

BARRIE TIER THREE WATER BUDGET AND LOCAL AREA RISK ASSESSMENT

APPENDIX B: RECHARGE ESTIMATION USING MIKE SHE (COMPANION REPORT)



CITY OF BARRIE TIER THREE RECHARGE ESTIMATION USING MIKE SHE TECHNICAL MEMORANDUM

Report Prepared for:

LAKE SIMCOE REGION CONSERVATION AUTHORITY

Prepared by:

AQUARESOURCE
A Division of
MATRIX SOLUTIONS INC.



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TABLE OF CONTENTS

1.0	OVER	RVIEW	1				
2.0	MIKE	SHE BACKGROUND	1				
3.0	MOD	EL DEVELOPMENT	5				
	3.1	Simulation Period	5				
	3.2	Model Domain and Grid Resolution	6				
	3.3	Climate Data	6				
	3.4	Topography and Drainage	8				
	3.5	River Network	8				
	3.6	Land use	8				
	3.7	Unsaturated zone	9				
	3.8 Saturated Zone						
	3.9	3.9 Pumping Wells					
4.0	MODEL CALIBRATION						
	4.1	4.1 Overview of Calibration Targets and Procedure					
	4.2	4.2 Streamflow Calibration and Verification Results					
		4.2.1 Overview of Calibration and Verification Metrics	16				
		4.2.2 Calibration Results	17				
		4.2.3 Verification Results	21				
	4.3	Groundwater Calibration Results	22				
	4.4	Snow Depth Results	23				
5.0	MOD	MODEL OUTPUT					
	5.1	5.1 Water Budget					
	5.2 Transient Groundwater Recharge Rates						
6.0	SUMI	MARY AND RECOMMENDATIONS	28				
7.0	REFE	REFERENCES					



LIST OF FIGURES

FIGURE 2-1	Process Schematic for MIKE SHE (DHI, 2011a)	2
FIGURE 2-2	Available Computational Methods for Major Processes in MIKE SHE (DHI, 2011a)	
FIGURE 3-1	Simplified Saturated Zone Layer Structure	
FIGURE 3-2	City of Barrie Combined Well System Annual Production Summary (IWC, 2010)	
FIGURE 3-3	Comparison of Average Annual Consumptive Water Use for 2008 and 2009 by Water Use	
	Sector	
FIGURE 4-1	Annual and Monthly Streamflow Depths for Streamflow Calibration Results	
FIGURE 4-2	Daily Streamflow Hydrograph and Ranked Duration Curves for Streamflow Calibration Resu	
FIGURE 4.2	A Clare Clare Control Control	
FIGURE 4-3	Annual Streamflow Depth at Lovers Creek Gauge from 2001-2009	
FIGURE 4-4	Annual and Monthly Streamflow Depths for Streamflow Verification Results	
FIGURE 4-5	Daily Streamflow Hydrograph and Ranked Duration Curve for Streamflow Verification Resul	
FIGURE 4-6	Timeseries of Simulated and Observed Snow Depth measurements	
FIGURE 4-7	Mean Monthly Observed and Simulated Snow Depth for 1998-2009	
FIGURE 5-1	Example of Transient Groundwater Recharge Rates	
	LIST OF MAPS	
MAP 3-1	MIKE SHE Model Domain	
MAP 3-2	Spatial Distribution of Climate Data	
MAP 3-3	5m Digital Elevation Model (DEM)	
MAP 3-4	River Network and Cross Sections	
MAP 3-5	Land Use Class	
MAP 3-6	Soil Classes	
MAP 3-7	Horizontal Hydraulic Conductivity in MIKE SHE Layer 1	
MAP 3-8	Vertical Hydraulic Conductivity in MIKE SHE Layer 1	
MAP 3-9	Boundary Conditions in MIKE SHE Layer 1 and 2	
MAP 3-10	Boundary Conditions in MIKE SHE Layer 3	
MAP 3-11	Subsurface Drainage Subwatershed Boundaries	
MAP 3-12	Modelled Pumping Wells	
MAP 4-1	Calibration Targets	
MAP 4-2	Simulated Groundwater Level Contours	
MAP 4-3	Observed Groundwater Level Contours	
MAP 5-1	Simulated Average Annual Groundwater Recharge	
MAP 5-2	Simulated Average Annual Evapotranspiration	
MAP 5-3	Simulated Average Annual Groundwater Discharge	
	LIST OF TABLES	
TABLE 2-1	Hydrologic Process Approximations in Barrie Tier Three Model	
TABLE 3-1	Time periods used for MIKE SHE modelling	
TABLE 3-2	Summary of Climate Input Data for 1990-2005 Period	7



TABLE 3-3	Summary of Climate Data for 2006-2009 Period	7
TABLE 3-4	Vegetation Parameters for Land Use Classes in MIKE SHE Model	9
TABLE 3-5	Land Use Classes and Parameters	9
TABLE 3-6	Calibrated Soil Parameters	10
TABLE 3-7	MIKE SHE Saturated Zone Horizontal (Kx) and Vertical (Kz) Hydraulic Conductivit to FEFLOW	
TABLE 4-1	Streamflow Monitoring Gauges and Calibration Targets	15
TABLE 4-2	R ² and Nash-Sutcliffe Coefficients for Comparison of Monthly Streamflow for Cal	libration Period
		21
TABLE 4-3	Groundwater Performance Statistics	23
TABLE 5-1	Overall Mean Annual Water Budget of MIKE SHE Model (1990-2009)	25
TABLE 5-2	Summary of Key Hydrologic Processes by Soil Class (1990-2009)	26
TABLE 5-3	Definition of Key Hydrologic Processes in MIKE SHE	27

APPENDIX

APPENDIX B1 Modelled Pumping Rates



1.0 OVERVIEW

This letter report documents the processes that were undertaken to develop groundwater recharge estimates for the City of Barrie Tier Three Study Area.

Groundwater recharge is defined as water which infiltrates into the upper soil zone, and percolates downward past the vegetative rooting zone. Once past the vegetative rooting zone, where evaporative losses occur, the remaining water will continue moving downwards until it reaches the saturated zone and enters the groundwater flow system. A groundwater recharge map illustrates the spatial distribution and amount of water entering the groundwater flow system over a given region and is typically expressed as an average annual depth over an area (mm/yr). The amount and timing of groundwater recharge is dependent on a number of factors, including: precipitation, surficial geology, soil moisture conditions, and evapotranspiration. Accurately estimating groundwater recharge requires the characterization and consideration of all major hydrologic processes.

For the City of Barrie Tier Three study, groundwater recharge was estimated by building and calibrating an integrated model using MIKE SHE (DHI 2011a, b). The groundwater recharge estimates were used as input to the three-dimensional groundwater flow model utilized in the Tier Three Local Area Risk Assessment. This memorandum outlines the methodology used to construct and calibrate the MIKE SHE model and subsequently create the groundwater recharge map. The memorandum contains the following sections:

- 1. **Overview.** This section provides an overview of the memo contents.
- 2. **MIKE SHE Background.** This section includes a brief description of the MIKE SHE modelling software and how it represents the hydrologic cycle.
- 3. **Model Construction.** This section provides details on all model input data and the parameters used to describe the physical system.
- 4. **Model Calibration.** This section describes the calibration and verification procedures and results.
- 5. **Model Output.** This section presents the results of the modelling exercise, including the annual average water budget and the spatial distribution of the simulated groundwater recharge.
- 6. **Summary and Recommendations.** This section provides a brief summary of the memorandum as well as recommendations as they pertain to the groundwater recharge estimates.

2.0 MIKE SHE BACKGROUND

MIKE SHE is a distributed hydrologic model that provides physically-based representations of the hydrologic cycle. It is an extension of the Systéme Hydrologique Européen (SHE) model and is maintained and distributed by DHI. The process schematic for MIKE SHE is shown in Figure 2-1. All land-based phases of the hydrologic cycle, including precipitation, overland flow, unsaturated flow, and saturated flow are calculated on the same (uniform) grid basis. Channel routing is the exception, for which MIKE SHE links to MIKE-11, a 1-D hydraulic model.



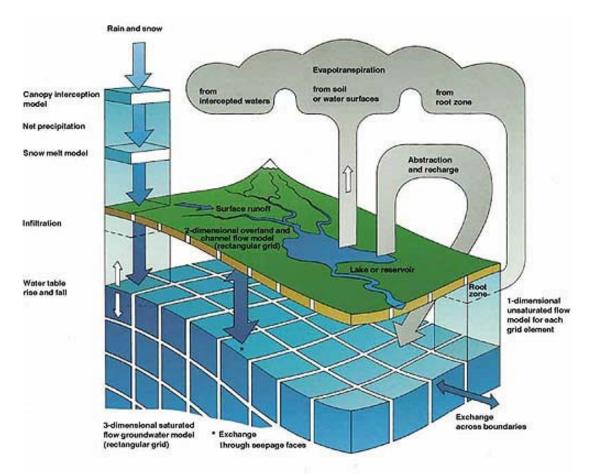


FIGURE 2-1 Process Schematic for MIKE SHE (DHI, 2011a)

MIKE SHE offers the flexibility to implement complex or simple approximations to hydrologic processes, as shown in Figure 2-2. The method selection depends on the main purpose or goal of the model and the availability of input data. This flexibility allows the modeller to operate the model with the minimum degree of complexity needed to accurately reproduce the behaviour of the system of interest. For example, if the main goal of the model is to produce groundwater recharge estimates, the modeller can select simple approximations for processes such as channel routing and complex approximations for saturated zone processes that simulate groundwater-surface water interaction. The methods selected for the Barrie Tier Three model are summarized in Table 2-1 and are discussed below.

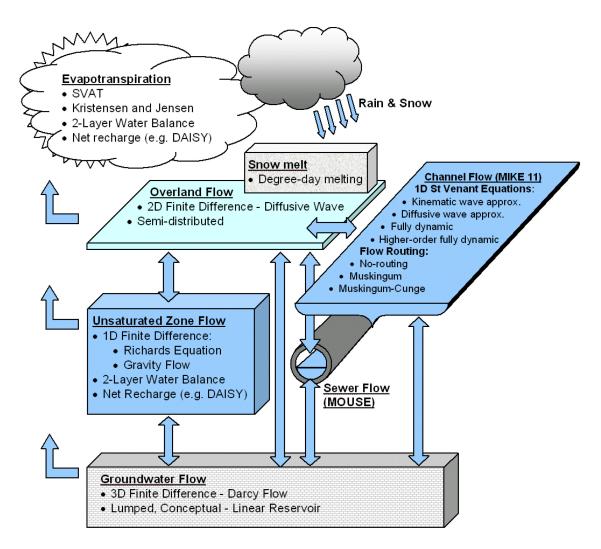


FIGURE 2-2 Available Computational Methods for Major Processes in MIKE SHE (DHI, 2011a)

Within MIKE SHE, liquid water is supplied to the ground surface after accounting for canopy interception and snowmelt processes. Overland runoff is generated when the rate of net precipitation is greater than the rate of infiltration. The algorithms available for infiltration in the unsaturated zone include: a 1-D finite difference approximation of the Richards equation; gravity flow; or a 2-layer water balance with or without the Green and Ampt infiltration routine. The Barrie Tier Three model utilizes the 2-layer water balance with Green and Ampt infiltration. All flow is assumed to be vertical in the unsaturated zone, with the depth of the unsaturated zone determined by groundwater heads (if utilizing the 3-D finite difference method for saturated flow) for that timestep. Water exchange from the unsaturated zone to the saturated zone is termed groundwater recharge.

Evaporation removes soil water content from the two layer unsaturated zone based on the specified potential evapotranspiration rate for that period, and the availability of soil water content. Potential evapotranspiration rates are supplied with a spatial distribution and generated outside of MIKE SHE. A root depth for differing land covers is also specified, which represents the depth of soil which water can be removed by evaporative processes. Water is removed via evaporation from the following storage elements: water held in canopy interception; water on the soil surface; or uptake of soilwater by vegetation from the root zone. Once the reservoirs all are emptied through evapotranspiration, no more



water is removed until a precipitation event or increased groundwater elevations replenish water content. Evaporation and sublimation also occur from the snowpack.

Once overland runoff is generated, there are two approximations available for overland routing: a lumped semi-distributed approach or a fully distributed approach. The lumped approach uses an empirical relationship between flow depth and surface detention and the Manning equation. The distributed approach relies on a 2-D diffusive wave approximation of the St. Venant equations, and is the method employed in the Barrie Tier Three model. In this approach, overland runoff is routed cell by cell over the ground surface until a MIKE-11 channel is reached. Runoff flowing from one cell to another is also available for infiltration. Runoff flowing to low areas that do not drain directly to a watercourse will pond, and will either evaporate or infiltrate into the unsaturated zone.

There are two methods available to represent saturated flow. The first is a lumped, subwatershed based method that relies on the linear reservoir approximation. All outflow from the linear reservoir is supplied to MIKE-11 as baseflow to streams within that catchment. This method is an extremely simplified representation of the groundwater system, and is common to most hydrologic models (e.g., GAWSER, HSPF, HEC-HMS). This method does not simulate groundwater flow, heads, or interactions with the surface water system. The second method relies on the solution of the 3-dimensional Darcy equation, using an iterative implicit finite difference technique, and is used in the Barrie Tier Three model.

Channel flow is handled through a two-way linkage between MIKE SHE and MIKE-11. Overland runoff, interflow and groundwater discharge enters the stream channel and is routed downstream. A variety of routing algorithms are available, ranging from relatively simple kinematic routing to the Dynamic Wave formulation of the Saint Venant equations. The Barrie Tier Three model utilizes the kinematic routing method to represent stream routing. Groundwater discharge/leakage into or out of the channel, is calculated based on the surface water elevation, groundwater head, and a river-bed conductance term. Leakage from the watercourse to the saturated zone is limited by the volume of water within the stream.



TABLE 2-1 Hydrologic Process Approximations in Barrie Tier Three Model

Hydrologic Process	Process Approximation
Overland Flow	Two-Dimensional - Diffusive Wave Approximation of St. Venant equations of flow
Channel Flow	Kinematic Routing
Evapotranspiration	Two-layer water balance model (mass balance approach)
Unsaturated Zone	One dimensional, two-layer water balance model
	Infiltration based on soilwater content parameters, soil conductivity and suction head
Saturated Zone	Three-Dimensional Finite Difference implementation of Darcy's equation
Timestep	Fixed at 1 hour

3.0 MODEL DEVELOPMENT

The following sections describe the setup of the Barrie Tier Three MIKE-SHE model, including the simulation period, model domain and spatial discretization, as well as the required input datasets.

3.1 Simulation Period

The time period selected for simulation should be reasonably consistent with the time frame of input datasets considered (e.g. land use data). Observation data should also be available during this period for model calibration and verification purposes. With this in mind, the most recent 20 years were used as the simulation period, i.e., 1990-2009. This period is reflective of available input data including climate data (Section 3.3), land use data (Section 3.6), pumping data (Section 3.9), and observed calibration data (Section 4.0).

The model was run for three years prior to the start of model simulation, i.e., 1987, to account for a 'warm-up' period wherein the model transitions from initial conditions to the dynamic conditions dictated by model inputs. Initial conditions were derived from a steady state simulation.

The Tier Three process requires the reliability of groundwater supply wells to be tested in a variety of climatic conditions. To do this, the transient groundwater recharge rates must be estimated and supplied to the FEFLOW model. To allow consideration of a longer time period, and subsequently a larger range of climate variability, the simulation period was extended to 1950-2009. This 60-year period includes two significant drought periods, the 1960s and the late 1990s. The first three years were excluded to account for a warm up period. These recharge rates are shown in Section 5.2.

TABLE 3-1 Time periods used for MIKE SHE modelling

Time Period	Model Use
1987-1990	Model 'Warm-Up' Period
1990-2009	Model Calibration/Verification Period (20 years consistent with timeframe of input datasets)
1950-2009	Model Simulation of Groundwater Recharge Rates (over large but reasonable range of expected climate variability)



3.2 Model Domain and Grid Resolution

The model domain was based on the Barrie Tier Three FEFLOW groundwater model domain, as shown on Map 3-1. Where the FEFLOW groundwater model domain coincided with streams (i.e., Marl Creek, Nottawasaga River, Baxter Creek and Banks Creek along the western and southern boundary), the MIKE SHE model included a 1 km buffer to ensure the lateral extent of the streams were captured within the MIKE SHE model. Kempenfelt Bay, and other portions of Lake Simcoe, were excluded from the MIKE SHE model domain as it is unnecessary for modelling and recharge mapping purposes (recharge assumed to be zero). The MIKE SHE model domain encompasses a total of 800 km² and is referred to in the following text as the 'Study Area'.

The grid resolution of the model is adaptable and can be set to any multiple integer of the input data. As the model resolution is a significant factor in the model run time, a balance between resolution and run time is needed. For the Barrie Tier Three model, a 200x200 m grid resolution was used.

3.3 Climate Data

Climate data was available for the period of 1950-2005 for a selection of Environment Canada climate stations, sourced from the Land Information Ontario (LIO) infilled climate dataset (LIO, 2008). This dataset was infilled to remove all data gaps and erroneous data by Schroeter and Associates (2007) based on the methodology outlined in Schroeter et al. (2000). Although the raw dataset included large gaps of data and was infilled, the resulting dataset was found to be acceptable and representative of climate for the time period it covered, thus an acceptable source for modelling data. Available climate data for the infilled stations include:

- Daily maximum and minimum temperature;
- Daily rainfall and snowfall; and
- Hourly rainfall.

From these datasets hourly precipitation and temperature time series were derived as model input. A synthetic hourly temperature dataset was derived assuming the maximum daily temperature occurred at 3:00 pm with the minimum daily temperature occurring at 3:00 am. Daily potential evapotranspiration rates were generated according to the Hamon Method (Hamon, 1961), which uses mean daily temperature, the climate station latitude and a monthly coefficient. The monthly coefficient used for the Hamon method in this model was 0.2095. The annual average temperature, precipitation and potential evapotranspiration over the 1990-2005 period are listed in Table 3-2.



