake pumping records (described in Section 2.4.5.5).

3.4.2.1 *Head Response in Municipal Wells*

Figure 3-8a to Figure 3-8f illustrate the water level results of the long-term model simulation in a sampling of wells from the four quadrants and also show the monthly average pumping rates associated with each well. The results for the other City of Guelph Municipal Wells are provided in Appendix B5. In order to compare the simulated and observed pattern of head fluctuations in the pumping wells, the model-predicted heads have been adjusted on a well-by-well basis, where required, to account for the absolute difference between the steady-state model-predicted heads and the observed head target used to calibrate the steady-state model. Presenting this data with a normalization of the model-predicted heads focuses the analysis on the model's response to the stress conditions and removes the effects of well losses, model geometry (e.g., difference between actual and modelled top of well elevations), and other artefacts arising from the model's approximation of a real-world system. Table 3-5 below summarizes the adjustments to the simulated Depth to Water levels for the transient model as compared to the difference (residual error) between the observed and simulated heads for the calibrated steady-state model.

Table 3-5 Adjustments to Simulated Depth to Water for Pumping Wells

Municipal Pumping Well	Observed Water Level (Calibration Target) (m)	Steady-state Simulated Water Level (m)	Steady-state Residual Error (m)	Transient Simulation Adjustment Required (m)
Arkell 1	322.9	322.5	-0.4	0
Arkell 14	316.0	315.2	-0.8	0
Arkell 15	317.6	315.4	-2.2	0
Arkell 6	313.7	314.6	0.9	0
Arkell 7	313.9	314.6	0.7	0
Arkell 8	313.9	314.6	0.7	0
Burke	319.2	324.1	4.9	4.5
Calico	309.1	315.3	6.2	3.5
Carter Wells	320.2	321.5	1.3	-3
Clythe Creek	321.4	317.1	-4.3	-8
Dean Ave.	289.7	295.8	6.1	6
Downey Rd.	297.0	294.8	-2.2	2.5
Emma	293.2	277.9	-15.3	-15
Helmar	303.5	321.7	18.3	18
Membro	287.7	292.8	5.1	5
Paisley	299.1	300.8	1.7	3
Park 1 and 2	291.8	283.6	-8.2	-8
Queensdale	289.9	299.1	9.2	18
Sacco	337.9	325.0	-12.9	-12.5
Smallfield	334.2	320.0	-14.3	n/a*
University	293.0	293.6	0.6	5
Water Street	290.4	297.3	6.9	5

*Smallfield had no observation data during period of interest

There is excellent agreement between the pattern of observed and model-predicted heads for most of the wells examined in the calibration. Some of the wells have observed water level fluctuations that are greater than the water level fluctuations predicted by the model. This is attributed to the averaging of municipal pumping rates over the monthly stress periods used in the simulation. The average monthly pumping rates produce model-predicted water levels that do not reflect the influence of day-to-day changes in pumping. Other noise in the observation data is introduced by a majority of the water levels being measured though air line type gauges that have their inherent inaccuracy and imprecision.

The steady-state model calibration effort concentrated on matching the 2008 data as representative of current conditions. Because of that, the geometry and condition of the pumping wells in 2008 will be most closely represented in the model, and thus the later period of the transient simulation will have a better match between observed and modelled data. Any changes to the wells (e.g., installation of liners, or rehabilitation of the well) that occurred in the time period of the transient verification exercise (1997-2005) may cause a mismatch between the observed and model-simulated data up to the time of the change, and a better match after the change. In general, the match is better after 2002 which also appears to correspond with an improvement in the quality (and quantity) of the field data being collected by the city.

Within the Southeast Quadrant, three wells are discussed here: Arkell 1, Arkell 8, and Burke. The model-predicted and observed depths to water levels reported for Arkell 1 are illustrated on Figure 3-8a. This overburden supply well located in the Arkell Spring Grounds has observed water levels that vary approximately 5 m over the period of analysis (1997-2005). The model-simulated depth to water level is presented as the black line on the figure and the observed water levels are presented on the graph with orange dots. Monthly average pumping rates are shown at the bottom of the figure. The water level trends in the observed water levels are matched by the model and the transient simulation data does not require any adjustment.

The results for Arkell 8, a deep bedrock well pumping from the Gasport Formation, are shown on Figure 3-8b. The observed data varies by over 10 m during 1997-2005. The model is able to match both the absolute water levels as well as the pattern of response to the variable pumping and recharge.

Figure 3-8c shows the transient simulation results for Burke well that draws water from both the shallow and deeper bedrock aquifers. The period after March 2002 displays the best match of the simulated and observed data. This corresponds to the installation of a new pump and some rehabilitation work on the well.

The results for the Downey Well are shown in Figure 3-8d as representative of wells in the Southwest Quadrant. In general, water levels in wells in this quadrant exhibit a large amount of interference due to the number of municipal wells pumping at variable rates from the Gasport Aquifer and therefore the observation data is inconsistent. However, the simulated water levels fluctuations at Downey have a good match with the observed water levels.

Figure 3-8e shows the results for the Paisley Well in the Northwest Quadrant. There is a good match to the data for the period after the most recent cycle of well rehabilitation (acidification) in 2003.

For the Northeast Quadrant, the results of the Park Wells are shown Figure 3-8f. Due to the close proximity of the Park Wells, they are modelled as one well in the FEFLOW model and thus only one simulated water level is shown. The simulated fluctuations at the modelled well are similar to the observed fluctuations for both wells.

3.4.2.2 *Discharge to Arkell Glen Collector*

Groundwater discharge at the Arkell Glen Collector was also simulated during the long-term transient simulation and is compared with observed flow data on Figure 3-9. The average monthly pumping rate from the Eramosa River to the Arkell Recharge System is also shown on this figure. The model-simulated flow is illustrated as the black line and the observed daily flows are shown as grey dots. Additionally, the average monthly observed collector flows are shown as a dashed red line. In general, the model slightly under predicts the quantity of flow at the collector during peak flow conditions, but there is a good match in the timing of flows between simulated and observed data especially for the later time period. Discrepancies may be account for by the following factors:

1. Until recently, the flows recorded for the Glen Collector were not observed directly, but were back-calculated by subtracting the volume of water extracted from the Arkell and Carter wells daily from the total volume of water flowing to the Woods Pumping Station through an aqueduct that includes the Glen Collector flows. Thus, because of storage in the aqueduct system, daily fluctuations in the pumping rates at the wells led to inaccuracies in the recorded Collector flows. This effect was observed in the field during a pumping test and documented in “Arkell Spring Grounds – Groundwater Supply Investigation” (Gartner Lee Limited 2003b).

4. The observed Arkell Glen Collector flows originally included flows from the Lower Road Collectors (see Figure 2-30) that were sealed in 2001 due to poor water quality. The Lower Road Collectors collected a large proportion of water that was recharged to the shallow aquifer by the Arkell Recharge System and these collectors contributed approximately 4,000 m^3/day of flow during peak flow seasons. The model only simulates the current configuration of the Arkell Glen Collectors and thus the discharge simulated does not include the pre-2001 contribution of the Lower Road Collectors.

5. During 2000 and 2001 the Arkell Spring Grounds were undergoing testing for the above mentioned study (Gartner Lee Limited 2003b). The Arkell pumping wells and the Eramosa Intake/Arkell Recharge System were used sporadically during these periods and this contributes to deviation in the data prior to 2002.

6. The model simulation used monthly averaged pumping rates for the wells and the Eramosa Intake/Arkell Recharge System which tends to smooth the simulated flow response by lowering the peaks and raising the valleys, as well as shifting the timing of the response slightly.