TABLE 3-2 Summary of Climate Input Data for 1990-2005 Period

AES ID	Station Name	Latitude	Longitude	Mean Annual Temperature 1990-2005 (0C)	Mean Annual Precipitation 1990-2005 (mm/yr)	Mean Annual PET* 1990-2005 (mm/yr)
6111859	Cookstown	44.21	-79.69	6.5	820	676
6110275	Angus Camphill	44.28	-79.85	6.8	838	692
6115099	Midhurst	44.45	-79.77	7.5	889	706
6112340	Essa Ont Hydro	44.35	-79.82	7.1	889	728
6110557	Barrie WPCC	44.38	-79.69	7.1	931	712

^{*}Note: PET is potential evapotranspiration and is computed according to the Hamon Method (Hamon, 1961). It is not climate data that is measured directly, but rather a hypothetical maximum evapotranspiration value calculated from available climate data.

Climate data from the above stations was spatially distributed throughout the model according to Thiessen polygons as shown in Map 3-2. The assumption inherent in the use of Thiessen polygons to distribute climate data, is that the data recorded at the climate station is representative for the entire area within that Thiessen polygon. As it is known that point measured climate data is often not representative of climate occurring over a large area (e.g., particularly during the summer thunderstorm season), this is a source of uncertainty.

For the 2006-2009 period, AquaResource completed an internal data fill-in exercise for hourly climate data obtained from Environment Canada. Within the Study Area, only the Barrie WPCC climate station had hourly data for the 2006-2009 period, which could be obtained from Environment Canada. Therefore, data from this station was used to represent the entire Study Area during this period. The data fill-in procedure was similar to the one utilized for the above mentioned 1950-2005 LIO infilled dataset. The annual average temperature, precipitation and evapotranspiration over the 2006-2009 period are listed in Table 3-3.

TABLE 3-3 Summary of Climate Data for 2006-2009 Period

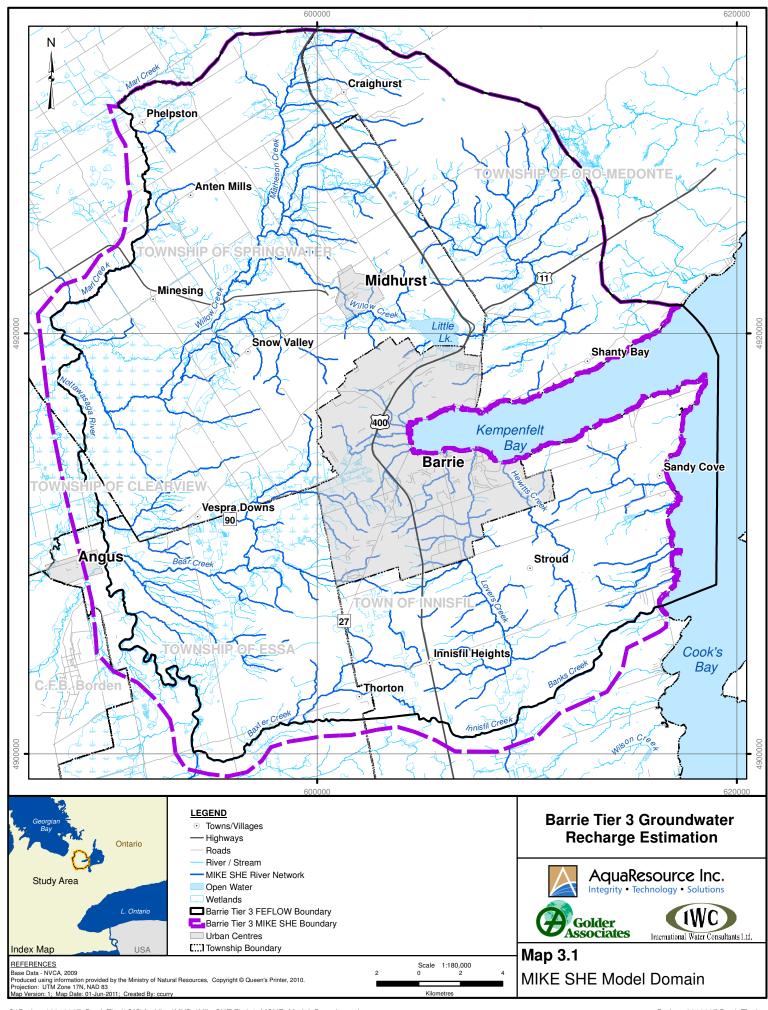
AES ID	Station Name	Latitude	Longitude	Mean Annual Temperature 2006-2009 (0C)	Mean Annual Precipitation 2006-2009 (mm/year)	Mean Annual PET* 2006-2009 (mm/year)
6110557	Barrie WPCC	44.38	-79.69	7.7	905	809

^{*}Note: PET is potential evapotranspiration and is computed according to the Hamon Method (Hamon 1961)

The Nottawasaga Valley Conservation Authority (NVCA) operates a snow course survey near Colwell, approximately 4 km east of Angus (Map 3-2). The snow course is located in a forested area (Tiffin Swamp) with snow depth measurements taken on the first and fifteenth of the winter months (December 1st to May 1st) from 1972-2010. There are significant data gaps from 1992-1997, with only about two measurements taken per year during this time. This snow survey data was used as a secondary calibration target, as discussed in Section 4.4.

In the model, actual evapotranspiration is estimated using a 2-layer water balance method. The method splits the unsaturated zone into two layers – one layer representing the root zone, from which evapotranspiration can occur, and the lower layer representing unsaturated zone storage, from where evapotranspiration cannot be extracted. This method requires an input of root depth time series and leaf area index time series (both shown in Table 3-4) as well as the reference evapotranspiration given in





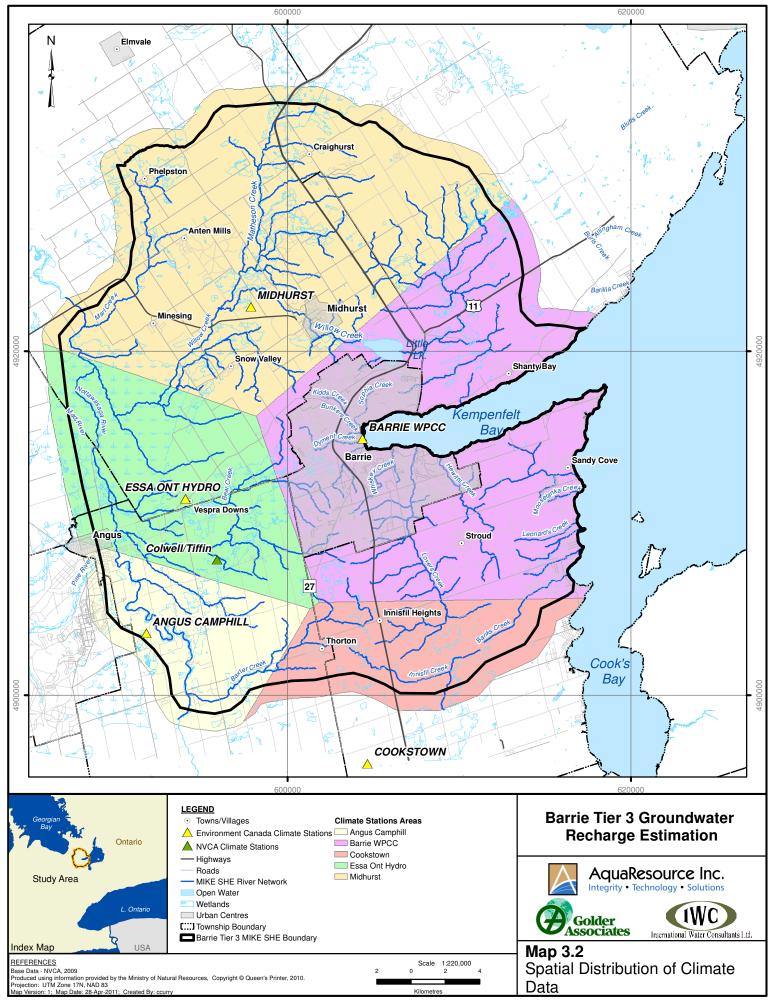


Table 3-2. It calculates evapotranspiration by first extracting from intercepted water (using the leaf area index), then ponded water, and finally from the root zone.

3.4 Topography and Drainage

A 5 m resolution Digital Elevation Model (DEM) supplied by the LSRCA was utilized to capture the topography of the Study Area, and is shown in Map 3-3. Dominant features in the Study Area include the Oro Moraine at a high of 412 metres above sea level (masl), the Innisfil Highlands at a high of 320 masl, the Minesing Wetland at a low of 181 masl and Kempenfelt Bay at 218 masl.

The Study Area encompasses two watersheds: the Nottawasaga River watershed and the Lake Simcoe watershed. The drainage divide follows the highlands of the Oro Moraine in the north, through Midhurst, along the western edge of the City of Barrie, to the Innisfil Highlands in the south. Major watercourses within the Study Area include Willow Creek and Matheson Creek in the north, which collect drainage from the Oro Moraine and flow into Minesing Wetland; and Lovers Creek in the south, which drains directly to Kempenfelt Bay.

3.5 River Network

A drainage layer describing the river network for the model region is required to simulate channel flow in the MIKE 11 modelling system. A simplified river network was created for use in both the FEFLOW and MIKE SHE/MIKE 11 models. Rivers were filtered based on orthoimagery, proximity to one another (>500 m apart), stream order (Strahler classification number ≥3) and stream length (>700 m). This filtering resulted in a simplified river network which captured the major streams within the model region. Slight differences exist between the drainage network used in the FEFLOW model and the MIKE SHE model, and are related to differing model requirements between the two models. The simplified stream network in MIKE SHE is shown in Map 3-4.

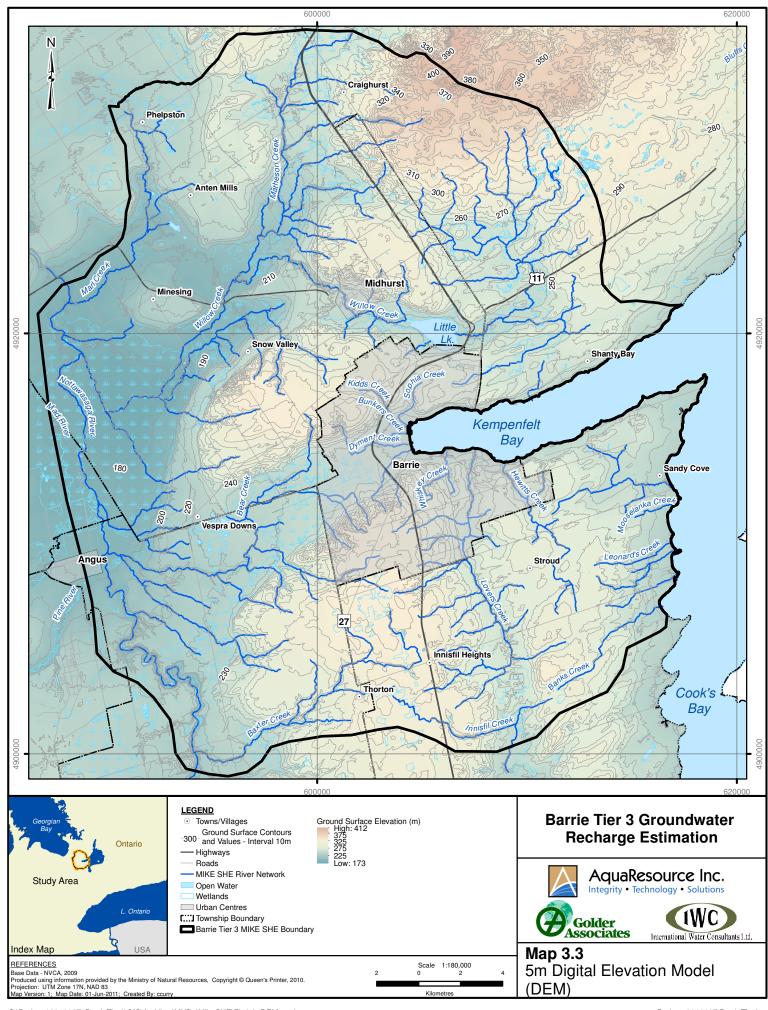
Cross sections of the water courses were developed at 500 m to 1,000 m intervals along the streams according to the 5 m DEM elevations. The cross sections are used in MIKE 11 for hydraulic routing computations. Discrepancies can exist between the ground surface elevations of the distributed model and the bank elevations of the hydraulic model. This is due to the relative coarseness of the distributed model resolution (200 m) relative to the high resolution data cross section elevations are derived from (5 m). To address this issue, cross section bank elevations were adjusted to better match the elevations of the distributed model. The cross sections are approximately 100 m wide.

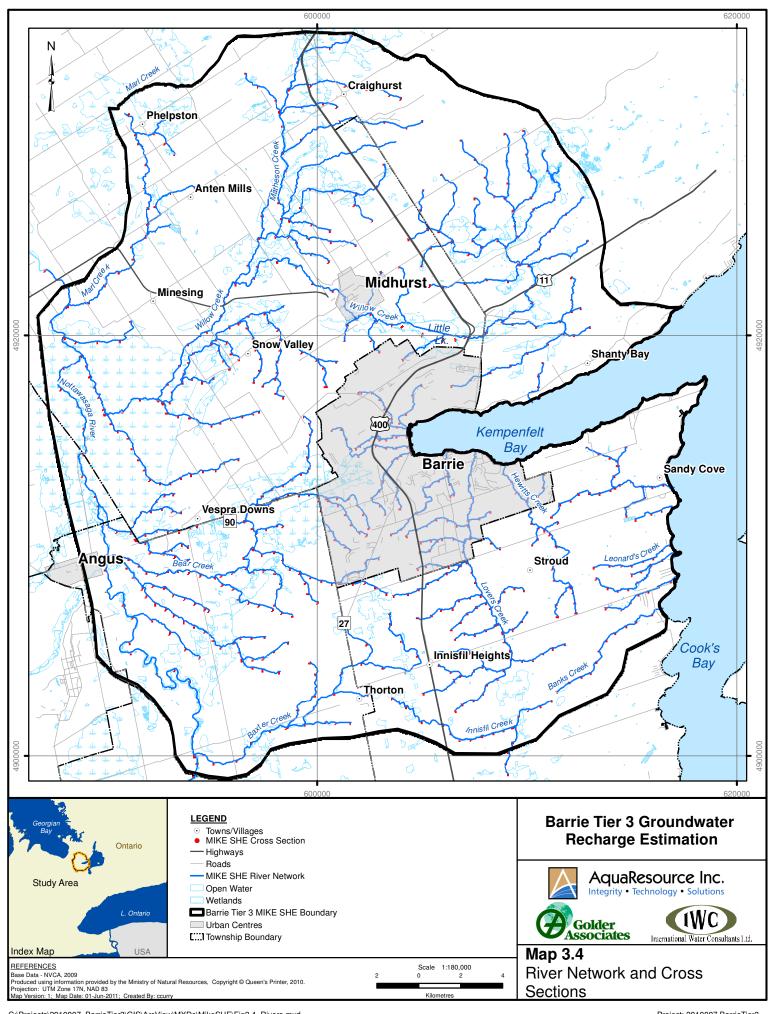
Channel routing is performed through simple kinematic routing. The kinematic routing uses a Manning's roughness coefficient of 0.05 for both the channel and floodplain, based on literature values (Bedient and Huber, 2002).

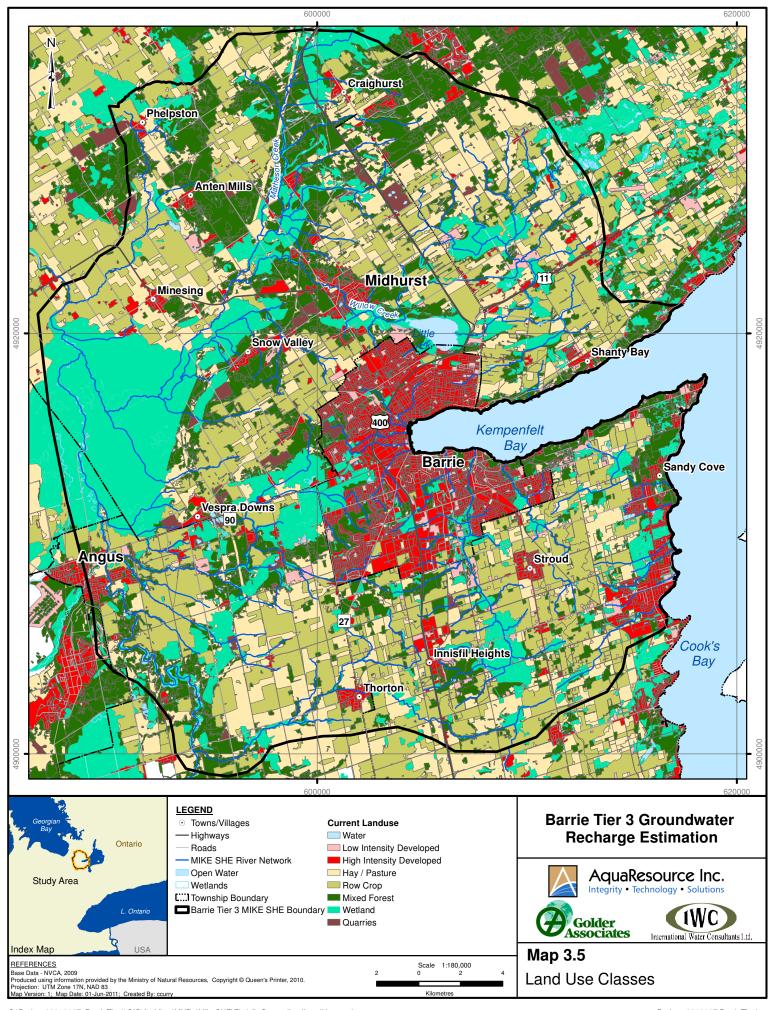
3.6 Land use

A land use map was created during the South Georgian Bay – West Lake Simcoe Tier Two Study (Golder and AquaResource, 2010). The land use mapping was based on land cover data from the LSRCA published in 2008 and from the Nottawasaga Valley Conservation Authority (NVCA) published in 2007. Similar to the Tier Two Study, in areas of overlap, the LSRCA data was used as it was the most recent data, and better overall data quality. Eight land use classes were created from the land use data, listed in Table 3-4 and shown on Map 3-5.









Vegetation parameters were assigned according to the land use class. These include a leaf area index and rooting depth time series to characterize the growth cycle of the vegetation. These parameters affect evapotranspiration and overland flow processes and are shown in Table 3-4. These parameters were based on literature values and previous modelling experience in the Grand River watershed using MIKE SHE.

TABLE 3-4 Vegetation Parameters for Land Use Classes in MIKE SHE Model

Land Use Class	Range of Monthly LAI* Values	Range of Monthly Root Depth Values (mm)
Low Density Urban/Rural Areas	2 - 4	750
High Density Urban	0.8 - 1.45	750
Hay/Pasture/Idle/Transitional	2.5 - 5	50 - 1000
Row Crops/ Intensive Agriculture	2.5 - 5	50 - 1000
Forests/Mixed Woods	5 - 7	1000 - 2000
Wetlands	2 - 4	200
Water, Pits, & Quarries	0	0

^{*}LAI is Leaf Area Index

Overland flow parameters were also assigned based on each land use class and include surface roughness, depression storage, and a paved runoff coefficient, as shown in Table 3-5. Surface roughness is used to approximate surface friction and is given by Manning's n coefficient. Depression storage represents the portion of rainfall trapped by surface topography which is left to infiltrate or evaporate following a rainfall event. Values were assigned based on literature (Chin, 2006) and modelling experience, and were adjusted during calibration.

A paved runoff coefficient was applied to highly urbanized areas to represent the fraction of directly connected impervious areas. The paved runoff coefficient defines the fraction of overland flow that is not infiltrated but instead is drained directly to storm sewers via the saturated zone drainage network. This is to simulate that paved areas typically drain to storm sewers, which drain directly to streams. The rural areas and highways did not contain significant directly connected impervious area under a 200 m grid resolution to be simulated as paved areas. A paved runoff coefficient of 0.3 was used for the Barrie Tier Three model.

TABLE 3-5 Land Use Classes and Parameters

Land Use Class	Surface Roughness (Manning's n)	Depression Storage (mm)	Paved Runoff Coefficient
Water	0.06	10	Null
Low Density Urban / Rural Areas	0.15	2	Null
High Density Urban	0.09	2	0.3
Hay / Pasture / Idle / Transitional	0.37	5	Null
Row Crops / Intensive Agriculture	0.37	2	Null
Forests / Mixed Woods	0.42	10	Null
Wetlands	0.42	9	Null
Pits /Quarries	0.05	1	Null

3.7 Unsaturated zone

The unsaturated zone in MIKE SHE represents the upper soil zone, in which infiltration, overland runoff, and the majority of evapotranspiration is generated. The unsaturated zone in the Barrie Tier Three MIKE



SHE model is characterized using the Quaternary geology from the Ontario Geological Survey (OGS, 2003). Further detail is described in the Conceptual Understanding Memorandum (AquaResource et al., 2011). The Quaternary geology classifications were simplified into four soil classes: gravel, sand, silt / till, and clay. The soil classes are shown in Map 3-6.

The soil classes are characterized in MIKE SHE according to their hydrologic properties, including infiltration rates and soilwater holding capacities. Soil parameter values were based on previous modelling experience in the region and through calibration. The calibrated soil parameters are listed in Table 3-6.

TABLE 3-6 Calibrated Soil Parameters

Soil Parameter	Gravel	Sand	Silt + Tills	Clays
Saturation Point	0.30	0.46	0.56	0.56
Field Capacity	0.20	0.23	0.46	0.46
Wilting Point	0.04	0.07	0.27	0.27
Infiltration Rate (m/s)	6E-6	4E-6	4E-8	1E-8
Suction Head (m)	-0.20	-0.25	-0.20	-0.20

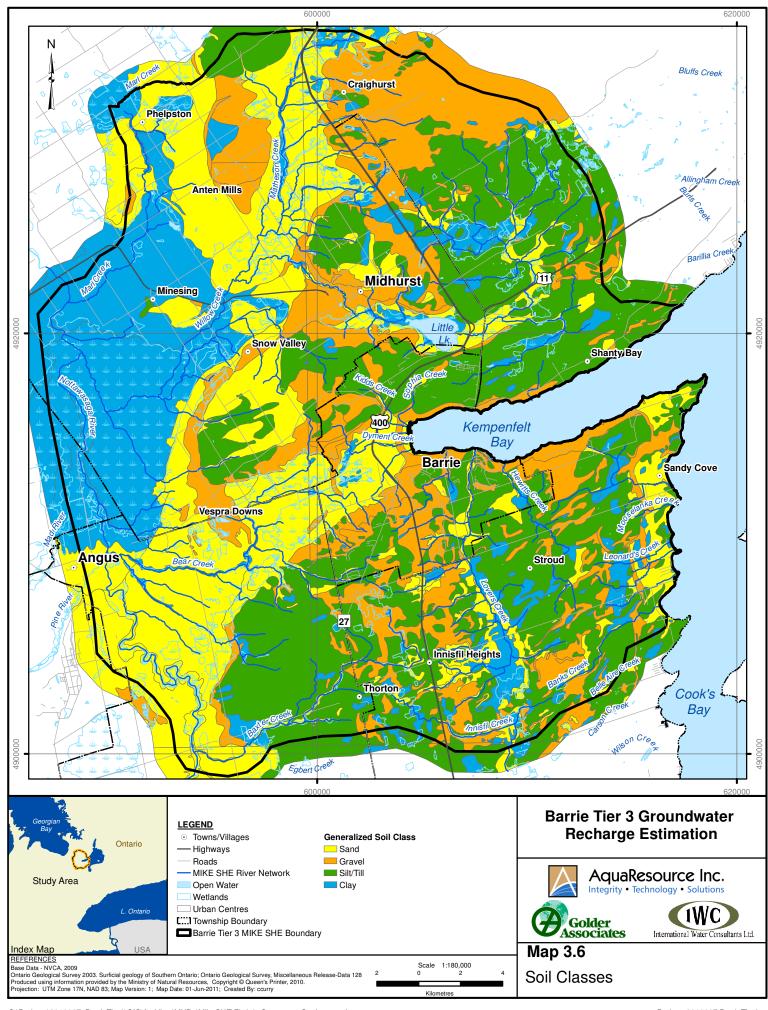
A limitation of the unsaturated zone representation in MIKE SHE is that it only considers flow in the vertical dimension. In areas with thick unsaturated materials this assumption of one-dimensional vertical flow may not be correct. Intervening low permeability lenses may promote horizontal rather than vertical flow, and cause water to be directed towards local watercourses, rather than the deeper groundwater flow system. It should also be noted that quaternary geology classifications are typically based on the first few meters of soil. Due to the thickness of the unsaturated zone in the highland areas (10-20 m), the geology classification may not be representative for the entire depth.

3.8 Saturated Zone

MIKE SHE represents the groundwater system through a three-dimensional representation of the subsurface using Darcy's equation. The layer structure and spatial hydraulic characteristics used in the Barrie Tier Three MIKE SHE model are based on the geologic layers and properties included in the FEFLOW 3-D groundwater flow model. The 9-layer structure found in the FEFLOW model was simplified to a 3-layer structure in MIKE SHE, as illustrated in Figure 3-1. The first layer represents a shallow aquifer system where the majority of interaction between groundwater and surface water occurs. This corresponds to the combination of the upper unconfined (UC) layer, aquifer 1 (A1), confining layer 1 (C1), and aquifer 2 (A2) in the FEFLOW model. The second layer is a confining layer corresponding to C2 in FEFLOW. The third layer represents the deep aquifer system, where most of the municipal wells are pumping from. This corresponds to the FEFLOW aquifers A3 and A4, with confining layers C3 and C4. The purpose of this simplified layer structure in MIKE SHE was to include sufficient layers to accurately characterize the subsurface, while keeping simulation times to reasonable lengths.

Aquifers A1 and A2 are modelled in the same layer due to having similar hydraulic heads and having limited data available in each aquifer. Water levels within these units are considered to represent the "shallow" water levels. "Deep" water levels are represented by Aquifers A3 and A4. As a result, it was important to accurately represent Aquitard C2, the primary aquitard between them. Having it represented in at least one unique model layer, the role of the aquitard is captured explicitly instead of being lumped in with surrounding aquifers.





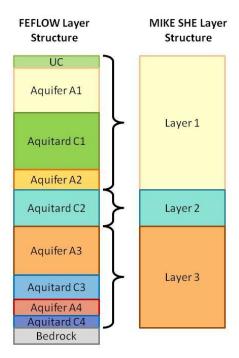


FIGURE 3-1 Simplified Saturated Zone Layer Structure

The saturated zone properties required in MIKE SHE include the horizontal (Kx) and vertical (Kz) hydraulic conductivities, initial water level elevations, as well as specific yield and specific storage. The hydraulic conductivities assigned to each layer reflect the controlling layer properties from the FEFLOW model layer. These are listed in Table 3-7. MIKE SHE was run in steady state mode to obtain initial groundwater elevations. A specific yield of 0.2 and specific storage of 1e-5 were used in the model.

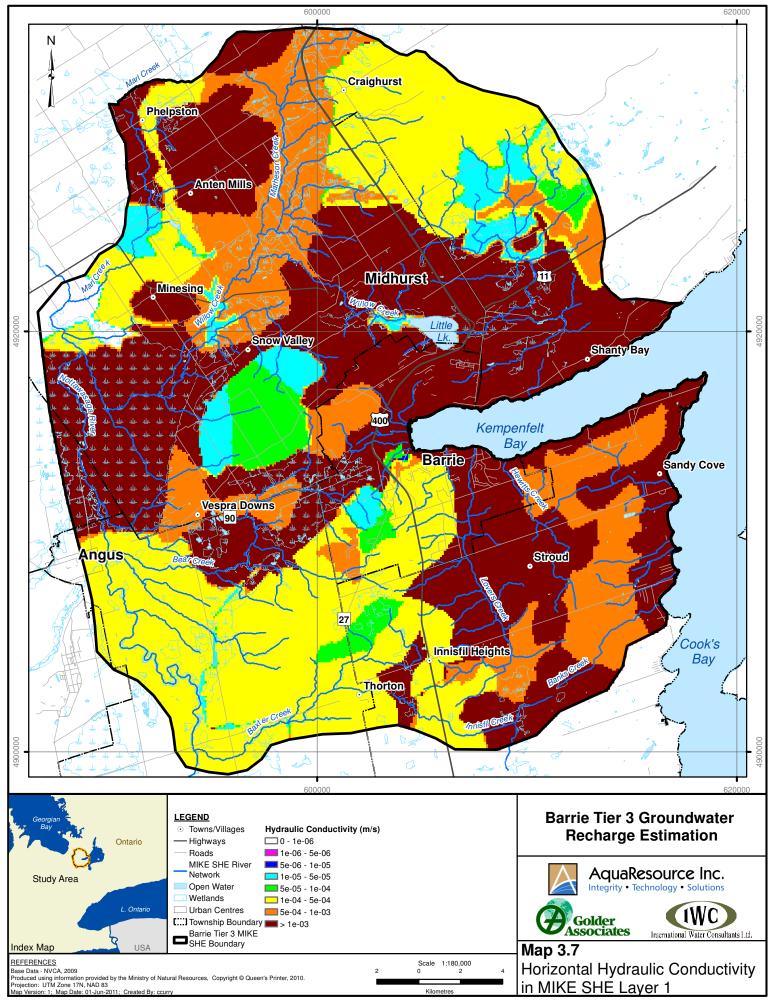
TABLE 3-7 MIKE SHE Saturated Zone Horizontal (Kx) and Vertical (Kz) Hydraulic Conductivities as Related to FEFLOW

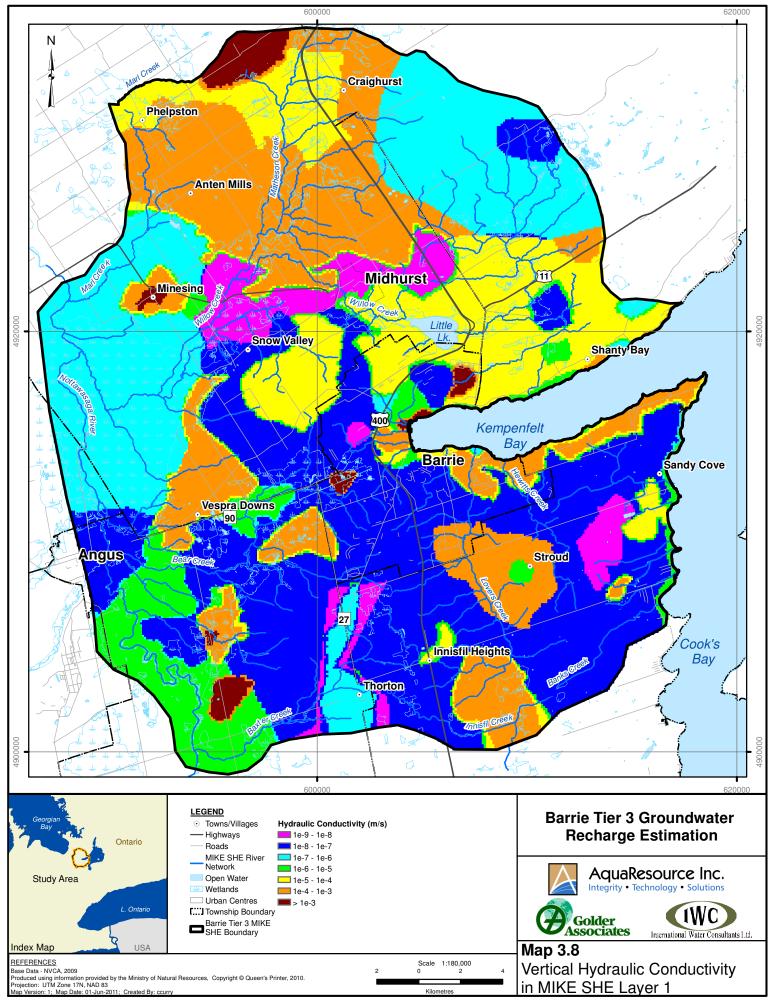
MIKE SHE Layer	FEFLOW Kx Layer	FEFLOW Kz Layer
1	A1	C1
2	C2	C2
3	А3	C3

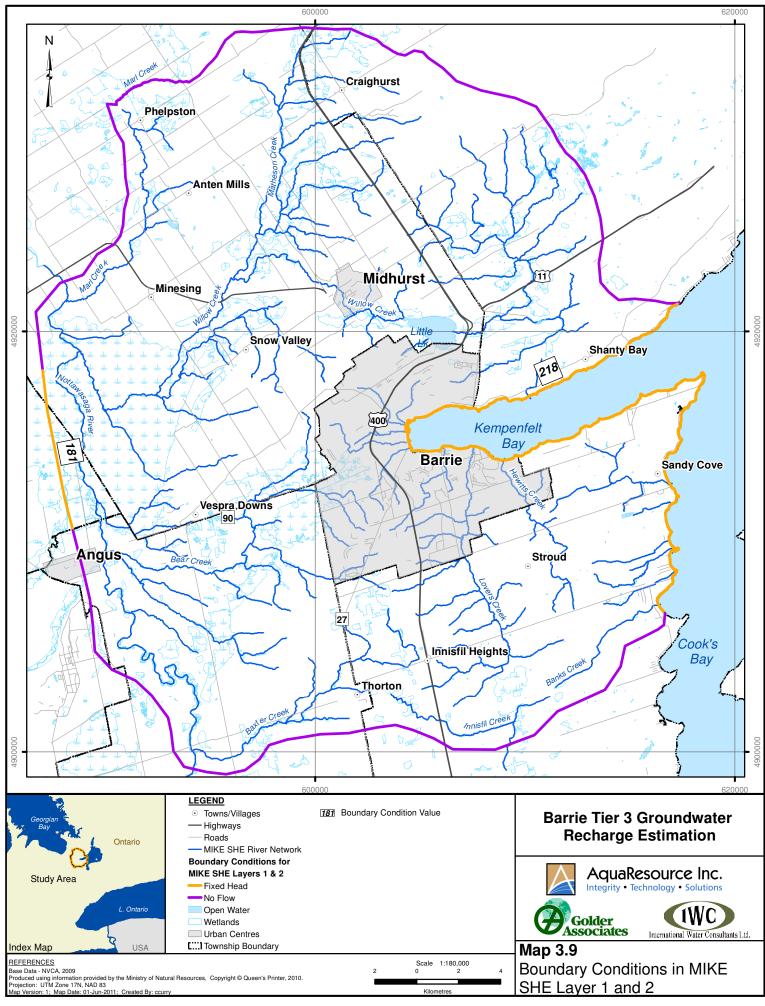
The simplification of the saturated zone was a limitation in the ability of the MIKE SHE model to accurately simulate groundwater flow. For example, in the highland areas, Layer 1 could represent a depth of up to 100 m of subsurface using a single geologic property (a single hydraulic conductivity). In reality there could be lenses of tighter materials that impede flow and that create preferential flow pathways. As such, the hydraulic conductivities of Layer 1 were adjusted during calibration in an attempt to account for the variation in geologic materials. The adjustments consisted of decreasing the hydraulic conductivity in the highland areas by a factor of 10 in the horizontal direction and a factor of 50 in the vertical direction. The layering structure of the saturated zone (i.e., Layer 1 is still very thick in those areas) remained a limitation of the model. The horizontal and vertical hydraulic conductivities in Layer 1 are shown in Map 3-7 and Map 3-8, respectively. Layer 2 and Layer 3 hydraulic conductivities did not differ from the FEFLOW properties and are therefore not shown here.