Given these factors, it is demonstrated that the model reasonably represents the discharge at the Arkell Glen Collector and that the conceptual model for the Arkell area is plausible.

Overall, there is good agreement between the model-simulated response of the groundwater system and the observed response for the municipal water-supply system. The pattern of changes in the Depth to Water levels in the municipal wells and the groundwater discharge at the Arkell Glen Collector is reasonably matched by the model thereby verifying its ability to represent transient stress conditions.

3.5 Calibrated Hydraulic Conductivities

The resulting hydraulic conductivities used in the calibrated City of Guelph Groundwater Flow Model are shown in Table 3-6.

Table 3-6 Calibrated Hydraulic Conductivities

Zone	Conductivity Zone Name	Kx (m/s)	Ky (m/s)	Kz (m/s)
Overburden A and B (Model Layers 1 to 3) – Figures 2-15 and 2-16				
a	Bedrock	3.00E-05	3.00E-05	3.00E-06
b	Clay	5.00E-06	5.00E-06	2.50E-06
c	Gravel	2.00E-04 to 5.00E-04 (no anisotropy)		
d	Hanlon Buried Valley Low K Zone	1.00E-07	1.00E-07	1.00E-08
e	Organic Deposits	5.00E-04	5.00E-04	5.00E-04
f	Port Stanley Till A	1.00E-06	1.00E-06	5.00E-07
g	Port Stanley Till B	1.00E-08	1.00E-08	1.00E-08
h	Sand	1.00E-04 to 5.00E-04 (no anisotropy)		
I	Sand and Gravel	2.50E-04	2.50E-04	2.50E-04
j	Sand and Gravel – Arkell and Torrence Creek	2.50E-03	2.50E-03	1.25E-05
k	Sand and Gravel - Hanlon Buried Valley	5.00E-04	5.00E-04	5.00E-04
l	Silt	1.00E-06	1.00E-06	5.00E-07
m	Tavistock Till	5.00E-06	5.00E-06	2.50E-06
n	Till	1.50E-06	1.50E-06	7.50E-07
o	Till - Arkell	1.00E-06	1.00E-06	5.00E-09
p	Till – Clythe Creek	5.00E-08	5.00E-08	5.00E-08
q	Till - Eastview Area	5.00E-08	5.00E-08	5.00E-08
r	Till - Moffat Moraine	5.00E-06	5.00E-06	2.50E-08
s	Wentworth Till - North	5.00E-05	5.00E-05	2.50E-05
t	Wentworth Till - South	5.00E-05	5.00E-05	2.50E-05
u	Wentworth Till (Weathered) - North	1.00E-05	1.00E-05	5.00E-06
v	Wentworth Till (Weathered) - South	1.00E-04	1.00E-04	5.00E-05
Bedrock (Model Layers 4 to 14) – Figures 2-17 to 2-24				
1	Contact Zone	3.00E-05	3.00E-05	3.00E-06
2	Contact Zone - Hanlon	5.00E-07	5.00E-07	1.00E-08
3	Gravel - Burke Carter Buried Valley	2.30E-03	2.30E-03	2.30E-03
4	Till - Burke Carter Buried Valley	8.00E-04	8.00E-04	8.00E-04
5	Contact Zone - East Cambridge	1.00E-04	1.00E-04	2.74E-05
6	Contact Zone - East Cambridge P10 Area	2.13E-03	2.13E-03	4.80E-05
7	Contact Zone - East Cambridge-G38 and G39 Area	6.55E-04	6.55E-04	6.24E-05
8	Contact Zone - East Cambridge-Pinebush Area	3.19E-03	3.19E-03	2.49E-04
9	Guelph Formation	2.00E-06	2.00E-06	2.00E-07
10	Guelph Formation - Hanlon	5.00E-07	5.00E-07	1.00E-08
11	Guelph Formation - East Cambridge-Southeast	4.29E-06	4.29E-06	2.51E-06
12	Guelph Formation - East Cambridge-West	8.53E-06	8.53E-06	8.53E-07
13	Guelph Formation - East Cambridge-Middle West	1.00E-06	1.00E-06	1.00E-07
14	Guelph Formation - East Cambridge-H4, P10, G5 Area	5.06E-05	5.06E-05	5.06E-07
15	Guelph Formation - East Cambridge-Middle North	1.01E-05	1.01E-05	1.01E-05
16	Guelph Formation - East Cambridge-Elgin St	1.10E-04	1.10E-04	2.90E-05
17	Guelph Formation - East Cambridge-G4 and P6 Area	2.38E-05	2.38E-05	8.45E-07
18	Guelph Formation - East Cambridge-Middleton St Well Field	1.00E-04	1.00E-04	1.00E-05
19	Guelph Formation - East Cambridge	2.00E-06	2.00E-06	1.82E-08
20	Guelph Formation - East Cambridge-Middle South	1.58E-05	1.58E-05	1.58E-05
21	Reformatory Quarry	3.00E-06	3.00E-06	3.00E-08
22	Reformatory Quarry - Hanlon	5.00E-07	5.00E-07	1.00E-08

Zone	Conductivity Zone Name	Kx (m/s)	Ky (m/s)	Kz (m/s)
23	Reformatory Quarry - East Cambridge - Clement Wellfield	1.87E-07	1.87E-07	9.35E-10
24	Reformatory Quarry - East Cambridge	5.30E-06	5.30E-06	5.64E-07
25	Vinemount A - Central	1.00E-07	1.00E-07	1.00E-09
26	Vinemount A - East	5.00E-06	5.00E-06	5.00E-08
27	Vinemount A - West	1.50E-07	1.50E-07	1.50E-09
28	Vinemount - East Cambridge / Goat Island	1.00E-06	1.00E-06	1.00E-07
29	Vinemount - East Cambridge	1.00E-07	1.00E-07	1.00E-09
30	Vinemount - East Cambridge - Thin	1.00E-07	1.00E-07	1.00E-08
31	Goat Island	5.00E-06	5.00E-06	8.33E-08
32	Goat Island - South City	1.00E-06	1.00E-06	1.00E-06
33	Goat Island - East Cambridge - Middle, Clement Mill	1.00E-06	1.00E-06	5.00E-09
34	Goat Island - East Cambridge - West	1.00E-06	1.00E-06	4.48E-07
35	Goat Island - East Cambridge	1.00E-06	1.00E-06	3.58E-08
36	Goat Island - East Cambridge - Central	1.00E-06	1.00E-06	5.07E-07
37	Upper Gasport	2.00E-06	2.00E-06	2.00E-07
38	Upper Gasport - Quarry	1.00E-05	1.00E-05	1.00E-05
39	Upper Gasport - South City	1.00E-06	1.00E-06	1.00E-06
40	Upper Gasport - East Cambridge	6.24E-05	6.24E-05	6.24E-06
41	Upper Gasport - East Cambridge - Central Transition Area	3.54E-06	3.54E-06	3.54E-07
42	Upper Gasport - East Cambridge - Middleton and Willard Area	8.00E-04	8.00E-04	8.00E-05
43	Upper Gasport - East Cambridge - Medium Transition Area	3.00E-05	3.00E-05	3.00E-06
44	Upper Gasport - East Cambridge - Low to Medium T	5.00E-06	5.00E-06	5.00E-07
45	Upper Gasport - East Cambridge - Low T	2.20E-06	2.20E-06	2.20E-07
46	Upper Gasport - East Cambridge - G18	1.96E-05	1.96E-05	1.96E-06
47	Upper Gasport - East Cambridge - P17, P11	3.54E-07	3.54E-07	3.54E-08
48	Middle Gasport A - Regional	8.00E-05	8.00E-05	4.00E-05
49	Middle Gasport B - Northwest - Sacco/Smallfield	1.50E-04	1.50E-04	1.50E-04
50	Middle Gasport C - North - Emma/EdinburghN/Guelph Lake	7.50E-05	7.50E-05	7.50E-05
51	Middle Gasport D - North - Helmar	3.00E-04	3.00E-04	3.00E-04
52	Middle Gasport E - Northwest Inner	1.50E-04	1.50E-04	1.50E-04
53	Middle Gasport F - North City - Park	3.15E-04	3.15E-04	3.15E-04
54	Middle Gasport G - Northwest City - Hauser/Calico	7.50E-05	7.50E-05	7.50E-05
55	Middle Gasport H - City Centre	5.00E-04	5.00E-04	5.00E-04
56	Middle Gasport I - East City - Scout Camp	3.00E-03	3.00E-03	3.00E-03
57	Middle Gasport J – Arkell	3.56E-03	3.56E-03	3.56E-03
58	Middle Gasport K - East – Carter	4.50E-04	4.50E-04	4.50E-04
59	Middle Gasport L – Quarry	5.00E-04	7.00E-04	7.00E-04
60	Middle Gasport M - South City - Downey/Ironwood/Steffler	5.00E-04	2.20E-03	2.20E-03
61	Middle Gasport N - Southeast - Burke/McCurdy	1.00E-06	1.00E-06	1.00E-06
62	Middle Gasport O – South	5.00E-04	4.00E-04	4.00E-04
63	Middle Gasport - East Cambridge - Central Transition Area	1.00E-04	1.00E-04	1.00E-05
64	Middle Gasport - East Cambridge	5.00E-04	5.00E-04	5.00E-05
65	Middle Gasport - East Cambridge - Lower K	1.00E-06	1.00E-06	1.00E-07
66	Lower Gasport	2.00E-06	2.00E-06	2.00E-08
67	Lower Gasport - South City	1.00E-06	1.00E-06	1.00E-06
68	Cabot Head	1.00E-10	1.00E-10	1.00E-12