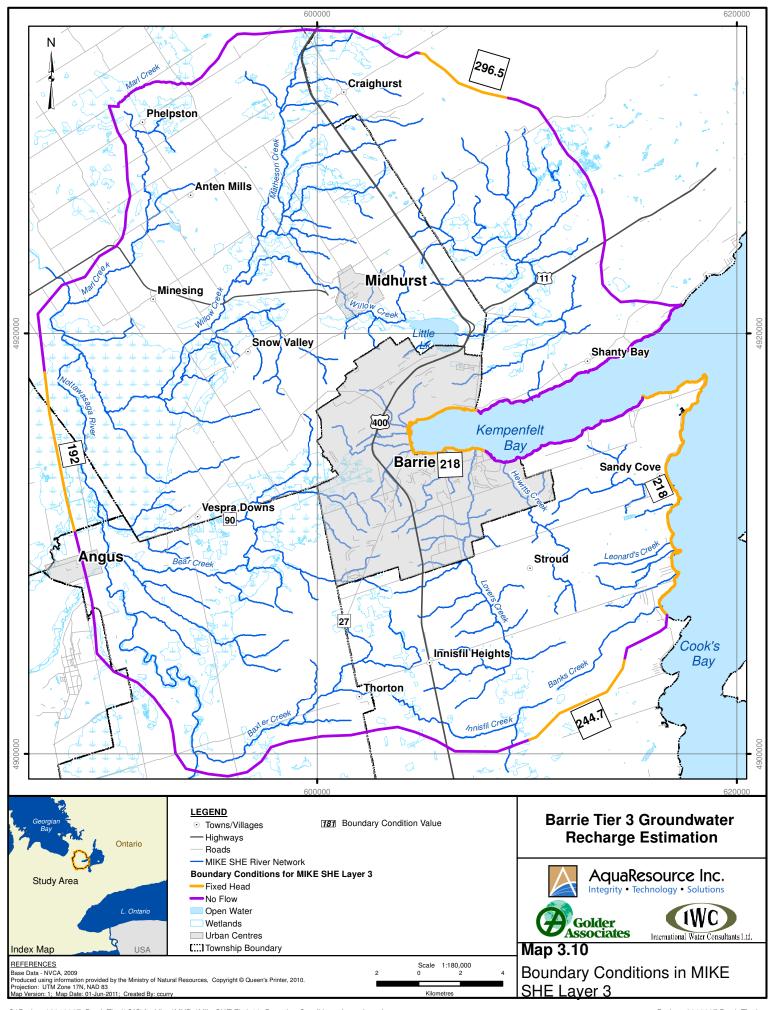
The boundary conditions specified in the MIKE SHE model are based on those used in the FEFLOW model and are shown in Map 3-9 for Layers 1 and 2 and Map 3-10 for Layer 3. Fixed head boundary











conditions were specified under the Minesing Wetland according to the shallow (181 masl for Layers 1 and 2) and deep (192 masl for Layer 3) water table contours included in the Conceptual Understanding Memorandum (AquaResource et al., 2011). Along Lake Simcoe, a fixed head boundary condition was specified at 218 masl for Layers 1 and 2. For Layer 3 only a portion of Kempenfelt Bay, mainly within the City of Barrie, was specified as a fixed head to coincide with observed water levels. Additional fixed head boundary conditions were set in Layer 3 at the Oro Moraine (296.5 masl) and Innisfil Highlands (244.7 masl) to account for the flux of water to and from the model boundary at these locations. Fixed head values were taken from observed water levels included in the Conceptual Understanding Memorandum (AquaResource et al., 2011).

The saturated zone in MIKE SHE also includes modelled subsurface "drains" which are used to represent the quick response of the groundwater system (interflow) to local streams. Overland runoff from paved areas is also sent to the subsurface drains. Subsurface drain flow occurs mainly after large rainfall events. When recharge to the saturated zone causes the water table level to rise above a user-defined drainage depth (drain level), a portion of that excess water from the saturated zone is routed to a river node to augment streamflow. Subsurface drain flow is routed to a river node using a linear reservoir technique, based on the drain level (steady state water table elevation) and leakage rate (1e-6 s⁻¹). One of the difficulties in simulating the Study Area was representing the interflow component in the highland areas. The best attempt was by placing the drains at or near the steady state water table. This way, when the transient water table was above the drains, drain flow is active and supplies water to the streams via 'interflow' and when the water table is below the drains, drain flow is inactive.

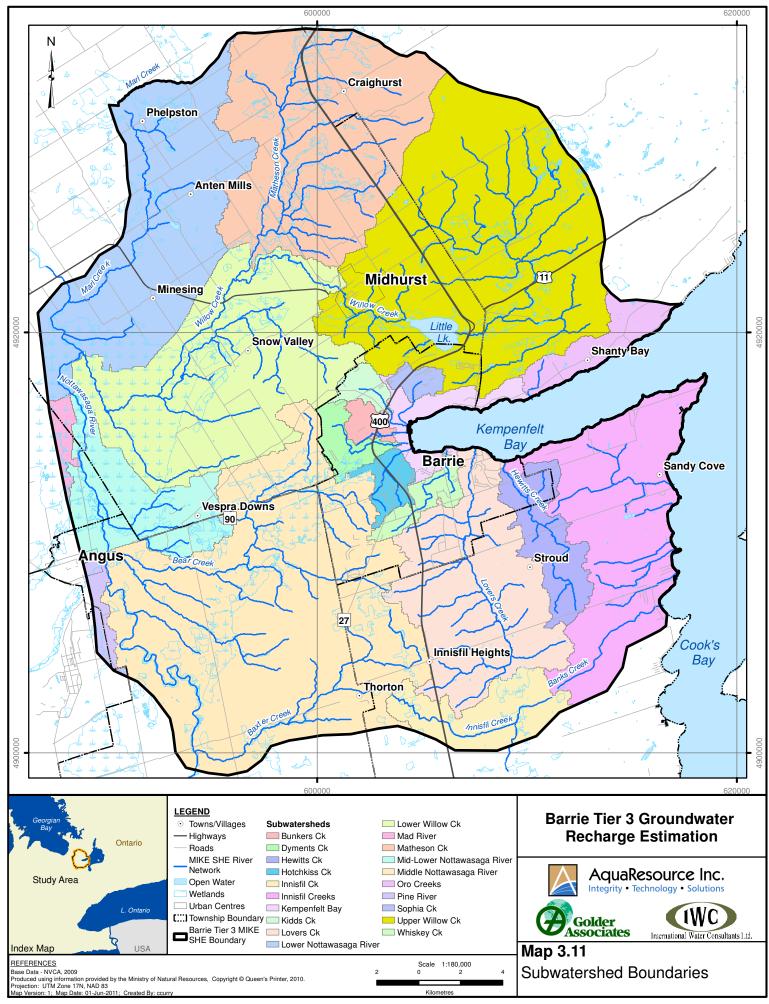
Subsurface drainage is determined spatially through user-defined drainage boundaries, called drain codes. All drainage generated within the same drain code is discharged to the nearest river node within that drainage boundary. The drain codes in the Barrie Tier Three model follow surface water subwatershed boundaries and are shown in Map 3-11.

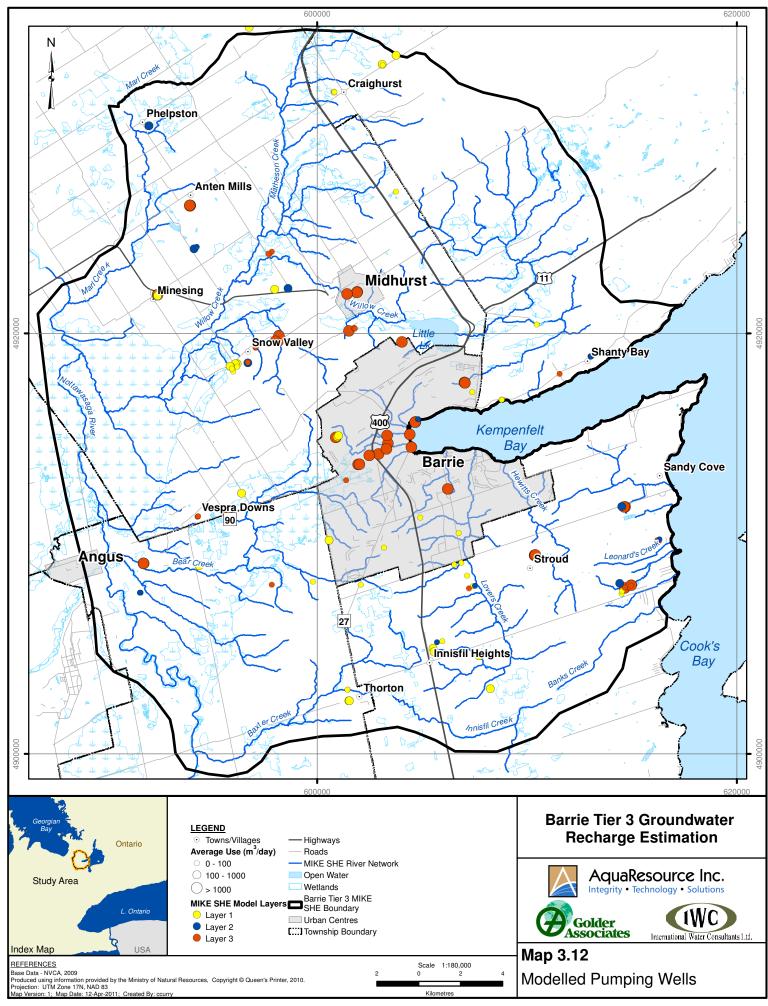
3.9 Pumping Wells

MIKE SHE has the ability to include water withdrawals in the model. The Barrie Tier Three MIKE SHE model includes all groundwater withdrawals associated with a Permit To Take Water from the Ontario Ministry of Environment (MOE), and are shown in Map 3-12. The colour of the point reflects which layer in the model the well is pumping from and the size of the point reflects the rate of pumping. The depth of the well screens are the same as those used in the FEFLOW model. The modelled pumping rates are described in the Conceptual Understanding Memorandum (AquaResource et al., 2011). The municipal pumping rates are the average annual reported rates for 2008. Non-municipal (private) pumping rates are the average annual consumptive rates for 2008. These are based on the reported water use in the MOE's Water Taking Reporting System (WTRS) for 2008; or, where this data is not available, the maximum permitted rate was combined with the estimated months of active pumping based on the purpose of the water taking. The pumping rate is then adjusted by a consumptive use factor to estimate the water which is consumed and not returned to the same source. The modelled pumping rates for all wells in the Study Area are included in Appendix B1.

There is a need for a long term record of reported rates that should be satisfied with the continued use of the WTRS. This would increase confidence in using a long term average pumping rates in model simulations. However, as the WTRS was being phased from 2005-2008, there is limited available reported data for non-municipal users. As the 2009 WTRS reported rates became available during the







course of this study, a comparison between the 2008 and 2009 consumptive rates was included to ensure the 2008 rates were representative pumping rates for model calibration (Appendix B1).

The municipal demand for the City of Barrie comprises 73% of the total consumptive demand in the Study Area (AquaResource et al., 2011). As seen in Figure 3-2, there has appeared to be a reduction in average water demand occurring after 2007. Water demand after 2007 is fairly stable, averaging approximately 40,000 m³/day. Figure 3-2 illustrates that the 2008 municipal rates are representative of the recent pumping conditions in the City of Barrie.

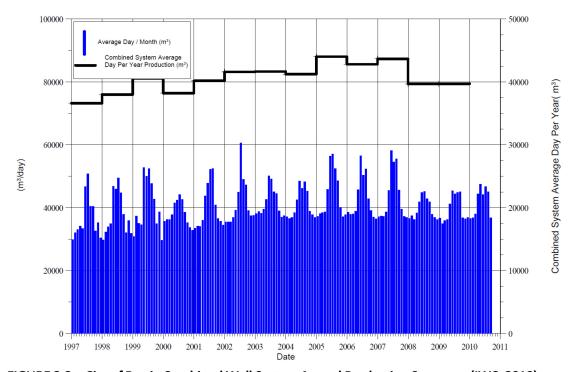


FIGURE 3-2 City of Barrie Combined Well System Annual Production Summary (IWC, 2010)

The remaining water demand consists of other municipalities water use (9%), commercial use (11%; i.e., mainly golf course irrigation and snowmaking), and other uses (7%; e.g., industrial, remediation and recreational). For these permits a comparison between the 2008 and 2009 consumptive rates is shown in Figure 3-3. Appendix B1 lists all wells in the Study Area and their 2008 and 2009 rates and data sources. Generally, the 2009 rates show a reduction in estimated pumping from 2008. This is mainly due to more permit holders reporting their pumping rates in the 2009 WTRS, whose pumping rates were estimated in 2008. As the 2008 rates are a more conservative estimate, these were used for steady state model calibration. It is clear that the non-municipal pumping rates are a source of uncertainty; however, as they amount to less than 20% of the total consumptive demand, it is unlikely that this uncertainty will significantly impact the model calibration. The uncertainty associated with the non-municipal pumping estimates, as it relates to the overall study objectives will be considered in the Local Area Risk Assessment.



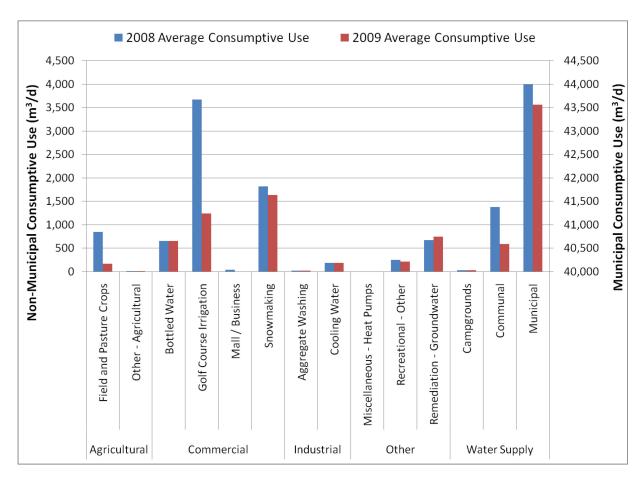


FIGURE 3-3 Comparison of Average Annual Consumptive Water Use for 2008 and 2009 by Water Use Sector

4.0 MODEL CALIBRATION

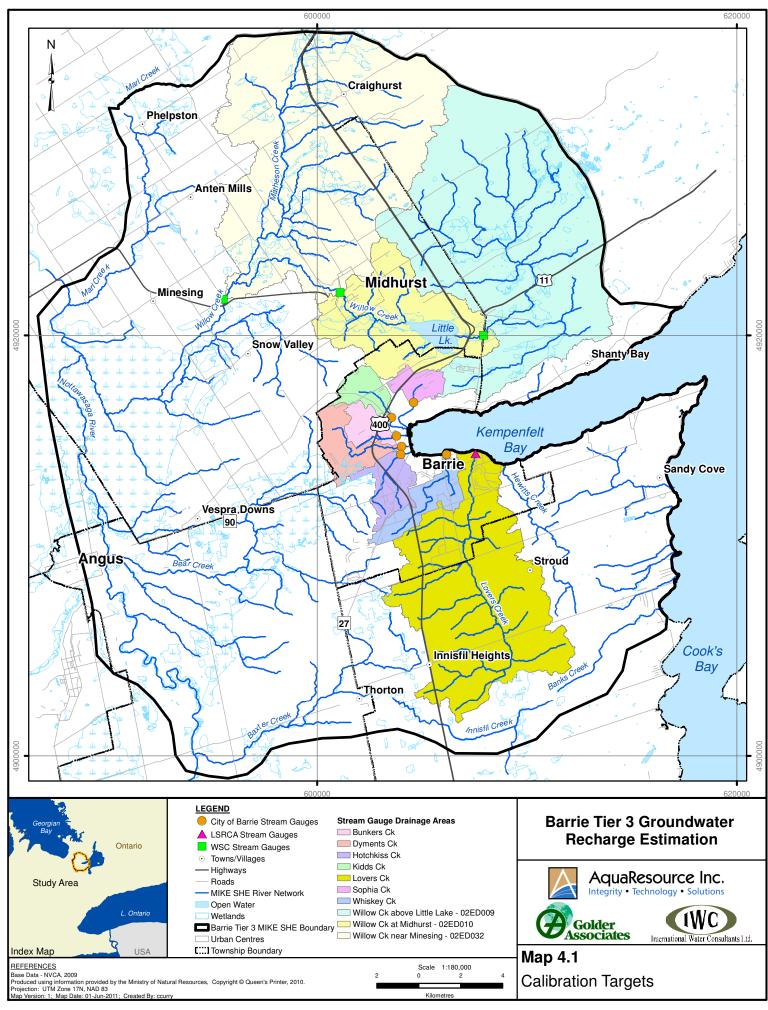
Model calibration involves adjusting hydrologic parameters to minimize differences between simulated and observed conditions. For this study, observed data included streamflow data from monitoring gauges, groundwater elevations from the MOE water well database, and snow depths from the NVCA snow course survey. The model calibration data, procedure and results are discussed below.

4.1 Overview of Calibration Targets and Procedure

The 1950-2009 simulation period was split into a calibration period, whereby the parameters were adjusted to match groundwater elevations, streamflow and annual water budget values; and a verification period, whereby the parameters were tested against a new set of input data. Due to the availability of observed streamflow and climate data, the model was calibrated over the 1990-2005 period and verified over the 2006-2009 period.

The primary calibration targets are streamflow monitoring gauges, listed in Table 4-1 and shown in Map 4-1. The groundwater levels are secondary targets as they represent average steady state groundwater elevations, whereas the MIKE SHE model is transient (changing over time). The groundwater levels were used to match general flow patterns and elevations. The snow depths





recorded at the snow course survey are tertiary targets, as there is only a single survey location in the Study Area which may not be representative of the entire area.

Streamflow calibration exercises for hydrologic modelling are typically approached in a structured hierarchical manner. Models are calibrated to a longer temporal scale (e.g., annual streamflow), and then sequentially moved to a shorter temporal scale (e.g., monthly streamflow). This approach ensures that regional processes, such as climate and evapotranspiration are well represented by the model, before effort is spent calibrating to local processes, such as channel routing. As groundwater recharge is generally an indication of the baseflow component of streamflow, the calibration also focused on matching the low flow months during the summer, and not on matching peaks flows. The streamflow monitoring gauges are listed in Table 4-1.

TABLE 4-1 Streamflow Monitoring Gauges and Calibration Targets

Station Name	Agency	Streamflow Record	Calibration (C) or Verification (V) Period	Drainage Area (km²)	Mean Annual Flow (m³/s)
02ED009 - Willow Creek above Little Lake	Water Survey Canada	1973- 1995*	Jan 1990 - July 1995 (C)	95	0.88
02ED010 - Willow Creek at Midhurst	Water Survey Canada	1973- 1998*	Jan 1990 - May 1998 (C)	127	1.20
02ED032 – Willow Creek near Minesing	Water Survey Canada	2006*-2008	Apr 2006 - Dec 2008 (V)	242	2.59
LS0101 - Lovers Creek at Tollendal	LSRCA	2001-2008	Jan 2001 – Dec 2004 (C)	60	0.76
Sophia Creek	City of Barrie	Mar-Dec 2004- 2010	N/A	2.3	0.03
Kidds Creek	City of Barrie	Mar-Dec 2004- 2010	N/A	4.5	0.08
Bunkers Creek	City of Barrie	Mar-Dec 2004- 2010	N/A	3.2	0.10
Dyments Creek	City of Barrie	Mar-Dec 2004- 2010	N/A	5.4	0.09
Hotchkiss Creek	City of Barrie	Mar-Dec 2004- 2010	N/A	4.5	0.08
Whiskey Creek	City of Barrie	Mar-Dec 2004- 2010	N/A	6.7	0.08

^{*}Data is incomplete for this year.



Once the calibration process began, a number of challenges were encountered with the streamflow data. The streamflow data at the Barrie Creeks gauges were recorded after the main spring freshet each year – some years starting in March and some as late as May. This prevented the comparison of simulated and observed mean annual flows. There were also some concerns with the accuracy of the applied rating curves in the relationship between river stage and discharge (e.g., due to vandalism and during high flow events). More confidence was given to the 2009-2010 data, as streamflow monitoring methods were improved and new instruments were implemented during this monitoring period (i.e., from leveloggers to ultrasonic sensors). Additional documentation on the streamflow monitoring program can be found in Stantec (2010) and Golder (2009). In addition, the urbanized hydrology of these catchments (i.e., channelized streams, storm sewers, and storm water management ponds) could not be included in the MIKE SHE model. As such, the Barrie Creeks gauges could not be used as calibration targets.

The Lovers Creek at Tollendal gauge is operated by LSRCA and there are measured streamflow data from 2001-2009. However, as outlined in the Conceptual Understanding Memorandum (AquaResource et al., 2011), the 2009 streamflow data has not been corrected for ice and was not used in this assessment. Prior to 2001, streamflow records at this location were synthetic estimates, and were estimated using a regression relationship and areally weighting flow from all gauged areas. Due to the uncertainty associated with this synthetic data, these data were not used in the assessment. While corrected streamflow data was available from 2001-2008, the calibration only considered data from 2001-2004. This was due to potential issues with the data from 2005-2008, as discussed further in Section 4.2.2.

Consideration was also given to spot flow measurements, as outlined in the Conceptual Understanding Memorandum (AquaResource et al., 2011). However, the majority of the low flow spot flow measurements were taken only on one date and represent a single snap shot in time that may not be representative of actual baseflow conditions, as suggested by coldwater stream mapping. Additional flow measurements were taken on several dates at three locations; however, these were not necessarily taken during baseflow conditions. As there is considerable uncertainty associated with the spot flow measurements, they were not used as calibration targets.

4.2 Streamflow Calibration and Verification Results

This section includes the calibration and verification results for the 1990-2005 period. The calibration targets include two Water Survey Canada stream gauges: 02ED009 - Willow Creek above Little Lake (Jan 1990 - July 1995), and 02ED010 - Willow Creek at Midhurst (Jan 1990 - May 1998); as well as one LSRCA stream gauge: Lovers Creek at Tollendal (Jan 2001 - Dec 2004). The verification target is the Water Survey Canada stream gauge 02ED032 - Willow Creek near Minesing (Apr 2006 - Dec 2008). The years with incomplete data are not included in the annual totals; however, the available data for those years are included in the monthly means and ranked duration curves.

4.2.1 Overview of Calibration and Verification Metrics

The calibration and verification portion of the modelling focuses on metrics to gauge the appropriateness of the model. This approach recognizes that no single metric is adequate to describe the model's ability to replicate observed flows. The calibration and verification metrics presented are as follows:

• Annual streamflow expressed as depth (mm) over the upstream area;



- Mean monthly streamflow expressed as depth (mm) over the upstream area;
- Daily hydrograph comparisons shown for a sample year;
- Ranked duration daily streamflow; and
- Monthly calibration statistics (log Nash-Sutcliffe and R² Coefficients).

Due to the log-normal distribution of streamflow, a normal Nash-Sutcliffe coefficient is heavily weighted towards higher flows. To provide a more accurate assessment of the overall model performance, the log Nash-Sutcliffe coefficient was calculated for this modelling exercise. According to Chiew and McMahon (1993) and Nash and Sutcliffe (1970), a Nash-Sutcliffe coefficient:

- Equal to 1 is a perfect fit;
- Greater than 0.8 is considered good;
- Greater than 0.6 is considered reasonable; and
- Less than zero implies the observed mean is a better predictor than the model.

These published ranges are not based on log-transferred values, so should be considered general guidelines for the log Nash-Sutcliffe coefficient calculated for this model evaluation.

The R^2 value is another indicator of data agreement. A value equal to 1 is a perfect fit. In this model evaluation, the log R^2 value was computed and used.

4.2.2 <u>Calibration Results</u>

The streamflow calibration results are illustrated in Figure 4-1 and Figure 4-2 below. Figure 4-1 shows the mean annual streamflow in the left column and the mean monthly streamflow in the right column. The top row is the Willow Creek above Little Lake gauge, the middle is the Willow Creek at Midhurst gauge, and the bottom is the Lovers Creek gauge. Observed streamflow is shown in blue and simulated is shown in red. As mentioned above, years with incomplete records of streamflow are not shown in the annual plots, but are included in the monthly plots. In the mean annual streamflow plots, the average annual is shown in the far right.

These calibration graphs show that generally the model is under predicting mean annual streamflow, primarily due to the lower spring flows. This is particularly evident at the Willow Creek above Little Lake gauge, where the majority of the drainage area is the Oro Moraine. As described earlier, the Oro Moraine has a significant depth of unsaturated materials. It is suspected that the assumption of only vertical flow in the unsaturated zone is lending itself to insufficient water being directed towards local streams on the Oro Moraine, and too much water being supplied to the deeper groundwater system.

Errors may also be introduced due to the spatial distribution of climate data. The climate data recorded at the climate station may not be representative of the climate over the entire watershed, particularly with respect to lake effect snow. Lake effect snow is often highly spatially variable, and is typically difficult to properly characterize given a sparse climate station network. This would lead to differences in the snow pack and therefore in the spring melt. In the summer months, the model is able to replicate low-flows much better, although simulated mean monthly flows are slightly higher than observed.



The main difference between the Willow Creek above Little Lake gauge and the Willow Creek at Midhurst gauge is the routing impacts of Little Lake; the drainage areas are very similar (95 and 127 km²). This is evident in the daily hydrographs shown for these two gauges in Figure 4-2. The observed streamflow for Willow Creek above Little Lake shows a peakier and more rapid response to storm events; whereas the Willow Creek at Midhurst gauge shows a much more muted, delayed response with lower peaks and a slow recession of streamflow. As the objective of the Barrie Tier Three MIKE SHE model is estimating recharge, not replicating hydraulic effects, the routing effects of Little Lake, which do not influence groundwater recharge estimates, were not taken into account.

For the Lovers Creek gauge, mean annual flows match very well, with the exception years after 2004 (Figure 4-3). Mean annual flow volumes increase from an approximate average of 300 mm/yr in 2001-2004 to 450 mm/yr in 2005 and greater than 700 mm/yr for following. Given mean annual precipitation rate is approximately 900 mm/yr and evapotranspiration is 500-550 mm/yr, streamflow yields of these magnitudes are not felt to be realistic. It is possible that changes in urban development over the upstream area changed the stage-discharge relationship that the existing rating curve was based on; or possibly the data are not corrected for ice impacts (as is known to be the case for 2009). From this it was determined that the observed data at Lovers Creek from 2005 onward was not reasonable for model calibration use. As such, the mean monthly flow depth was computed for 2001-2004. This shows a reasonable fit between simulated and observed data, with simulated flow for the month of August being slightly higher than observed. This is likely due to summer thunderstorms, as the low flows match very well in the daily hydrograph (Figure 4-2) and it is mainly differences in peaks that are affecting the overall average flow depth.

Also included in Figure 4-2 are the ranked daily duration curves for the three gauges. A ranked duration curve compares the ranked daily simulated streamflow and ranked daily observed streamflow. It provides the viewer with the ability to determine model performance over the entire flow regime. Periods of extreme low flow are represented by those flows exceeded 90-100% of the time, with high flows exceeded 0-10% of the time. The ranked duration curve for Willow Creek above Little Lake shows an acceptable fit between simulated and observed daily flows with high flows a bit too low and low flows a bit too high. The Willow Creek at Midhurst gauge is impacted by routing effects of Little Lake which are not included in the model. The ranked duration curve for the Lovers Creek gauge shows a very good match between simulated and observed flows.



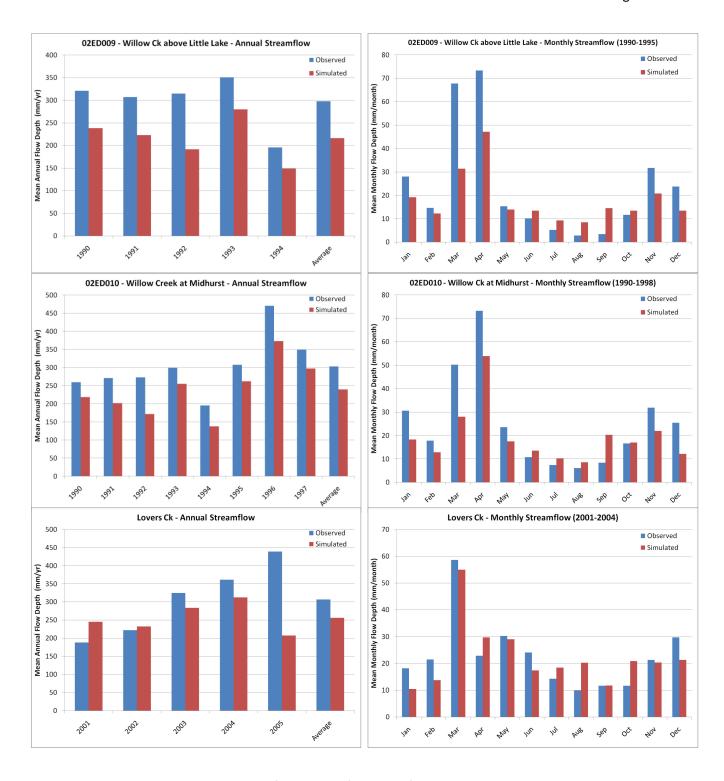


FIGURE 4-1 Annual and Monthly Streamflow Depths for Streamflow Calibration Results

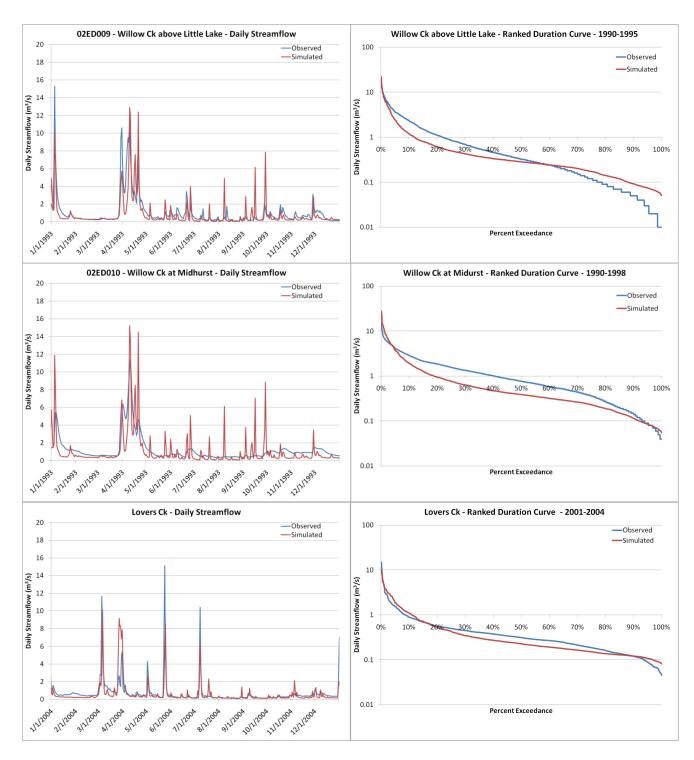


FIGURE 4-2 Daily Streamflow Hydrograph and Ranked Duration Curves for Streamflow Calibration Results

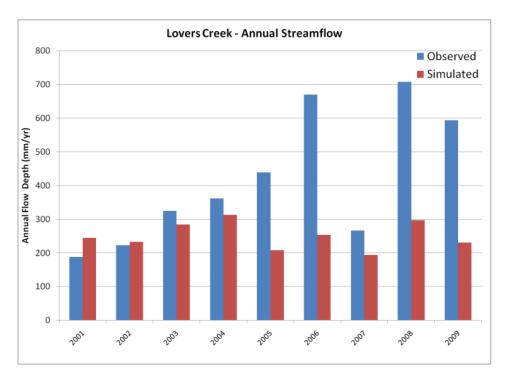


FIGURE 4-3 Annual Streamflow Depth at Lovers Creek Gauge from 2001-2009

The monthly calibration statistics for the three streamflow gauges are shown in Table 4-2. The R² values are reasonable for Willow Creek and a bit lower for Lovers Creek but still fairly reasonable. The Nash-Sutcliffe coefficients are fairly reasonable for the three gauges.

TABLE 4-2 R² and Nash-Sutcliffe Coefficients for Comparison of Monthly Streamflow for Calibration Period

Station Name	Calibration Period	Log R2	Log Nash-Sutcliffe
02ED009 - Willow Creek above Little Lake	1990 - July 1995	0.73	0.61
02ED010 - Willow Creek at Midhurst	1990 - May 1998	0.75	0.50
LS0101 - Lovers Creek at Tollendal	2001-2004	0.57	0.53

4.2.3 Verification Results

With the omission of the Lovers Creek gauge streamflow data from 2005 onward (Figure 4-3), the only streamflow data available for the verification period is the Willow Creek near Minesing gauge from April 2006 to December 2008. This gauge is located at Willow Creek below the confluence with Matheson Creek (Map 4-1) and therefore adds a new portion of the Study Area with which to validate the model.

Figure 4-4 shows the mean annual streamflow depth for 2007 and 2008 and the mean monthly streamflow depth for 2006-2008. The limited time period associated with observed streamflow values from this gauge limit the usefulness of this comparison, as a single misrepresented rainfall or snowmelt event may significantly skew the comparison. That being said, these figures show a reasonable match between simulated and observed streamflow. Similarly to the Willow Creek above Little Lake gauge, the spring flows are low; however the summer flows are matching well. Figure 4-5 shows the daily hydrograph for 2008 and the ranked duration curve. The summer low flows are matching reasonably



well; the main differences in the summer hydrographs appear to be due to climate (localized thunderstorms). The winter and spring low flows are lower than observed, which is also seen in the ranked duration curve.

Overall, the streamflow calibration and verification results show that the model is able to reasonably replicate observed streamflow conditions, particularly in the summer months when baseflow conditions are indicative of groundwater recharge.

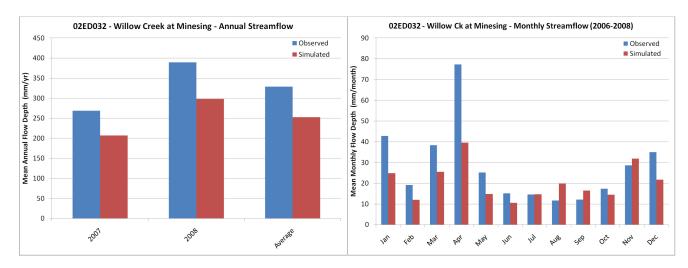


FIGURE 4-4 Annual and Monthly Streamflow Depths for Streamflow Verification Results

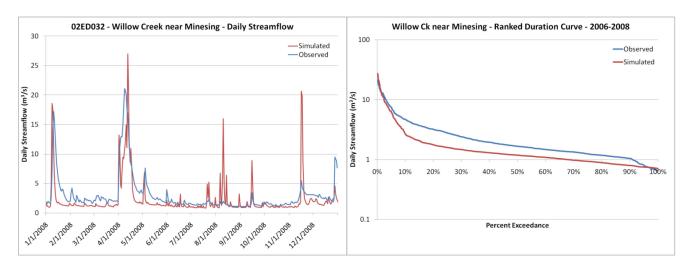


FIGURE 4-5 Daily Streamflow Hydrograph and Ranked Duration Curve for Streamflow Verification Results

4.3 Groundwater Calibration Results

To provide an indication of how well the MIKE SHE model is replicating groundwater conditions, simulated groundwater levels were compared to observed levels. It should be noted that groundwater conditions were not a primary observation set used during model calibration, but were rather used as a secondary confirmation of model performance. The following maps/metrics were used in the consideration of how well the MIKE SHE model was replicating saturated conditions:



- Simulated (Map 4-2) and interpreted (Map 4-3) groundwater level contours for Layer 1; and
- Groundwater performance statistics (Table 4-3).

The simulated water table contours are shown in Map 4-2 (i.e., the groundwater elevation for Layer 1) and the interpreted water table contours based on observed water levels in boreholes within Layer 1 are shown on Map 4-3. The borehole locations are also shown in Map 4.3. As shown on this map, there is a lack of data within the Minesing Wetland. The general patterns between the simulated and observed groundwater elevation contours are very similar. The Oro Moraine matches well, while the details in the observed water level contours are not replicated in the simulated contours. The smoothing of water level contours can be expected due to the simplification of the hydrostratigraphic layer structure in the MIKE SHE model.

A number of performance statistics were computed for both the shallow aquifer (Layer 1) and deep aquifer (Layer 3) as shown in Table 4-3. The normalized root mean square for both Layer 1 and 3 are less than 10%.