Table 3-7 compares the range of the calibrated bedrock conductivities with the hydraulic conductivity from bedrock hydraulic tests completed within individual formations at boreholes with high level of geologic control/reliability. In general the calibrated values for hydraulic conductivity lie within the range of field results for each of the bedrock formations as well as the range of values used in previous studies (see Table 5.0 in Appendix A: Characterization Report [Golder 2011]).

Table 3-7 Ranges of Model Calibrated Hydraulic Conductivity vs. Field Test Results

Unit Description	Calibrated Horizontal Hydraulic Conductivity (m/s)	Calibrated Vertical Hydraulic Conductivity (m/s)	High Quality Bedrock Borehole Test Results Horizontal Hydraulic Conductivity (m/s)[1]			
			No. of Tests	Min	Max	50th percentile
Guelph Formation	1.0e-6 to 1.0e-4	1.8e-8 to 2.9e-5	13	4.E-07	6.E-04	4.E-06
Eramosa Formation - Reformatory Quarry Member	5.0e-7 to 5.3e-6	1.0e-8 to 5.6e-7	15	2.E-07	2.E-04	3.E-06
Eramosa Formation - Vinemount Member	1.0e-7 to 5.0e-6	1.0e-9 to 5.0e-8	7	5.E-07	3.E-05	5.E-06
Goat Island Formation	1.0e-6 to 8.0e-5	8.3e-8 to 4.0e-5	13	9.E-08	4.E-04	5.E-06
Upper Gasport Formation[2]	1.0e-6 to 1.0e-5	2.0e-7 to 1.0e-5	45	2.E-08	5.E-04	5.E-06
Middle Gasport Formation[3]	1.0e-6 to 3.6e-3	1.0e-6 to 3.6e-3	26	2.E-06	1.E-02	2.E-04
Lower Gasport Formation[2]	2.0e-6	2.0e-8	45	2.E-08	5.E-04	5.E-06

1 Field Test Results are taken from Table 5 of Appendix A: Characterization Report
2 Field Test Results correspond to "Gasport (outside high permeability zones)" shown on Table 5 of Appendix A: Characterization Report
3 Field Test Results correspond to "Gasport (within high permeability zones)" shown on Table 5 of Appendix A: Characterization Report

3.6 Calibration Results

This section summarizes the results of the calibrated model. From these results, it is concluded that the model is suitably calibrated as follows:

- Qualitatively, the simulated groundwater level contours and vertical hydraulic gradients are consistent with the conceptual model;
- Regionally, the error based on the difference between observed and simulated water levels is minimized and there are no spatial trends in this error that are expected to impact predictions;
- Locally within the City of Guelph, the simulated heads at most of the high-quality observation wells are close to observed values; and
- Simulated groundwater discharge rates agree favourably with the majority of the baseflow estimates.

3.6.1 Qualitative Model Results

The following section outlines the model predicted water levels in the overburden and the potentiometric surface in shallow and deep bedrock aquifers across the Study Area. These maps are compared and contrasted with the observed water level maps produced by contouring the water levels reported in the MOE water wells as well as the high-quality monitoring and observation wells.

3.6.1.1 *Water Table*

Figure 3-10 illustrates the water table surface simulated by the calibrated steady-state groundwater flow model. The water table generally mimics the ground surface topography and is strongly influenced by surface water features. The shallow groundwater divide along the boundary with the Credit River watershed generally coincides with the surface water divide. The shallow groundwater divide along the Grand River Watershed boundary south of Mill Creek is not coincident with the surface water boundary and this is consistent with previous modelling efforts and interpretations.

Figure 3-11 illustrates the simulated water table surface in the vicinity of the City of Guelph. This figure illustrates the significant impact of surface water features on shallow groundwater within the City of Guelph. The effects of the Glen Collector System in the Arkell Spring Grounds can be observed on Figure 3-11 where the water table contours are influenced by both the injection and collection of water.

3.6.1.2 *Shallow Bedrock (Contact Zone)*

Figure 3-12 and Figure 3-13 illustrate the predicted steady-state potentiometric surface in the Contact Zone (Slice 5 located at the bottom of Layer 4 - Contact Zone) for the entire Study Area and within the City of Guelph, respectively. In general, the shallow bedrock potentiometric surface is very similar to the water table surface, except that the contours are slightly smoother due to the shallow bedrock system being slightly less sensitive to surface water features.

3.6.1.3 *Gasport Aquifer*

Figure 3-14 and Figure 3-15 illustrate the predicted steady-state potentiometric surface in the Middle Gasport Layer (i.e., Slice 12 – Top of Layer 12) for the entire Study Area and within the City of Guelph, respectively. In general, the groundwater divide in the Gasport Aquifer appears to follow the surface water divide between the Grand River and Credit River watersheds. This is not the case along the divide between Grand River watershed and the Hamilton Region Conservation Authority to the south.

As shown on Figure 3-14, the deeper aquifer is influenced by some of the regional groundwater discharge features (i.e., the Eramosa River and Blue Springs Creek) where ground surface topography is incised into the deeper bedrock system. There is very little influence by smaller streams. In general, the simulated potentiometric surface contours generally compare well with the observed deep aquifer potentiometric surface contours illustrated on Figure 2-9.

Within the City of Guelph (Figure 3-15) there appears to be limited interaction between the deep aquifer and surface water bodies, although interaction can be seen along the Eramosa River and Blue Springs Creek upstream of the Arkell Spring Grounds. The effects of municipal and non-municipal wells pumping from the Gasport aquifer can be seen where depressions in the potentiometric surface are evident around not only various well fields, but through the middle of the City of Guelph's higher permeability aquifer zones.

3.6.1.4 *Vertical Hydraulic Gradient*

Figure 3-16 illustrates the model-predicted hydraulic head difference between the Contact Zone (Slice 5) and Gasport (Slice 12) layers. The map is shaded to highlight areas having the strongest upwards (green) and downwards (dark blue) directed bedrock gradients. The figure also shows the interpreted extent of the Vinemount aquitard. Within this area the aquitard would impede the flow of groundwater even in the presence of a strong vertical gradient. Vertical head differences to the east of the Vinemount aquitard boundary are minimal given that the Gasport aquifer is generally present at the top of bedrock.

In general, the map illustrates that there are small downwards gradients into the Gasport Formation across a large amount of the Study area, and that there are upwards gradients in the vicinity of surface water features. The largest head differences are highlighted as dark blue and correspond to those areas in the Gasport Aquifer which experience significant drawdown due to the municipal supply wells.

3.6.2 <u>Quantitative Model Results</u>

The following sections outline the calibration of the model from a quantitative perspective. In general, the model-predicted water levels fall within a reasonable margin of error from the observed water levels. Furthermore, the model-predicted discharge to streams is consistent with baseflow estimates.

3.6.2.1 *Hydraulic Head Scatter Plots*

The steady-state calibration involved comparing simulated hydraulic heads against those measured in high-quality monitoring wells and with static water levels reported in the MOE water well records.

Scatter plots (Figure 3-17 to Figure 3-20) are used to visualize the goodness-of-fit for hydraulic head targets with model-simulated heads plotted on the vertical axes, and observed hydraulic heads plotted on the horizontal axes. The lines corresponding to an exact match are 45-degree lines going through the origin of the plots (1:1 lines). Deviations of ±10 m and ±20 m are shown on the plots as parallel lines offset from the 1:1 lines. As an example, points falling outside of the ±20 deviation lines represent observation locations where the simulated hydraulic head differs from the observed value by more than 20 m. This difference may be due to model error, assumptions in the conceptual model, or may also be due to errors associated with the field-observed data itself.

Overall, the scatter plots for the various subsets of calibration targets illustrate that the groundwater calibration error is generally distributed above and below the 1:1 lines, and there is no strong bias towards over-estimating or under-estimating groundwater levels. These trends appear to be consistent throughout the targets with the range in scatter being constant across the range of observed water levels.

3.6.2.2 *Calibration Statistics – Hydraulic Heads*

Table 3-8 lists calibration statistics that are computed as measures of the goodness of fit between model-simulated and observed hydraulic heads. The scatter plots (Figure 3-17 to Figure 3-20) can be referenced to help visualize the statistics. These statistics are computed for various subsets of the complete calibration dataset as follows:

1. All Targets - this dataset includes all high-quality wells and MOE Water Well Records;

2. All Targets Above Vinemount - this dataset includes all high-quality wells and MOE Water Well Records with an estimated measurement location in overburden and shallow bedrock (i.e., Model Layers 1 to 6);

3. All Targets Below Vinemount - this dataset includes all high-quality wells and MOE Water Well Records with an estimated measurement location below the Vinemount aquitard (i.e., Model Layers 10 to 14);

4. MOE Water Well Records - this dataset includes only MOE Water Well Records; and

5. High-Quality Wells - this dataset includes only high-quality observation data.

Table 3-8 Hydraulic Head Calibration Statistics

Calibration Statistic	All Targets (1)	All Targets Above Vinemount (2)	All Targets Below Vinemount (3)	MOE Water Well Records (4)	High-Quality Wells (5)
Number of Calibration Targets	11,041	5,447	5,059	10,643	398
Mean Error (ME)	-0.17 m	-0.57 m	0.39 m	-0.13 m	-1.0 m
Mean Absolute Error (MAE)	4.2 m	3.9 m	4.4 m	4.2 m	2.7 m
Root Mean Squared Error (RMS)	5.6 m	5.4 m	5.9 m	5.7 m	4.0 m
Normalized Root Mean Squared Error (NRMS)	2.1%	2.0%	2.3%	2.1%	2.8%
Range in Observed Water Levels	266.3 m	266.3 m	259.7 m	266.3 m	143.6 m

The calibration statistics, as listed in the above table, are discussed in the following subsections.

Mean Error (ME)

The Mean Error (ME) is a measure of whether, on average, simulated water levels are higher or lower than those observed. Ideally, the ME should be as close as possible to zero. This statistic indicates that on average, for all the targets (Subset 1), the simulated water levels are lower than the observed values by 0.17 m. The ME indicates that on average the simulated water levels above the Vinemount (Subset 2) are underestimating observed values by 0.57 m. For targets below the Vinemount (Subset 3), on average, the numerical model is overestimating hydraulic heads by 0.39 m. Using just MOE targets (Subset 4), simulated heads are an average of 0.13 m lower than the targets.

For the high-quality wells alone (Subset 5), on average, the numerical model is underestimating hydraulic heads by 1.0 m. However, this error is small given the amount of drawdown due to pumping in the Gasport aquifer.

Mean Absolute Error (MAE)

The Mean Absolute Error (MAE) is a measure of the average deviation between simulated and observed water levels. During model calibration, this statistic should be minimized as much as possible. The numerical model produces simulated heads for all the targets that have a MAE of 4.2 m with similar values for the other subsets that include the MOE wells.

The MAE for the high-quality wells is 2.7 m, which is better than for the entire calibration dataset. It is expected that this statistic should be lower for high-quality data given the greater certainty of these water level measurements.

Root Mean Squared Error (RMSE)

The Root Mean Squared Error (RMSE) is similar to standard deviation in providing a measure of the degree of scatter about the 1:1 line. The RMSE is calculated by averaging the squares of each residual error and then taking the square root of that average. In squaring the residual errors, the RMSE gives higher weighting to larger residuals. When compared to the Mean Absolute Error (MAE), the greater the difference between the MAE and the RMSE (which will always be equal or greater than the MAE), the greater the variance in the individual residuals. Based on professional experience, it is generally not possible to achieve a RMSE less than 5 m when using water well record data, as this amount of error may be due to limitations of the dataset including inaccuracies in well elevation, well location, and water level measurements. Lower values of RMSE are typically sought after for high-quality data, and the statistics achieved may be a reflection of several factors including: the complexity and suitability of the conceptual model, seasonal water level and pumping fluctuations, and model error.

For the complete target dataset, the model has a RMSE of 5.6 m meaning that the majority of predicted water levels would fall within 5.6 m of the observed value. The error is similar for the other datasets that include the MOE wells. For the calibration targets above the Vinemount, the simulated heads have a RMSE of 5.4 m. The wells below the Vinemount have an RMSE of 5.9 m and thus show a slightly greater variance in the individual residuals than those above the Vinemount.

High-quality wells have an RMSE of 4.0 m and this is within an acceptable range considering the complexity of hydrogeological system in and around the City of Guelph and the amount of drawdown due to municipal pumping.

Normalized Root Mean Squared Error (NRMSE)

The Normalized Root Mean Squared Error (NRMSE) is calculated by dividing the Root Mean Squared Error (RMSE) by the maximum range in observed water level elevations. This percentage value allows the goodness-of-fit in one model to be compared to another model regardless of the scale of the model.

The NRMSE for the current model considering all calibration targets is 2.1% which is very good based on professional experience with other nearby modelling studies. In comparison, the same statistic calculated for the Guelph-Puslinch Groundwater Flow Model (Golder 2006a) was 2.9%, which demonstrates the impact of improvements made in the current model.