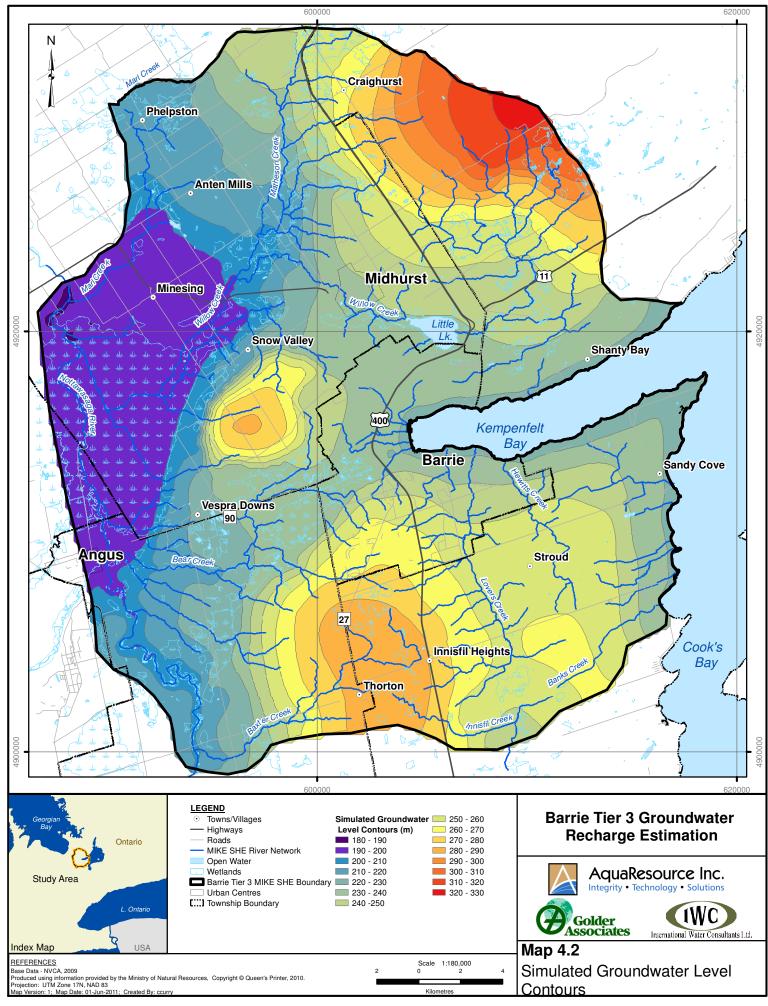
TABLE 4-3 Groundwater Performance Statistics

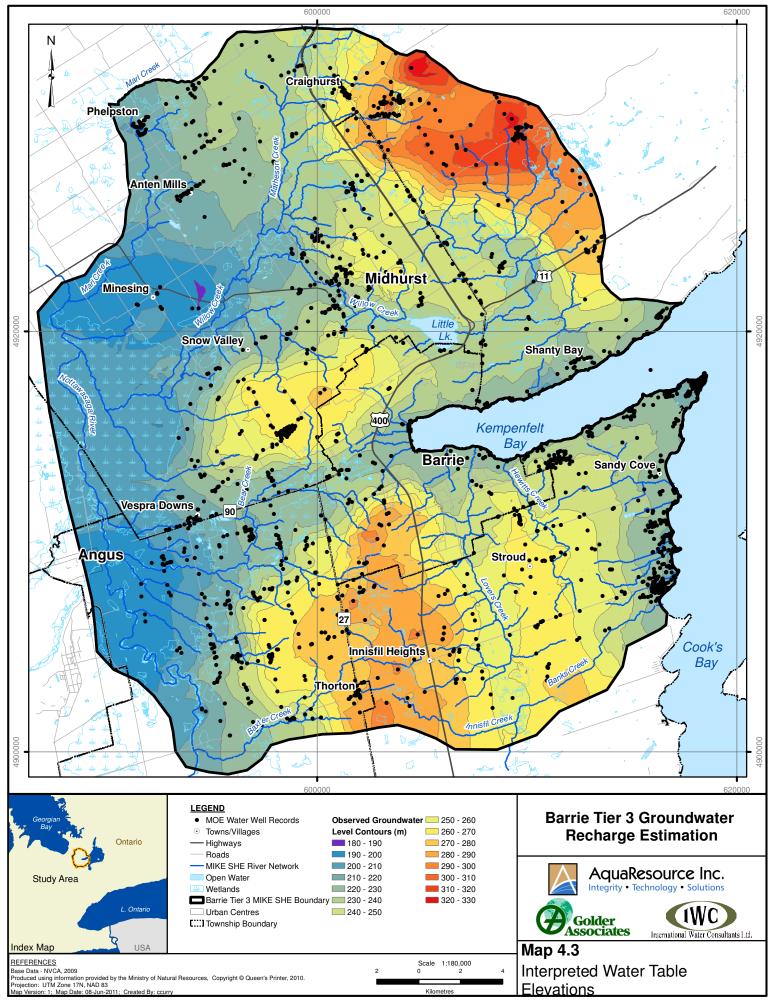
Metric	MIKE SHE Layer 1	MIKE SHE Layer 3
Number of Wells	1698	330
Mean Error	-7.3 m	-4.0 m
Mean Absolute Error	9.0 m	6.9 m
Root Mean Square Error (RMSE)	13.4 m	9.3 m
Normalized RMS	9.3 %	8.5%
Min Head	186.8 masl	181.4 masl
Max Head	331.0 masl	290.4 masl
R ²	0.82	0.63

4.4 Snow Depth Results

The snow depths recorded from the NVCA snow course survey near Colwell (Map 3-2) are shown in Figure 4-6 for 1990-2009. Measurements are taken on the first and fifteenth of the winter months (December 1st to May 1st). As seen from the figure, observed data is missing from 1992-1997. The snow depths were exported from MIKE SHE for the grid cell matching the snow course survey. The snow depths were compared by snow water equivalent (in mm). Due to the data gap in the observed timeseries, the mean monthly snow depths were compared from 1998-2009, as shown in Figure 4-7. There is very good agreement between the simulated and observed snow depths. This increases our confidence in the model's ability to simulate snow processes, although this confirmation is limited to the southern region. As this is the only snow survey in the Study Area, it was not possible to verify other portions of the Study Area, such as the northern region, where different climatic patterns occur.







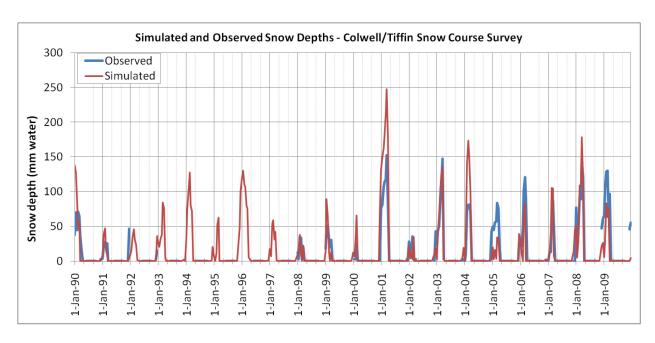


FIGURE 4-6 Timeseries of Simulated and Observed Snow Depth measurements

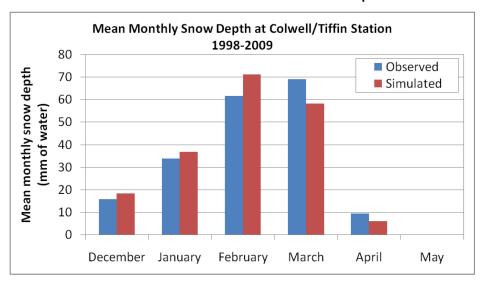


FIGURE 4-7 Mean Monthly Observed and Simulated Snow Depth for 1998-2009

5.0 MODEL OUTPUT

The model was run from 1987-2009 and output was taken for 1990-2009 to determine long-term water budget conditions. The mean annual water budget is presented in tabular and spatially distributed (mapping) formats below.

5.1 Water Budget

A water budget consists of computing the inflows and outflows to the model as well as any changes in storage. The mean annual water budget for 1990-2009 is listed in Table 5-1. The inflows to the model



are precipitation plus inflow through the model boundary. The total mean annual inflow to the model is 899 mm/yr. The outflow from the model includes evapotranspiration, any model boundary outflow, pumping from the groundwater system and streamflow. The total mean annual outflow from the model is 907 mm/yr. The total inflow (899 mm/yr) minus the total outflow (907 mm/yr) equals the change in storage (-8 mm/yr). Negative change in storage indicates a reduction in internal storage, whereby 8 mm/yr of outflow is from storage.

TABLE 5-1 Overall Mean Annual Water Budget of MIKE SHE Model (1990-2009)

	Water Budget Component	Mean Annual Rate (mm/yr)
>	Precipitation	895
Inflow	Boundary Inflow	4
Ξ	Total Inflow	899
	Evapotranspiration	549
>	Boundary Outflow	52
Outflow	Pumping	23
ō	Streamflow	281
	Total Outflow	907*
	Canopy Storage Change	0
i i	Snow Storage Change	-5
Change ir Storage	Overland Storage Change	0
Stc	Subsurface Storage Change	-3
J	Total Change in Storage	-8

^{*}Note: Addition of outflow values may not equal total outflow value. Difference due to rounding.

The equation used for evaluating the change in storage of the water budget includes factors for precipitation, evapotranspiration, streamflow, groundwater flow, and pumping that move water across the model boundaries (Equation 3.1). Because groundwater recharge/discharge is an internal process in this integrated model, it is not included in the equation.

Equation 5.1 MIKE SHE Water Balance

$$\Delta S = P - ET - Q_{SW} - Q_{GW} - PU$$

$$\Delta S = 895 - 549 - 281 - (52 - 4) - 23$$

$$\therefore \Delta S = -8 \frac{mm}{year} *$$

*Note: Values may not balance exactly due to rounding.

 ΔS - Change in Storage

P - Precipitation

ET - Evapotranspiration

 Q_{SW} - Streamflow or Surface Water Flow

 \mathcal{Q}_{GW} - Groundwater flow

PU - Pumping

E - Error



A summary of the key hydrologic processes is listed in Table 5-2, including precipitation, evapotranspiration, groundwater recharge and groundwater discharge; the processes are shown for each soil class and for the entire Study Area. These key processes are defined in Table 5-3 as they are computed in MIKE SHE.

The spatial distribution of evapotranspiration, groundwater recharge and groundwater discharge are shown on Map 5-1, Map 5-2, and Map 5-3, respectively. These maps illustrate the direct model output and are intended to show the regional trends in evapotranspiration, groundwater recharge and groundwater discharge; they reflect idealized local conditions and thus are not intended to be used for the precise cell-by-cell values. The groundwater recharge map is only recommended to be used as input in to the FEFLOW groundwater flow model.

Evapotranspiration is highest in areas where ponded water occurs (groundwater discharge areas) along Willow Creek, Lovers Creek and in Minesing Wetland. Evapotranspiration is also high in forested areas, such as within the Oro Moraine and near Anten Mills. Due to impervious land cover reducing soilwater content, evapotranspiration is lowest within the urban areas of the City of Barrie.

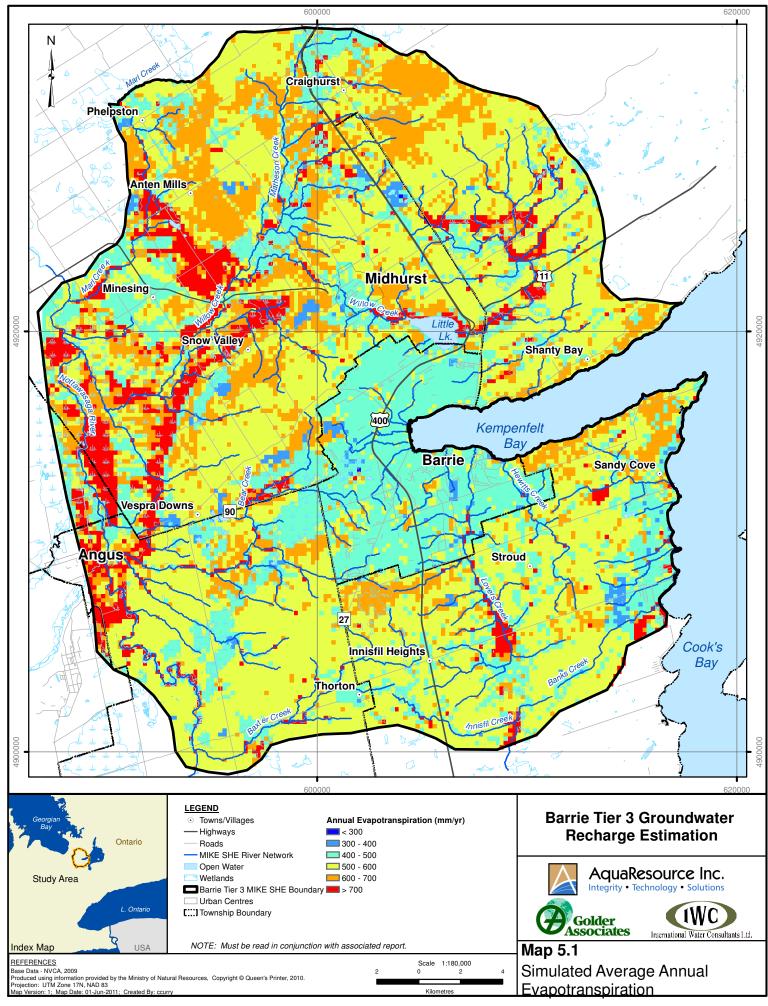
As can be expected, groundwater recharge is higher in areas with high permeability soils, i.e. sands and gravels, and lower in tighter soils, i.e., silts/tills, and clays. The urbanized areas within the City of Barrie have lower recharge rates due to the impervious fraction which limits the volume of water that can infiltrate. In the Study Area, the groundwater system plays a major role in determining groundwater recharge. In groundwater discharge areas (e.g., wetlands), recharge is zero or very low as the water table is at or near ground surface. The integrated model also provides insight regarding areas with very high recharge rates (e.g., >500 mm/yr). These areas are along the boundaries between soils of high permeability (gravels and sands) and low permeability (silts/ tills and clays). In these areas, the low permeability soils generate overland runoff that flows onto high permeability soils, where it infiltrates and recharges the groundwater system.

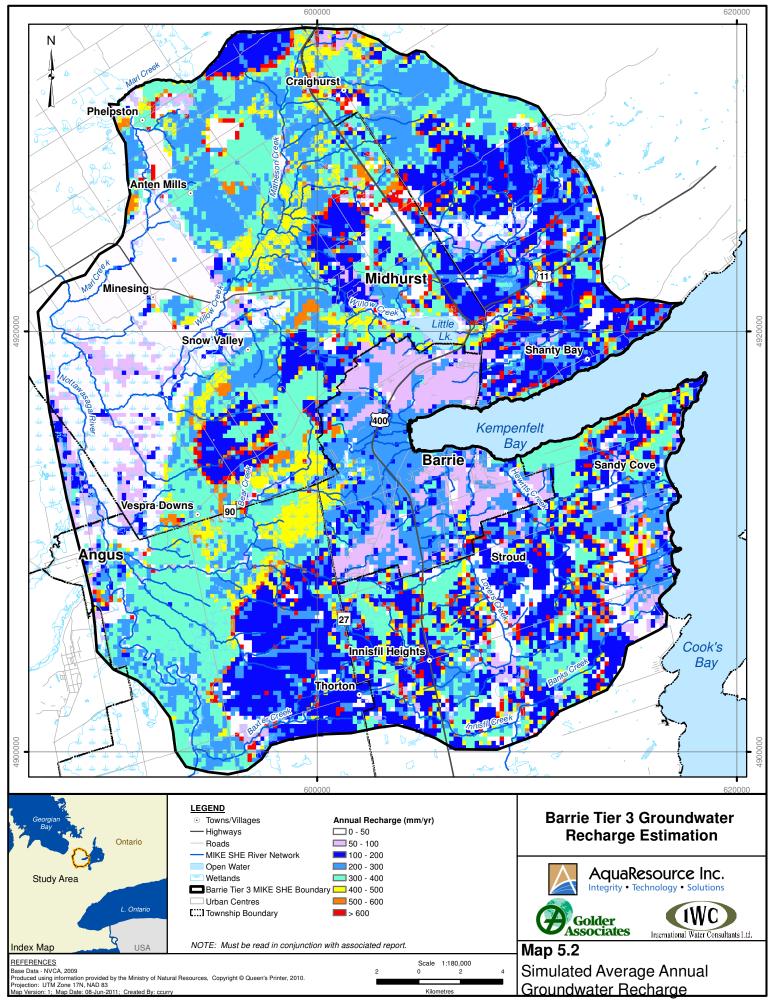
Groundwater discharge occurs when the water table is at ground surface, mainly in wetland areas. The highest discharge areas are along the main branches of Willow Creek, Matheson Creek, Bear Creek, Lovers Creek, Innisfil Creek and the Nottawasaga River. Groundwater discharge occurs at a lesser rate throughout the Minesing Wetland.