The NRMSE for high-quality wells is 2.8% which is also very good.

3.6.2.3 *Spatial Maps of Residuals*

Plotting the residual errors (i.e., differences between simulated and observed water levels) on a map illustrates the spatial distribution of the calibration results, highlighting spatial trends where the model may be overestimating or underestimating groundwater levels. Figure 3-21 and Figure 3-22 illustrate the residuals for the calibration targets in Layers 1 to 6 and 10 to 14, respectively. On these figures, the size of each point represents the magnitude of the error. Orange points denote targets where water levels are overestimated, and blue points denote targets where water levels are underestimated.

Ideally, a well-calibrated model should have a random distribution of error across the model domain and these spatial distribution plots should display a random distribution of small points with blue and orange points appearing together. In reality, a model developed at the scale of the City of Guelph Groundwater Flow Model will have areas where the conceptual model is less representative of actual conditions and this will translate into regions where there are a higher proportion of calibration targets that are under- or overestimated.

Maps of residuals can sometimes be misleading with areas that appear to have a high proportion of targets that are over- or underestimated. The size of those points may be large and misrepresent the fact that there may be an equivalent number of points in the area that are smaller representing a well-calibrated area. As discussed earlier, because of their number, water well records offer a tremendous benefit in developing a regional conceptual model and understanding the regional hydrogeological flow system. However, there are many sources of error associated with these data. Additionally, there may be highly localized variances in the geology and hydrogeology that cannot be either interpreted or reflected in the groundwater flow model.

As illustrated on Figure 3-21, a high proportion of calibration targets in the west of the Study Area are screened in the shallow bedrock above Vinemount the layers. Where the Gasport Formation and other deep bedrock aquifers subcrop east of the City of Guelph, there is a higher proportion of water wells screened in the deeper bedrock layers (Figure 3-22).

With respect to those targets above Vinemount (Figure 3-21), spatial trends can be observed as follows:

- Water levels in the southwest corner of the domain around Cambridge are underestimated shown by a concentration of larger blue points. Bedrock in this area is pumped extensively by the Region of Waterloo and further calibration effort would be needed to achieve better results.

- There appear to be a wide range of over-predicted and under-predicted water levels in the Galt and Paris Moraine areas south-east of the City of Guelph. This may be due to the variable hummocky topography and complex shallow hydrogeology associated with the moraines.

With respect the targets below the Vinemount, which are mainly in the Gasport Formation, Figure 3-22 illustrates some different trends as follows:

- There are trends of overestimated and underestimated water levels in the Credit River Watershed and along the Niagara Escarpment. It is noted that the Gasport Formation is represented in the model as a hydrostratigraphic unit with constant hydraulic properties throughout the entire area and the presence of trends may be due to that simplification.

- While there are no significantly large spatial trends near the City of Guelph, the model over predicts heads in these areas show be the concentration of orange points: along a section of the Upper Speed River north of Guelph Lake; near the headwaters of Blue Springs Creek; within the Credit

River Watershed; and in the topographic highs near Hillsburgh. All of these areas are relatively small and should not negatively affect the model results at a regional scale or within the City of Guelph.

Figure 3-23 is a map of residuals for the high-quality wells. As illustrated on this figure, the calibration residuals are smallest in the areas surrounding Arkell Springs and the Southwest Quadrant suggesting that those areas within the City of Guelph have the best calibration. This is expected as those areas within the City of Guelph have received the most attention in terms of groundwater monitoring, testing, and characterization.

Groundwater levels in the Northeast Quadrant are underestimated, and this may be due to the conceptual model applied in the area as previously discussed in Section 3.3.4. Although the monitoring network in other areas of the City of Guelph is sparse, the residuals where observation data exists do suggest that groundwater levels are underestimated elsewhere in the Gasport aquifer. This may be a reflection of the uncharacterized aspects of the fractured rock aquifer that are not represented in the model and the potential for groundwater to be leaking into the aquifer through the Vinemount aquitard. Calibration is generally better in the overburden and shallow bedrock.

3.6.2.4 *Baseflow*

In addition to calibrating against hydraulic head targets, the model's prediction of groundwater discharge to surface water features was compared with baseflow calibration targets. A match between simulated and observed flows is critical to ensure that groundwater recharge rates are reasonable, and to provide validation for future water budget estimates.

As discussed previously, two sets of baseflow calibration targets were developed from continuous stream gauges and from spotflow measurements. Figure 3-4 shows the locations of all baseflow calibration targets and the subwatersheds associated with the measurements. These targets are listed in Table 3-2 above.

Figure 3-24 shows the model-simulated groundwater discharge rates in relation to the estimated range of baseflow measurements for 22 monitoring locations within larger subwatersheds. As illustrated on the chart, there is a broad range of stream baseflow targets (grey bars) which reflects the range of baseflow estimates collected, and also the uncertainty associated with baseflow separation estimates from the continuous stream gauges. The blue squares on the graph represent the model-simulated groundwater discharge rates along the stream or river reach. Figure 3-25 compares the model simulated groundwater discharge rates with the baseflow targets for 24 monitoring locations within smaller subwatersheds.

For the larger subwatersheds (Figure 3-24), model predictions of groundwater discharge nearly all fall within the estimated range of values. Groundwater flow to these larger surface water features is influenced by regional conditions, and the match between observed and simulated values suggests that groundwater recharge rates applied on the model are reasonable.

For the smaller subwatersheds (Figure 3-25), model predictions of groundwater discharge are generally consistent with observations, but there are some inconsistencies. For these smaller streams, there is less certainty that baseflow measurements reflect average annual conditions. In addition, there is greater likelihood that baseflow is influenced by smaller-scale hydrogeologic features not included in the model, or that the regional hydrogeologic model is less representative of that area. Most importantly, the baseflow associated with those small features may be outside of the precision of the model.

Baseflow calibration for the larger subwatersheds is discussed below:

- Blue Springs Creek - Blue Springs Creek is incised into the Gasport Aquifer and is a regional groundwater discharge feature. Simulated groundwater discharge agrees very favourably with estimated baseflow range. In particular, the simulated groundwater discharge at Water Survey of Canada Gauge 2GA031 (WSC Blue Springs Ck near Eden Mills) agrees very well with the reliable baseflow estimated from continuous streamflow data.

- Eramosa River - Similar to Blue Springs Creek, the Eramosa River is a regional groundwater discharge feature, and after its confluence with Blue Springs Creek, represents the drainage area of a large proportion of the study area. Simulated groundwater discharge is within the estimated range.

- Mill Creek - Simulated groundwater discharge into Mill Creek is consistent with estimated values. On Figure 3-24, the simulated discharge at Water Survey of Canada Gauge 2GAC19 (GRCA Mill Ck at SR 10) is lower than the estimated range based on baseflow separation, but there are concerns that ice jamming at this gauge results in over-prediction of baseflow.

- Speed River - Simulated groundwater discharge into the Speed River is in the high end of the estimated range at most of the spot flow locations. However, these ranges are only based on three spot flow measurements and may not be indicative of average annual baseflows. For the two gauges, simulated discharge is with the estimated range of baseflow.

Baseflow calibration to the smaller subwatersheds is generally very good. There are fewer baseflow measurements for most of these streams and more variability due potentially to local hydrogeologic conditions not represented in the conceptual model. This is most evident for Hopewell Creek where the absence of the Vinemount aquitard in this area results in a discharge of excessive volumes of water. During model calibration, recharge and hydrogeologic parameters were adjusted within the range supported by the conceptual model. Although these adjustments succeeded in reducing the discharge estimates, the final results remain slightly higher than the calibration range.