TABLE 5-2 Summary of Key Hydrologic Processes by Soil Class (1990-2009)

Soil Class	Total Area (km²)	Percent of Study Area (%)	Precipitation (mm/yr)	Evapotranspiration (mm/yr)	Groundwater Recharge (mm/yr)	Groundwater Discharge (mm/yr)
Gravel	168	21	899	546	370	5
Sand	238	30	889	561	351	249
Silt/Till	241	30	899	523	181	26
Clay	151	19	892	576	30	241
Study Area	797	100	895	549	243	129







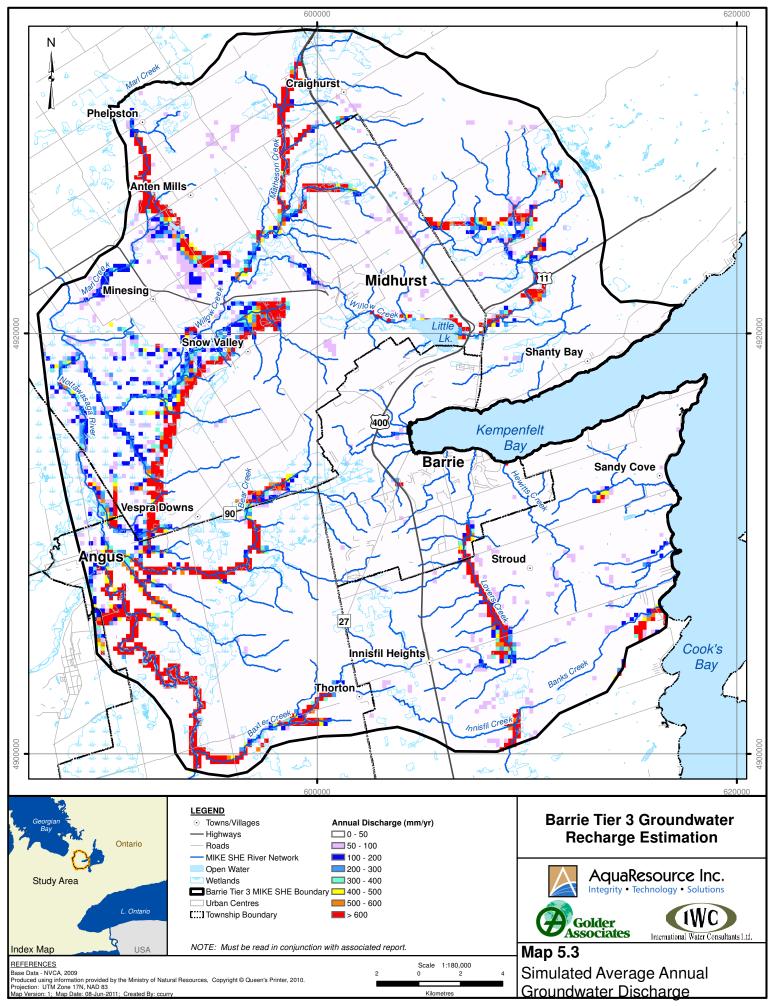


TABLE 5-3 Definition of Key Hydrologic Processes in MIKE SHE

Term	Definition in MIKE SHE
Evapotranspiration	Evaporation from snow, intercepted water, ponded water and soil + Transpiration from root zone + Evapotranspiration from saturated zone
Groundwater Recharge	Infiltration downward from the unsaturated zone to the saturated zone
Groundwater Discharge	Upward flow from saturated zone to overland flow + Saturated zone baseflow to rivers

5.2 Transient Groundwater Recharge Rates

Long-term transient, or time-varying, groundwater recharge rates are used for the transient evaluation of water levels within municipal pumping wells using the FEFLOW groundwater model. To obtain longterm transient groundwater recharge rates, the MIKE SHE model was run using all available climate data, i.e., from 1950-2009, with the first 3 years used as the 'warm up' period. This period includes two significant droughts; the most severe drought is in the 1960s and a less severe drought in the late 1990s. A timeseries of mean monthly groundwater recharge was computed from a representative grid cell for each climate zone (Map 3-2 and soil class (Map 3-6). There are a total of 5 climate zones and 4 soils groups, therefore 20 representative time series were generated. The representative grid cell was selected such that it was not located in a groundwater discharge zone and it was within 10 mm of the mean annual groundwater recharge rate over the represented climate zone/soil group (a few representative clay grid cells were outside this range, as fewer grid cells were located outside discharge areas). An example of the transient recharge is shown in Figure 5-1 for silt/tills in the Barrie climate zone. The monthly recharge varies significantly throughout the period. The black line shows the 12month moving average which highlights the long-term trends. The early 1960s and late 1990s show lower monthly recharge rates during these periods of drought. As the 1960s had lower groundwater recharge rates, it is recommended that this period be used in the Tier Three Risk Assessment.

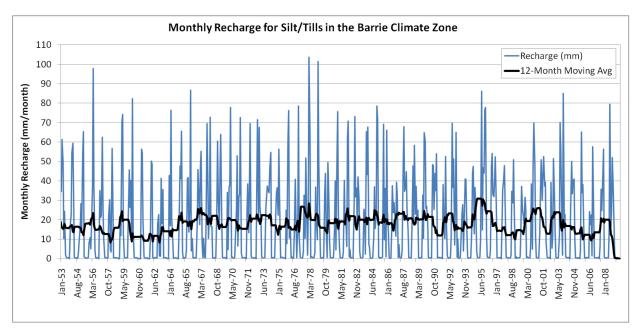


FIGURE 5-1 Example of Transient Groundwater Recharge Rates



6.0 SUMMARY AND RECOMMENDATIONS

A three dimensional, integrated model was constructed for the Barrie Tier Three Study Area (800 km²) using the MIKE SHE software. The model was calibrated using available streamflow data for three streamflow monitoring gauges:

- Willow Creek above Little Lake (1990-1995);
- Willow Creek at Midhurst (1990-1998); and
- Lovers Creek at Tollendal (2001-2004).

The model was then verified using streamflow data from a fourth stream gauge:

Willow Creek near Minesing (2006-2008).

An investigation of additional streamflow data at the Barrie Creeks gauges (2004-2009), the Lovers Creek gauge (2005-2009), and at spot flow measurement locations led to the conclusion that these data were not appropriate for model calibration. Additional calibration targets included groundwater elevations throughout the Study Area and snow depths from a snow survey in the southern portion of the Study Area. The calibration resulted in a reasonable match between simulated and observed data which provided confidence that the model output (i.e., groundwater recharge) is appropriate to use in the FEFLOW groundwater model.

The overall water budget and key hydrologic processes were computed and mapped. The mean annual groundwater recharge for the 1990-2009 period was used as input to the steady state FEFLOW groundwater model. Transient recharge rates were computed on a monthly basis from 1953-2009 and were used in the transient calibration of the FEFLOW model.

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BARRIE TIER THREE WATER BUDGET AND LOCAL AREA RISK ASSESSMENT RECHARGE ESTIMATION USING MIKE SHE

APPENDIX B1: MODELLED PUMPING RATES

Appendix B1 Modelled Pumping Rates

Table B-1 Well Information and 2008 and 2009 Pumping Rates

Major Category	Specific Purpose	Permit Number	Well ID	Model Easting	Model Northing	Top of Screen (m)	Bottom of Screen (m)	Community	Max Permitted (m³/d)	Well Name	2008 Rep./ Est.	2008 Data Source	2008 Average Consumptive Use (m³/d)	2009 Rep. /Est.	2009 Data Source	2009 Average Consumptive Use (m³/d)
Agricultural	Field and Pasture Crops	03-P-1069	69	596398	4912393	0.1	4.0		981.936	Dugout Pond	Est.		161.4	Est.		161.4
Agricultural	Field and Pasture Crops	1664-6W3MCU	158	596761	4934571	81.1	85.7		2589.12	Well 1	Est.		681.0	Rep.	2009 WTRS	0.0
Agricultural	Other - Agricultural	00-P-1210	2	602081	4908050	0.2	3.1		681.372	Dugout Pond	Rep.	2008 WTRS	5.3	Rep.	2009 WTRS	2.5
Commercial	Bottled Water	5524-6PEK3Q	347	605712	4905321	85.3	87.5		354.24	Well 1	Rep.	2008 WTRS	0.0	Rep.	2009 WTRS	0.0
Commercial	Bottled Water	5524-6PEK3Q	348	605968	4905369	71.9	78.0		792	Well 2	Rep.	2008 WTRS	0.0	Rep.	2009 WTRS	0.0
Commercial	Bottled Water	8141-7BYRP2	468	607723	4904671	22.6	25.0		400	Well 2	Est.		200.0	Est.		200.0
Commercial	Bottled Water	8141-7BYRP2	469	607723	4904671	22.6	25.0		400	Well 3	Est.		200.0	Est.		200.0
Commercial	Bottled Water	8531-6ASQXU	483	608252	4903121	62.8	65.8		720	Well 1	Est.		248.6	Est.		248.6
Commercial	Golf Course Irrigation	0040-733RE2	27	603756	4933236	81.7	86.9		981.936	Irrigation Well	Est.		339.0	Est.		339.0
Commercial	Golf Course Irrigation	0040-733RE2	28	603101	4932804	2.0	10.6		2945.808	Irrigation Pond	Rep.	2008 WTRS	138.8	Rep.	2009 WTRS	179.7
Commercial	Golf Course Irrigation	0040-733RE2	29	603126	4932775	66.1	67.1		65.462	Clubhouse Well	Rep.	2008 WTRS	1.3	Rep.	2009 WTRS	1.1
Commercial	Golf Course Irrigation	0386-7AMLUY	81	598132	4919616	62.5	68.9		1636.56	Well 1-4/93	Est.		1145.6	Rep.	2009 WTRS	33.9
Commercial	Golf Course Irrigation	0386-7AMLUY	82	598177	4919891	48.2	57.6		982	Well 2-1/93	Est.		687.4	Rep.	2009 WTRS	21.6
Commercial	Golf Course Irrigation	0386-7AMLUY	83	598008	4919625	48.2	57.6		2618.64	Irrigation Pond	Est.		753.3	Rep.	2009 WTRS	0.0
Commercial	Golf Course Irrigation	3124-6J5T9M	239	594132	4924022	0.7	41.7		564.403	Pump House	Est.		129.9	Rep.	2009 WTRS	2.1
Commercial	Golf Course Irrigation	3474-759GY9	255	610681	4920539	45.4	47.9		200	Heritage Well	Rep.	2008 WTRS	9.9	Rep.	2009 WTRS	19.9
Commercial	Golf Course Irrigation	3474-759GY9	256	610464	4920431	0.3	0.8		2000	Heritage Pond	Rep.	2008 WTRS	42.3	Rep.	2009 WTRS	54.2
Commercial	Golf Course Irrigation	4755-73RHNU	316	606539	4908998	13.7	15.2		6.72	Clubhouse Well	Rep.	2008 WTRS	3.0	Rep.	2009 WTRS	8.0
Commercial	Golf Course Irrigation	4755-73RHNU	317	606872	4909093	0.8	6.6		1091.04	Dugout Pond	Rep.	2008 WTRS	26.8	Rep.	2009 WTRS	129.9
Commercial	Golf Course Irrigation	5447-6QWR7W	343	594380	4908956	0.0	5.4		2561.22	Irrigation Pond	Rep.	2008 WTRS	102.3	Rep.	2009 WTRS	190.3
Commercial	Golf Course Irrigation	5813-6U2S3J	355	607415	4907971	0.2	4.0		1136.5	Irrigation Pond	Rep.	2008 WTRS	62.2	Rep.	2009 WTRS	59.6
Commercial	Golf Course Irrigation	5813-6U2S3J	356	607524	4907993	80.2	82.6		262.08	Well 2	Rep.	2008 WTRS	0.0	Rep.	2009 WTRS	0.0
Commercial	Golf Course Irrigation	5813-6U2S3J	357	607232	4907870	105.2	108.2		1569.6	Well 3	Rep.	2008 WTRS	0.0	Rep.	2009 WTRS	0.0
Commercial	Golf Course Irrigation	5813-6U2S3J	358	607151	4908478	36.6	40.2		31.822	Well 1	Rep.	2008 WTRS	3.0	Rep.	2008 WTRS	3.0



Commercial Golf Co Commercial Golf Co Commercial Mall / B Commercial Snowm Industrial Aggrega		Number	Well ID	Model Easting	Model Northing	Top of Screen (m)	Bottom of Screen (m)	Community	Max Permitted (m³/d)	Well Name	2008 Rep./ Est.	2008 Data Source	2008 Average Consumptive Use (m³/d)	2009 Rep. /Est.	2009 Data Source	2009 Average Consumptive Use (m³/d)
Commercial Golf Co Commercial Mall / B Commercial Snowm Industrial Aggregating	Course Irrigation	6824-68XPUW	404	606744	4910509	0.0	0.2		218.208	Main Irrigation Pond	Est.		50.2	Rep.	2009 WTRS	11.3
Commercial Mall / B Commercial Snowm Commercial Snowm Commercial Snowm Commercial Snowm Commercial Snowm Commercial Snowm Industrial Aggregation	Course Irrigation	7455-6QPLB5	423	599800	4908200	0.0	1.8		1817.76	Dugout Pond	Rep.	2008 WTRS	65.9	Rep.	2009 WTRS	71.5
Commercial Snowm Commercial Snowm Commercial Snowm Commercial Snowm Commercial Snowm Commercial Snowm Industrial Aggregation	Course Irrigation	7542-6P8M92	432	600566	4910182	43.9	48.5		327.058	Well 1/94	Est.		112.9	Est.		112.9
Commercial Snowm Commercial Snowm Commercial Snowm Commercial Snowm Commercial Snowm Industrial Aggregation	/ Business	5372-6SYPRA	340	603184	4909825	62.5	71.6		715.68	Well 1/06	Est.		39.2	Rep.	2009 WTRS	0.0
Commercial Snowm Commercial Snowm Commercial Snowm Commercial Snowm Industrial Aggregation	making	6845-6D7NUT	405	596189	4918575	0.0	2.1		13092.48	Pond Winter	Rep.	2008 WTRS	347.8	Rep.	2009 WTRS	155.6
Commercial Snowm Commercial Snowm Commercial Snowm Commercial Snowm Industrial Aggrega Industrial Cooling	making	6845-6D7NUT	406	596190	4918418	0.0	1.4		981.936	Pond 1 Winter	Rep.	2008 WTRS	32.0	Rep.	2009 WTRS	27.3
Commercial Snowm Commercial Snowm Commercial Snowm Industrial Aggregation	making	6845-6D7NUT	407	596004	4918188	0.0	1.0		981.936	Pond 2 Winter	Rep.	2008 WTRS	26.8	Rep.	2009 WTRS	26.5
Commercial Snowm Commercial Snowm Industrial Aggrega Industrial Cooling	making	6845-6D7NUT	408	595945	4918328	0.0	0.8		2618.496	Pond 3 Winter	Rep.	2008 WTRS	31.8	Rep.	2009 WTRS	45.7
Commercial Snowm Industrial Aggrega Industrial Cooling	making	6845-6D7NUT	409	596095	4918554	0.0	1.8		1309.248	Pond Summer	Est.		143.5	Est.		143.5
Industrial Aggregation Industrial Cooling	making	6845-6D7NUT	410	595878	4918441	0.0	1.2		523.699	Pond Summer	Est.		322.8	Est.		322.8
Industrial Cooling	making	6845-6D7NUT	411	595848	4918451	0.0	1.3		5564.304	Berry Hill Pond	Est.		914.7	Est.		914.7
C	egate Washing	4105-7EENGW	272	603760	4926740	0.0	0.4		7980	Source Pond	Rep.	2008 WTRS	19.7	Rep.	2009 WTRS	20.5
Miscellaneous Heat Pu	ng Water	6313-5Z4NC5	373	603300	4914507	47.9	52.7		300	Private Well	Est.		180.8	Est.		180.8
	Pumps :	2677-63PK84	216	604912	4911259	19.4	29.3		260	Well 2	Est.		0.0	Est.		0.0
Miscellaneous Heat Pu	Pumps :	2677-63PK84	217	608801	4916852	19.3	34.5		0.136	Well 2	Est.		0.0	Est.		0.0
Miscellaneous Heat Pu	Pumps :	2677-63PK84	218	608801	4916852	19.3	34.5		0.068	Injection Well 3	Est.		0.0	Est.		0.0
Miscellaneous Heat Pu	Pumps :	2677-63PK84	219	608801	4916852	19.3	34.5		0.095	Well 4	Est.		0.0	Est.		0.0
Miscellaneous Heat Pu	Pumps 9	92-P-3093	548	607394	4917219	45.1	45.7		98.194	Well 2	Est.		0.0	Est.		0.0
Recreational Other -	r - Recreational	5353-5W4LB8	333	598611	4922161	23.2	27.7		357.12	Artesian Well	Rep.	2008 WTRS	119.5	Rep.	2009 WTRS	212.4
Recreational Other -	r - Recreational	5353-5W4LB8	334	597977	4922110	23.2	27.7		1889.672	Pond	Rep.	2008 WTRS	126.5	Rep.	2009 WTRS	0.0
Remediation Ground	ndwater	1315-6W3QAS	135	600889	4915049	88.2	112.4		262.08	Well 1	Rep.	2008 WTRS	163.6	Rep.	2009 WTRS	143.7
Remediation Ground	ndwater	1315-6W3QAS	136	600950	4915097	19.8	35.1		458	Well 2	Rep.	2008 WTRS	308.3	Rep.	2009 WTRS	310.9
Remediation Ground	ndwater	1315-6W3QAS	137	601019	4915147	23.5	35.7		360	Well 3	Rep.	2008 WTRS	172.3	Rep.	2009 WTRS	273.2
Remediation Ground	ndwater !	5006-7CVGHZ	322	604814	4915929	17.5	37.1		130.9	Pump Station 1	Rep.	2008 WTRS	0.0	Rep.	2009 WTRS	0.0
Remediation Ground	ndwater !	5006-7CVGHZ	323	604814	4915929	17.5	37.1		589	Pump Station 2	Rep.	2008 WTRS	23.3	Rep.	2009 WTRS	17.5
Water Supply Campgr	ogrounds :	3772-6EQGSY	260	597740	4923757	73.1	73.2		38.7	Well 1	Est.		3.8	Est.		3.8
Water Supply Campgr	ogrounds :	3772-6EQGSY	261	597843	4923884	73.1	73.2		68.37	Well 3	Est.		6.7	Est.		6.7
Water Supply Campgr							33.2		46.44	Well 4	Est.		4.6	Est.		4.6