3.6.3 Parameter Sensitivity – PEST Results

As described previously, the steady-state model calibration for the groundwater flow model was assisted through the use of PEST v.12 (Doherty 2010). PEST (Parameter ESTimation) was used to help optimize the hydraulic conductivity parameters in the model, whereby PEST conducts a series of model runs where each model parameter is adjusted one at a time to determine the sensitivity of each of the parameters within the model. The sensitivity of a parameter (such as hydraulic conductivity) refers to how sensitive the model calibration is to a change in the parameter value. After completion, the calibration sensitivity provides insight into the parameterization of the model and identifies:

- the parameter values that are well-supported by field observations;
- the parameters that can be estimated using automated parameter estimation routines (e.g., PEST) to optimize model calibration;
- the relative influence of each parameter in model calibration; and

- the potential for new observations to improve the estimation of a parameter.

The "single-parameter sensitivity analysis" approach used in this study involves undertaking multiple simulations whereby each model input parameter (hydraulic conductivity or recharge) is modified one at a time from the base case representation. The model is re-run and the simulation output (e.g., head or discharge) is compared to the base case. As shown in Equation 1, a sensitivity value is calculated for each observation target with respect to each input parameter.

Equation 1: Calculation of sensitivity

$$Sensitivity\ of\ H_i\ with\ respect\ to\ K_j = \left(\frac{\mathrm{H}_{base.i} - \mathrm{H}_i}{\mathrm{K}_{base.j} - \mathrm{K}_j}\right) * \mathrm{K}_{base.j}$$

Where H_i = the simulated value of the *i*th Observation

K_j = the *j*th Parameter

$H_{base.i}$ = the base case simulated value of the *i*th Observation

$K_{base.j}$ = the base case value of the *j*th Parameter

The goal of the sensitivity analysis is to identify those parameters that have the largest influence on the simulations and to evaluate the observation data that is available to constrain/estimate that parameter. The normalized sensitivity coefficient (NSC) is a useful measure of parameter sensitivity output by PEST. The NSC is a dimensionless positive number, whose value indicates the relative importance of a model parameter on the model, that is, the relative sensitivity of the particular model output with respect to the changing of the particular model parameter.

Table 3-9 summarizes the NSC's for each of the hydraulic conductivity zones in the model based solely on the City of Guelph High-quality calibration targets. The data are summarized by listing the maximum normalized sensitivity coefficient and the square root of the mean of the squares (RMS) for the normalized sensitivity coefficients for three groups of targets. The RMS provides a measure of the degree of spread of the normalized sensitivity coefficients calculated in each zone and weights the largest coefficients more through squaring the NSC.

In the table, results shaded in grey indicate a zone where the RMS of the normalized sensitivity coefficient and/or the maximum NSC is greater than 5 and less than 10. Results shaded in grey with the value bold and underlined have a RMS and/or maximum of the normalized sensitivity coefficient greater than 10. These thresholds were selected only to illustrate those parameters having the highest normalized sensitivity coefficient.

Table 3-9 Normalized Sensitivity Coefficient for High-Quality Calibration Target Groups

Param	Description	Arkell Springs		Above Vinemount		Below Vinemount	
		RMS	Max NSC	RMS	Max NSC	RMS	Max NSC
100	Global Recharge	6.9	**<u>13.2</u>**	8.6	**<u>18.6</u>**	6.4	**<u>15.1</u>**
10050	Overburden A Organic Deposits	0.6	1.1	1.7	6.5	1.9	6.4

Param	Description	Arkell Springs		Above Vinemount		Below Vinemount	
		RMS	Max NSC	RMS	Max NSC	RMS	Max NSC
10100	Overburden A Sand	8.0	**25.8**	2.8	**20.3**	2.1	4.4
10110	Overburden A Sand	0.2	0.6	4.3	**14.7**	2.4	6.5
10200	Overburden A Gravel	1.5	1.8	2.3	**14.4**	2.1	7.8
10210	Overburden A Gravel	2.6	3.0	6.6	**30.8**	3.7	**11.5**
10215	Overburden A Gravel	1.6	2.8	3.4	**16.8**	2.0	4.6
10220	Overburden A Gravel	0.9	1.1	0.9	2.6	1.7	9.9
10230	Overburden A Gravel	6.3	7.9	5.1	**16.3**	7.4	**16.1**
10240	Overburden A Gravel	1.3	1.7	1.3	4.2	1.7	3.2
10300	Overburden A - Silt	2.8	3.6	2.9	8.3	3.7	7.9
10500	Overburden A - Till	0.4	0.5	0.4	1.1	0.5	1.0
10505	Overburden A - Tavistock Till	2.2	2.8	2.3	6.3	3.0	6.9
10550	Overburden A - Port Stanley Till A	3.6	4.6	3.1	**12.2**	3.7	9.2
10555	Overburden A - Port Stanley Till B	1.1	1.4	2.0	**13.7**	1.9	6.8
10557	Overburden A - Till – Eastview Area	5.1	6.4	5.1	**17.0**	6.8	**11.9**
10575	Overburden A - Wentworth Till – (Weathered) South	4.0	**14.6**	5.1	**21.5**	4.5	**11.9**
10576	Overburden A - Wentworth Till (Upper) North	9.0	**11.3**	7.4	**23.4**	**10.7**	**23.1**
10600	Overburden A - Clay	0.9	1.1	1.0	2.7	1.2	2.5
10815	Overburden A - Gravel - Hanlon Torrence Creeks	**18.4**	**56.5**	**12.6**	**26.5**	3.0	6.4
10830	Overburden A - Till - Moffat Moraine	0.8	1.1	0.9	2.3	1.1	2.2
10840	Overburden A - Till – Arkell Area	8.1	**10.1**	7.3	**20.6**	**10.1**	**19.7**
10998	Overburden A - Hanlon Buried Valley Low K Zone	0.3	0.4	2.2	**19.0**	0.3	0.9
10999	Overburden A - Sand and Gravel -Hanlon Buried Valley	6.9	8.7	5.7	**18.0**	8.0	**17.6**
20400	Overburden B - Hanlon Area Sand and Gravel	5.3	6.6	4.2	**12.8**	6.3	**12.6**
20450	Overburden B - Sand and Gravel Hanlon Buried Valley	0.5	0.7	2.5	**10.2**	0.8	1.7
20460	Overburden B - Hanlon Buried Valley Low K Zone	8.0	9.9	7.1	**20.1**	9.9	**19.4**
20575	Overburden B - Wentworth Till – South	2.6	8.1	4.1	**16.9**	4.3	**13.1**
20576	Overburden B - Wentworth Till – North	2.4	3.0	2.4	7.5	3.0	5.4
20815	Overburden B - Till - Eramosa River Area	4.8	6.0	4.3	**12.7**	5.8	**10.8**
30400	Contact Zone	6.1	**11.0**	**10.5**	**65.5**	8.2	**27.1**
30440	Contact Zone – Hanlon	0.4	0.5	2.1	**15.3**	0.6	1.0
30460	Contact Zone - Burke Carter Buried Valley	4.7	6.0	3.6	**20.7**	5.7	**26.0**
30470	Contact Zone – East Cambridge Wells	0.0	0.1	0.1	0.2	0.1	0.4
40000	Guelph Formation	4.2	5.3	4.8	**19.0**	5.4	**10.3**
40040	Guelph Formation – Hanlon	1.2	1.6	2.2	**11.0**	1.6	3.5
50000	Reformatory Quarry	0.8	2.0	3.0	**19.5**	1.1	3.7
50040	Reformatory Quarry – Hanlon	5.3	6.7	5.0	**15.5**	6.8	**12.4**
50060	Till - Burke Carter Buried Valley in RQ and GF	4.9	6.2	3.6	**11.8**	5.7	**12.5**
50070	Reformatory Quarry - East Cambridge Well G5	0.3	0.4	0.3	1.0	0.4	0.8
60000	Vinemount A – West	3.3	4.3	2.4	6.7	4.7	**22.7**

Param	Description	Arkell Springs		Above Vinemount		Below Vinemount	
		RMS	Max NSC	RMS	Max NSC	RMS	Max NSC
60010	Vinemount A – East	2.6	3.3	2.4	6.4	3.1	6.8
60050	Vinemount A – Central	29.8	37.1	20.9	92.9	46.6	92.0
90000	Goat Island	4.2	5.0	3.0	25.1	3.8	15.4
90040	Goat Island - Middle Gasport West	0.0	0.0	0.6	4.6	1.2	6.0
90050	Goat Island - South City	1.3	1.6	1.4	3.8	2.0	6.2
100000	Upper Gasport	2.7	5.5	2.5	19.9	3.3	14.5
100040	Upper Gasport - Middle Gasport West	0.8	1.0	1.3	3.4	1.8	3.5
100050	Upper Gasport - South City	1.4	1.8	1.6	4.6	3.8	18.1
100075	Upper Gasport – Quarry	6.9	8.6	4.9	13.2	8.9	20.9
110100	Middle Gasport A – Regional	19.3	24.2	8.1	44.1	22.4	54.4
110302	Middle Gasport I - East City - Scout Camp	2.5	4.7	2.1	6.3	3.3	6.9
110303	Middle Gasport F - North City - Park	0.9	1.1	0.4	1.2	0.7	2.0
110304	Middle Gasport H - City Centre	4.6	6.3	2.6	10.7	7.9	29.5
110305	Middle Gasport L – Quarry	1.9	3.9	3.3	10.9	6.1	14.1
110306	Middle Gasport J – Arkell	2.2	5.5	0.6	1.8	0.8	1.5
110307	Middle Gasport O – South	0.3	0.4	1.6	4.1	6.8	29.2
110308	Middle Gasport K - East – Carter	1.7	3.3	4.7	14.4	8.7	20.0
110309	Middle Gasport G - Northwest City - Hauser/Calico	1.1	1.5	3.4	23.7	8.2	29.8
110310	Middle Gasport N - Southeast - Burke/McCurdy	1.0	1.3	1.2	3.3	2.8	13.5
110313	Middle Gasport C - North - Emma/EdinburghN/Guelph Lake	1.5	2.1	2.0	14.7	5.2	24.2
110314	Middle Gasport B - Northwest - Sacco/Smallfield	2.0	2.6	2.8	21.3	5.7	28.8
110315	Middle Gasport E - Northwest Inner	0.6	0.9	1.4	6.8	2.4	12.2
110316	Middle Gasport D - North - Helmar	1.5	2.0	1.1	3.1	2.1	8.6
110320	Middle Gasport M - South City - Downey/Ironwood/Steffler	1.9	4.4	2.5	8.6	13.5	101.5
110481	Gasport - Duke81	0.4	0.6	0.5	1.4	0.6	1.3
110482	Gasport - Duke82	5.3	6.7	4.4	13.8	6.3	13.6
110483	Gasport - Duke83	3.8	4.7	3.6	11.2	4.8	8.7
110484	Gasport - Duke84	1.6	2.1	1.7	5.2	2.1	3.9
110485	Gasport - Duke85	1.5	2.0	1.7	4.5	2.1	4.8
110486	Gasport - Duke86	8.1	10.1	6.9	20.8	9.8	20.5
110487	Gasport - Duke87	0.6	0.8	0.6	1.7	0.8	1.5
110488	Gasport - Duke88	0.0	0.1	0.1	0.3	0.1	0.4
110490	Gasport - Duke90	1.6	2.0	1.6	4.9	2.0	3.9
110491	Gasport - Duke91	6.5	8.1	5.8	16.7	8.1	16.1
110492	Gasport - Duke92	2.1	2.6	2.1	6.7	2.7	5.0
110493	Gasport - Duke93	0.3	0.3	0.3	0.8	0.4	1.7
110494	Gasport - Duke94	1.7	2.2	1.8	5.0	2.3	5.2
110495	Gasport - Duke95	2.1	2.8	2.3	6.5	3.0	7.0

Param	Description	Arkell Springs		Above Vinemount		Below Vinemount	
		RMS	Max NSC	RMS	Max NSC	RMS	Max NSC
110496	Gasport - Duke96	1.4	1.8	1.4	4.5	1.8	3.4
110498	Gasport - Duke98	1.5	1.9	1.6	4.4	2.0	4.5
110499	Gasport - Duke99	3.7	4.6	3.4	**10.1**	4.7	8.8
120000	Lower Gasport	2.0	2.5	1.4	3.9	2.0	5.1
120050	Lower Gasport - South City	1.6	2.1	1.8	4.9	2.6	8.3

As identified in the above table, some of the most sensitive parameters are as follows:

- Vinemount A – Central. The normalized sensitivity coefficients for each of the groups of targets are most sensitive to the hydraulic conductivity of the Vinemount A – Central zone. This sensitivity was specifically observed when completing the transient calibration in the southeast quadrant, which clearly illustrated that a hydraulic conductivity equal to $1x10^{-9}$ m/s produced the optimal set of hydraulic heads and vertical gradients. The maximum normalized sensitivity coefficients for this unit are greater than 90.

- Middle Gasport A – Regional. The steady-state calibration effort identified the sensitivity of simulated heads, across the model, to the hydraulic conductivity of the Middle Gasport zone outside of the City of Guelph. This high permeability layer is treated as a single hydraulic conductivity zone outside of the City of Guelph and represents a complex and interconnected set of fractures and other secondary permeability through the Gasport Aquifer. The maximum normalized sensitivity coefficients for this unit are greater than 50.

- Contact Zone. The hydraulic conductivity of the Contact Zone throughout much of the model has a significant influence on hydraulic heads in each of the groups of targets. Similar to the Middle Gasport A – Regional zone, the Contact Zone is present across the entire model. While it is treated as a single hydrostratigraphic unit, its composition and hydraulic properties would tend to vary spatially depending on the nature of rock and overburden sediments, and the degree of weathering experienced over time. Similar to the way that the Middle Gasport Unit has been spatially discretized within the City of Guelph, it is expected that additional zonation and parameterization of the Contact Zone would be required for other local assessments within the City of Guelph. The maximum normalized sensitivity coefficients for this unit are greater than 60.

- Overburden A - Gravel – Hanlon/Torrence Creeks. Hydraulic heads in the Arkell Springs area and in high-quality observation points above the Vinemount are relatively sensitive to the hydraulic conductivity of the Overburden A gravels in the Hanlon and Torrence Creek areas. The maximum normalized sensitivity coefficients for this unit are greater than 50.

- Overburden A - Wentworth Till (Upper) North. Hydraulic heads for each of the groups are relatively sensitive to the hydraulic conductivity of the area simulated as Overburden A - Wentworth Till (Upper) North. The hydraulic conductivity of this unit influences hydraulic heads throughout the south of the City of Guelph thus influencing all three sets of targets.

- Overburden A Till – Arkell Area. Hydraulic heads in each of the three groups are relatively sensitive to the hydraulic conductivity of the Overburden A Till – Arkell Area due to it's proximity to a larger number of calibration targets.

- Global Recharge. Hydraulic heads throughout the model are moderately sensitive to groundwater recharge adjustments made across the model.

3.6.4 Groundwater Model Calibration Assessment

Overall, the calibration results show that the model is suitably calibrated for the Tier Three Assessment and that the Model can be used as a tool for prediction of groundwater flow directions and water quantity assessment. Qualitatively, the simulated groundwater level contours and vertical hydraulic gradients are consistent with observed conditions. Regionally, the error based on the difference between observed and simulated water levels is minimized and there are no spatial trends in this error that are expected to impact predictions. Locally within the City of Guelph, the simulated heads at most of the high-quality observation wells are close to observed values and the model accurately predicts the flow system response to stresses due to increased pumping of the Gasport Formation. Transient verification simulations have shown the model is able to represent the shallow and deeper groundwater systems' response to varying recharge and pumping stresses. And finally, simulated groundwater discharge rates agree favourably with a majority of the baseflow estimates.

4.0 REFERENCES

A&A (Acres and Associated). 2002. Hydrogeological Study / Source Water Characterization Assessment, Final report for the City of Guelph.

AECOM Canada Ltd. 2009. Blue Springs Creek – Surface Water Monitoring Report. Draft for discussion Jan 2009. Prepared for the City of Guelph.

AquaResource, Inc. 2007a. Source Water Protection Project – Groundwater Study. Prepared for City of Guelph.

AquaResource, Inc. 2007b. Source Water Protection Project – Surface Water Study. Prepared for City of Guelph.

AquaResource, Inc. 2008. Memorandum - Summer/Fall 2008 Baseflow Monitoring Program Summary. Submitted to the City of Guelph December 2008.

AquaResource, Inc. 2009a. Grand River Watershed – Integrated Water Budget Report.

AquaResource, Inc. 2009b. Integrated Water Budget Report – Tier 2. Credit Valley Source Protection Area

AquaResource, Inc. 2010. City of Guelph Source Protection Project – Vulnerability Report.

Beak Consultants Ltd. 1995. Delineation of the Capture Zone for the Middleton Street Well Field, Cambridge.

Bellamy, S., Boyd, D., Whiteley, H. 2003. *Baseflow Separation Techniques.* Grand River Conservation Authority.

Brunton, F.R. 2009. Update of revisions to the Early Silurian stratigraphy of the Niagara Escarpment: integration of sequence stratigraphy, sedimentology and hydrogeology to delineate hydrogeologic units; in Summary of Field Work and Other Activities 2009, Ontario Geological Survey, Open File Report 6240, p.25-1 to 25-20.

Conestoga Rovers and Associates (CRA). 2008. Geology and Water Resources Assessment Report - Acton Quarry Extension.

Diersch, H.-J. G., 2006. FEFLOW 5.3 – Finite Element Subsurface Flow and Transport Simulation System, User's Manual. WASY GmbH. Berlin, Germany.

Doherty, J. 2010. PEST Model-Independent Parameter Estimation, User Manual: 5th Edition

Duke Engineering and Services (Canada) Inc. 1998. Cambridge Capture Zone Modelling Project - Final Report.

EarthFx. 2009. Simulation of Groundwater Flow in the Vicinity of the Cedarvale Wellfield, Georgetown, Ontario - Model development and calibration report: prepared for the Regional Municipality of Halton - Planning and Public Works.

Earth Tech Canada Inc., Lura Consulting, Lotowater Geoscience Consultants Ltd., C.N. Watson and Associates Ltd. 2007. City of Guelph Water Supply Master Plan. Draft Final Report. Report to the City of Guelph.

Gartner Lee Limited, Jagger Hims Limited and Braun Consulting Engineers. 1999. The City of Guelph Water Supply System Study – Resource Evaluation.

Gartner Lee Limited. 2003a. Guelph-Eramosa Township Groundwater Study, preliminary draft report prepared for Guelph-Eramosa Township and Ontario Ministry of the Environment.

Gartner Lee Limited. 2003b. Arkell Spring Grounds – Groundwater Supply Investigation. Prepared for City of Guelph.

Golder Associates. 2006a. Guelph-Puslinch Groundwater Protection Study. Prepared for the Grand River Conservation Authority.

Golder Associates. 2006b. Wellington County Groundwater Protection Study. Prepared for the Grand River Conservation Authority.

Golder Associates. 2006c. Microbial Contamination Control Plan: Carter Wells, Arkell Glen Collector and Arkell Well PW-1. Final Report for the City of Guelph.

Golder Associates. 2010. City of Guelph Southwest Quadrant Water Supply Class Environmental Assessment – Interim Draft Hydrogeologic Report. Prepared for the City of Guelph, August 2010.

Golder Associates. 2011. Draft Appendix A – Characterization Report, City of Guelph Tier Three Water Budget and Local Water Quantity Risk Assessment.

Grand River Conservation Authority, Conservation Ontario. 2005. Establishing Environmental Flow Requirements for Selected Streams in the Grand River Watershed. Report to the Ontario Ministry of Environment.

Greenhouse, J.P., and Karrow, P.F. 1994. Geological and geophysical studies of buried valleys and their fills near Elora and Rockwood, Ontario. Canadian Journal of Earth Sciences, 31:1838-1848.

Jagger Hims Limited. 1995. Ground Water Resources Study, Northeast Quadrant, City of Guelph, Volume 1.

Jagger Hims Limited. 1998a. Aquifer Performance Evaluation, Northwest Quadrant, City of Guelph, Volume 1.

Jagger Hims Limited. 1998b. Aquifer Performance Evaluation, Southwest Quadrant, City of Guelph, Volume 1.

Jagger Hims Limited. 1998c. Aquifer Performance Evaluation, Southeast Quadrant, City of Guelph, Volume 1.

Johnson, M.D., Armstrong, D.K., Sanford, B.V., Telford, P.G. and Rutka, M.A. 1992. Paleozoic and Mesozoic Geology of Ontario; in Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.905-1008.

Lotowater Ltd. 1997. Study of the Hydrogeology of the Cambridge Area.

MOE. 2001. Groundwater Studies (2001/2002) – Technical Terms of Reference. ISBN 0-7794-2398-4. PIBS 4197e.

MOE. 2008. Clean Water Act, 2006 - Technical Rules: Assessment Report.

MOE. 2006a. ASSESSMENT REPORT: Draft Guidance Module 3, Groundwater Vulnerability Analysis

MOE. 2006b. ASSESSMENT REPORT: Draft Guidance Module 4, Surface Water Vulnerability Analysis

Ontario Geological Survey. 2003. Surficial Geology of Southern Ontario. Ontario Geological Survey, Miscellaneous Release-Data 128.

Resource Management Strategies, Inc. 2009. City of Guelph Water Conservation and Efficiency Strategy Update.

Waterloo Hydrogeologic Inc. 2008. Technical Memorandum Regional Municipality of Waterloo Groundwater Model Calibration Results

Schroeter & Associates. 2004. GAWSER: Guelph All-Weather Sequential-Events Runoff Model, Version 6.5, Training Guide and Reference Manual. Submitted to the Ontario Ministry of Natural Resources and the Grand River Conservation Authority.

Spitz, K., and J. Moreno. 1996. A Practical Guide to Groundwater and Solute Transport Modeling. John Wiley & Sons, Inc. New York, NY.

Totten Sims Hubicki. 1997. Torrance Creek Subwatershed Study – Phase I. Final Characterization Report submitted to the City of Guelph and Grand River Conservation Authority.

US Army Corps of Engineers, Hydrologic Engineering Center. 2002. HEC-RAS River Analysis System – Users Manual.