Major Category	Specific Purpose	Permit Number	Well ID	Model Easting	Model Northing	Top of Screen (m)	Bottom of Screen (m)	Community	Max Permitted (m³/d)	Well Name	2008 Rep./ Est.	2008 Data Source	2008 Average Consumptive Use (m ³ /d)	2009 Rep. /Est.	2009 Data Source	2009 Average Consumptive Use (m³/d)
Water Supply	Campgrounds	96-P-5022	570	595712	4911521	56.7	57.9		106.04	Well	Est.		12.2	Est.		12.2
Water Supply	Communal	02-P-1193	54	597842	4908046	101.8	122.1		326.88	Well 1	Rep.	2008 WTRS	5.8	Rep.	2009 WTRS	4.9
Water Supply	Communal	1586-62FLP2	151	611554	4918074	59.2	70.7		81	O'Brien House Well	Est.		16.2	Est.		16.2
Water Supply	Communal	6334-72JP7N	377	591987	4929882	36.6	40.2		547.2	Well 1	Est.		109.4	Rep.	2009 WTRS	5.4
Water Supply	Communal	6334-72JP7N	378	591979	4929876	36.3	39.3		655.2	Well 2	Est.		131.0	Rep.	2009 WTRS	4.9
Water Supply	Communal	87-P-3008	494	614679	4911754	74.4	78.0		1113.77	Well 1	Est.		371.3	Rep.	2009 WTRS	184.7
Water Supply	Communal	87-P-3008	495	614638	4911757	73.5	77.1		1113.77	Well 2	Est.		371.3	Rep.	2009 WTRS	182.5
Water Supply	Communal	87-P-3008	496	614512	4911771	43.6	49.7		1113.77	Well 3	Est.		371.3	Rep.	2009 WTRS	190.2
Water Supply	Municipal	00-P-1368	13	610360	4909456	105.8	110.3	Stroud	677.16	Well 1	Rep.	Town of Innisfil	165.6	Rep.	2009 WTRS	3.5
Water Supply	Municipal	00-P-1368	14	610356	4909438	102.1	107.0	Stroud	397.44	Well 2 Standby	Rep.	Town of Innisfil	165.6	Rep.	2009 WTRS	0.8
Water Supply	Municipal	00-P-1368	15	610386	4909474	103.9	109.7	Stroud	1637.28	Well 3	Rep.	Town of Innisfil	165.6	Rep.	2009 WTRS	489.5
Water Supply	Municipal	0421-7B4TCZ	86	591722	4909066	46.6	54.0	Angus	1296	Well 1 (McGeorge)	Rep.	NVCA	305.8	Rep.	2009 WTRS	194.6
Water Supply	Municipal	0421-7B4TCZ	87	591721	4909070	46.3	53.6	Angus	1296	Well 2 (McGeorge)	Rep.	NVCA	283.2	Rep.	2009 WTRS	378.0
Water Supply	Municipal	0421-7B4TCZ	89	591558	4907667	36.3	39.9	Angus	1800	Well 4	Rep.	NVCA	0.0	Rep.	2009 WTRS	3.9
Water Supply	Municipal	0421-7B4TCZ	90	591587	4907673	36.6	39.6	Angus	654.624	Well 5	Rep.	NVCA	0.0	Rep.	2009 WTRS	15.4
Water Supply	Municipal	0421-7B4TCZ	91	591567	4907669	37.8	39.0	Angus	1800	Well 6	Rep.	NVCA	0.0	Rep.	2009 WTRS	97.5
Water Supply	Municipal	0507-6B9S5G	96	601910	4921975	73.2	77.7	Midhurst	622	Well 2	Rep.	NVCA	129.2	Rep.	2009 WTRS	110.9
Water Supply	Municipal	0507-6B9S5G	97	601894	4921956	70.7	78.6	Midhurst	2900	Well 3	Rep.	NVCA	436.7	Rep.	2009 WTRS	386.5
Water Supply	Municipal	0507-6B9S5G	98	601427	4921884	69.8	75.9	Midhurst	2000	Well 4	Rep.	NVCA	209.6	Rep.	2009 WTRS	217.5
Water Supply	Municipal	0507-6B9S5G	99	601513	4920127	79.2	83.5	Midhurst	1068	Well 5	Rep.	NVCA	304.2	Rep.	2009 WTRS	280.8
Water Supply	Municipal	0621-62MR3A	106	594314	4911296	58.2	64.3	Vespra Downs	168.9	Well 1-93	Rep.	NVCA	38.9	Rep.	NVCA	38.9
Water Supply	Municipal	0621-62MR3A	107	594336	4911308	57.6	60.7	Vespra Downs	168.9	Well 1-91	Rep.	NVCA	0.3	Rep.	2009 WTRS	0.2
Water Supply	Municipal	1732-5YHR7D	164	614518	4907629	14.9	17.4	Alcona	262.973	Well 1B	Rep.	Golder	0.0	Rep.	Golder	0.0
Water Supply	Municipal	1732-5YHR7D	165	614540	4907749	16.9	18.8	Alcona	262.973	Well 2	Rep.	Golder	0.0	Rep.	Golder	0.0
Water Supply	Municipal	1732-5YHR7D	166	614659	4907911	78.0	82.6	Alcona	468.846	Well 3	Rep.	Golder	0.0	Rep.	Golder	0.0
Water Supply	Municipal	1732-5YHR7D	167	614663	4907898	76.5	84.1	Alcona	539.149	Well 3B	Rep.	Golder	0.0	Rep.	Golder	0.0
Water Supply	Municipal	1732-5YHR7D	168	614961	4908001	67.1	70.1	Alcona	294.882	Well 4R	Rep.	Golder	0.0	Rep.	Golder	0.0
Water Supply	Municipal	1732-5YHR7D	169	614415	4908117	19.5	22.6	Alcona	306.985	Well 5	Rep.	Golder	0.0	Rep.	Golder	0.0



Major Category	Specific Purpose	Permit Number	Well ID	Model Easting	Model Northing	Top of Screen (m)	Bottom of Screen (m)	Community	Max Permitted (m³/d)	Well Name	2008 Rep./ Est.	2008 Data Source	2008 Average Consumptive Use (m ³ /d)	2009 Rep. /Est.	2009 Data Source	2009 Average Consumptive Use (m ³ /d)
Water Supply	Municipal	1732-5YHR7D	170	614967	4908022	71.9	74.9	Alcona	363.101	Well 6	Rep.	Golder	0.0	Rep.	Golder	0.0
Water Supply	Municipal	2372-75VHJ5	201	601784	4920238	68.6	73.2	Midhurst	466.56	Del Trend Well 1	Rep.	NVCA	11.1	Rep.	NVCA	11.1
Water Supply	Municipal	2372-75VHJ5	202	601795	4920244	64.0	68.6	Midhurst	466.56	Del Trend Well 2	Rep.	NVCA	17.7	Rep.	2009 WTRS	4.0
Water Supply	Municipal	2372-75VHJ5	203	601776	4920263	61.3	71.3	Midhurst	786.24	Del Trend Well 3	Rep.	NVCA	75.7	Rep.	2009 WTRS	120.9
Water Supply	Municipal	2828-7GDPJ2	225	603373	4914759	96.0	107.0	Barrie	6552	Well 3A	Rep.	NVCA	2378.6	Rep.	NVCA	2378.6
Water Supply	Municipal	2828-7GDPJ2	226	607015	4917670	80.2	97.2	Barrie	6552	Well 13	Rep.	NVCA	1995.2	Rep.	NVCA	1995.2
Water Supply	Municipal	2828-7GDPJ2	227	603330	4915148	50.0	56.1	Barrie	6552	Well 4	Rep.	NVCA	1695.0	Rep.	NVCA	1695.0
Water Supply	Municipal	2828-7GDPJ2	228	602927	4914267	88.4	106.7	Barrie	6552	Well 5	Rep.	NVCA	2893.7	Rep.	NVCA	2893.7
Water Supply	Municipal	2828-7GDPJ2	229	602484	4914189	85.3	100.6	Barrie	6552	Well 7	Rep.	NVCA	4756.1	Rep.	NVCA	4756.1
Water Supply	Municipal	2828-7GDPJ2	230	607042	4917649	77.1	93.0	Barrie	6552	Well 9	Rep.	NVCA	3457.0	Rep.	NVCA	3457.0
Water Supply	Municipal	2828-7GDPJ2	231	606225	4912601	85.6	93.3	Barrie	4546	Well 10	Rep.	City of Barrie	2124.0	Rep.	City of Barrie	2124.0
Water Supply	Municipal	2828-7GDPJ2	232	604690	4915794	47.2	61.3	Barrie	9100	Well 11	Rep.	NVCA	3248.7	Rep.	NVCA	3248.7
Water Supply	Municipal	2828-7GDPJ2	233	604499	4914593	73.8	88.7	Barrie	9100	Well 12	Rep.	City of Barrie	2124.0	Rep.	City of Barrie	2124.0
Water Supply	Municipal	2828-7GDPJ2	234	604660	4915782	39.6	61.0	Barrie	9100	Well 14	Rep.	NVCA	1634.9	Rep.	NVCA	1634.9
Water Supply	Municipal	2828-7GDPJ2	235	604411	4915199	45.7	51.2	Barrie	9100	Well 15	Rep.	City of Barrie	2124.0	Rep.	City of Barrie	2124.0
Water Supply	Municipal	2828-7GDPJ2	236	604037	4919591	61.3	73.5	Barrie	7862	Well 16	Rep.	NVCA	4778.8	Rep.	NVCA	4778.8
Water Supply	Municipal	2828-7GDPJ2	237	601953	4913766	77.1	86.3	Barrie	11232	Well 17	Rep.	NVCA	3166.4	Rep.	NVCA	3166.4
Water Supply	Municipal	2828-7GDPJ2	238	602010	4913778	87.5	106.1	Barrie	11232	Well 18	Rep.	NVCA	3217.3	Rep.	NVCA	3217.3
Water Supply	Municipal	2828-7GDPJ2	599	601385	4913027	84.4	93.6	Barrie	7862.4	Well 19	Rep.	City of Barrie	0.0	Rep.	City of Barrie	0.0
Water Supply	Municipal	4624-6HKPJW	307	600803	4931465	24.4	27.4	Craighurst	64	Well 1	Rep.	SSEA	0.1	Rep.	2009 WTRS	0.0
Water Supply	Municipal	4624-6HKPJW	308	600807	4931504	24.1	25.9	Craighurst	140	Well 2	Rep.	SSEA	11.5	Rep.	2009 WTRS	11.1
Water Supply	Municipal	4624-6HKPJW	309	600830	4931482	29.0	30.8	Craighurst	229	Well 3	Rep.	SSEA	20.7	Rep.	2009 WTRS	19.8
Water Supply	Municipal	6733-6GDQYK	397	592395	4921852	29.6	34.7	Minesing	327	Well 2	Rep.	Golder	119.0	Rep.	2009 WTRS	73.8
Water Supply	Municipal	6733-6GDQYK	398	592369	4921832	30.5	35.1	Minesing	327	Well 3	Rep.	Golder	119.0	Rep.	2009 WTRS	1.4
Water Supply	Municipal	6733-6GDQYK	399	592390	4921798	34.4	38.1	Minesing	412	Well 4	Rep.	Golder	137.0	Rep.	2009 WTRS	0.0
Water Supply	Municipal	7274-6K8R94	418	601508	4902530	48.5	51.5	Thornton	522.72	Well 1	Rep.	NVCA	106.7	Rep.	NVCA	106.7
Water Supply	Municipal	7274-6K8R94	419	601528	4902528	46.6	49.7	Thornton	522.72	Well 2	Rep.	NVCA	121.6	Rep.	NVCA	121.6
Water Supply	Municipal	7274-6K8R94	420	601457	4903056	27.4	31.1	Thornton	492.48	TW1-69	Rep.	NVCA	82.1	Rep.	2009 WTRS	83.3



Major Category	Specific Purpose	Permit Number	Well ID	Model Easting	Model Northing	Top of Screen (m)	Bottom of Screen (m)	Community	Max Permitted (m³/d)	Well Name	2008 Rep./ Est.	2008 Data Source	2008 Average Consumptive Use (m³/d)	2009 Rep. /Est.	2009 Data Source	2009 Average Consumptive Use (m³/d)
Water Supply	Municipal	7274-6K8R94	421	601446	4903058	25.9	29.0	Thornton	325.32	Tw2-69	Rep.	NVCA	59.8	Rep.	2009 WTRS	61.7
Water Supply	Municipal	7511-5MLRGP	426	593955	4926082	64.9	68.0	Anten Mills	417.6	Well 1	Rep.	Golder	138.0	Rep.	2009 WTRS	0.4
Water Supply	Municipal	7511-5MLRGP	427	593940	4926072	65.2	68.3	Anten Mills	360	Well 2	Rep.	Golder	120.0	Rep.	2009 WTRS	0.4
Water Supply	Municipal	7511-5MLRGP	428	593932	4926084	59.1	66.8	Anten Mills	780	Well 3	Rep.	Golder	283.0	Rep.	2009 WTRS	158.6
Water Supply	Municipal	7520-6LJTGX	429	613036	4918913	54.0	58.5	Shanty Bay	305	Well 1	Rep.	SSEA	42.7	Rep.	2009 WTRS	34.7
Water Supply	Municipal	7520-6LJTGX	430	613042	4918902	40.8	45.4	Shanty Bay	305	Well 2	Rep.	SSEA	48.8	Rep.	2009 WTRS	47.0
Water Supply	Municipal	7520-6LJTGX	431	613027	4918911	58.5	65.8	Shanty Bay	610	Well 3	Rep.	SSEA	54.9	Rep.	2009 WTRS	68.7
Water Supply	Municipal	7650-6CFRPK	435	596698	4918601	62.5	72.5	Snow Valley	1634.4	Well 3	Rep.	NVCA	175.5	Rep.	2009 WTRS	43.2
Water Supply	Municipal	7650-6CFRPK	436	596700	4918617	62.8	72.5	Snow Valley	1634.4	Well 4	Rep.	NVCA	0.5	Rep.	2009 WTRS	135.0
Water Supply	Municipal	7650-6CFRPK	437	597076	4919325	59.4	65.5	Snow Valley	700	Well 1	Rep.	NVCA	53.2	Rep.	2009 WTRS	55.6
Water Supply	Municipal	7650-6CFRPK	438	597075	4919340	61.0	67.1	Snow Valley	700	Well 2	Rep.	NVCA	53.8	Rep.	2009 WTRS	58.1
Water Supply	Municipal	8306-7JYPWU	472	605518	4905031	68.3	77.4	Innisfil Heights	2937.6	Well 2	Rep.	Town of Innisfil	170.1	Rep.	2009 WTRS	219.2
Water Supply	Municipal	8306-7JYPWU	473	605560	4904863	61.3	68.9	Innisfil Heights	3110.4	Well 3	Rep.	Town of Innisfil	170.1	Rep.	2009 WTRS	184.2
Water Supply	Municipal	00-P-1370	16	616284	4910121	65.5	70.1	Alcona	228.96	Well 1	Rep.	Golder	0.0	Rep.	2009 WTRS* Golder	53.4 0.0
Water Supply	Municipal	00-P-1370	17	616213	4910177	48.8	52.4	Alcona	249.12	Well 2	Rep.	Golder	0.0	Rep.	2009 WTRS* Golder	70.4 0.0
Water Supply	Municipal	00-P-1370	18	616317	4910201	35.0	37.5	Alcona	0	Well 3	Est.	Golder	0.0	Est.	Golder	0.0

 $[\]hbox{^*\,MOE\, records from the Water\, Taking\, Reporting\, System\, do\, not\, agree\, with\, local\, understanding.}$





BARRIE TIER THREE WATER BUDGET AND LOCAL AREA RISK ASSESSMENT

APPENDIX C: GROUNDWATER FLOW MODEL CONSTRUCTION AND CALIBRATION (COMPANION REPORT)



CITY OF BARRIE GROUNDWATER FLOW MODEL CONSTRUCTION AND CALIBRATION TECHNICAL MEMORANDUM

Report Prepared for:

LAKE SIMCOE REGION CONSERVATION AUTHORITY

Prepared by:

AQUARESOURCE
A Division of
MATRIX SOLUTIONS INC.



July 2013 Breslau, Ontario



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DISCLAIMER

We certify that we supervised and carried out the work as described in this report. The report is based on and limited by circumstances and conditions referred to throughout the report and on information available at the time of the site investigation. AquaResource has exercised reasonable skill, care and diligence to assess the information acquired during the preparation of this report. AquaResource believes this information is accurate but cannot guarantee or warrant its accuracy or completeness. Information provided by others was believed to be accurate but cannot be guaranteed.

This report is prepared for the sole benefit of Lake Simcoe Region Conservation Authority, and is solely warranted for the purposes outlined in this report. Any uses which a third party makes of this report, or any reliance on decisions made based on it, are the responsibility of such third parties. AquaResource, a Division of Matrix Solutions Inc. accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report.

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A Division of
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TABLE OF CONTENTS

1.0	INTRO	DUCTION	V	1							
	1.1	Overvie	ew	1							
	1.2	Study A	Area	1							
	1.3	Project	Goals and Objectives	2							
	1.4	Scope a	and Approach	3							
2.0	HYDR	OGEOLOG	GIC FRAMEWORK UPDATE	3							
	2.1	Concep	otual Model Modifications	3							
	2.2	Concep	otual Model Overview	5							
	2.3	Hydrogeologic Unit Mapping									
	2.4	3-D Hy	drogeologic Unit Model	6							
3.0	GROU	NDWATE	R FLOW MODEL	6							
	3.1	Modell	ing Process	7							
		3.1.1	Model Set Up	7							
		3.1.2	Steady-State Calibration.	7							
		3.1.3	Transient Calibration/Long Term Verification	8							
		3.1.4	Sensitivity Analysis	8							
	3.2	Model	8								
	3.3	3-D Fin	ite Element Mesh	9							
	3.4	Bounda	ary Conditions	9							
		3.4.1	External Regional Flow Boundary Conditions	10							
		3.4.2	Surface Water Boundary Conditions	10							
			3.4.2.1 Rivers and Streams	11							
			3.4.2.2 Lakes and Wetlands	11							
		3.4.3	Recharge	12							
		3.4.4	Pumping Wells	12							
	3.5	Model	Properties	13							
		3.5.1	Hydraulic Conductivity	13							
		3.5.2	Unsaturated Flow Parameters	14							
	3.6	Transient Model Setup									
		3.6.1	Aquifer Storage	14							



4.0	CALIBI	RATION A	PPROACH	16						
	4.1	Steady-	State Calibration Datasets	17						
		4.1.1	Surface Water Data Set	17						
		4.1.2	Hydraulic Head Data Set	17						
		4.1.3	High Quality Datasets	18						
		4.1.4	Transient Calibration Dataset	18						
		4.1.5	Calibration Measures	19						
5.0	CALIBI	RATION R	ESULTS	20						
	5.1	Quantit	ative Assessment	20						
		5.1.1	Calibration to Baseflow Estimates	20						
		5.1.2	Calibration to Hydraulic Heads	21						
		5.1.3	Transient Calibration Results	27						
	5.2	Qualita	tive Assessment	30						
		5.2.1	Simulated Shallow Aquifer (A1) Equipotential Contours	30						
		5.2.2	Simulated Deep Aquifer (A3) Equipotential Contours	31						
		5.2.3	Vertical Hydraulic Gradient	31						
		5.2.4	Groundwater Discharge to Surface Water	31						
	5.3	Overall	Groundwater Model Calibration Assessment	32						
6.0	GROU	NDWATE	R FLOW MODEL LIMITATIONS	32						
	6.1	Scale		33						
	6.2	Charact	erization Data	33						
	6.3	Calibra	tion Data	33						
	6.4	Limitati	ons of the Modelling Approach	34						
7.0	SUMN	1ARY AND	CONCLUSIONS	35						
8.0	REFER	ENCES		35						
			LIST OF FIGURES							
FIGUR	E 5.1	Com	parison of Simulated and Observed Baseflow (m³/s) for 1980-2010	21						
FIGUR	E 5.2	Scat	Scatter Plot of Calibration Residuals by Aquifer							
FIGUR	E 5.3	Calc	Calculated Vs. Observed Range of Head within the City of Barrie Monitoring Networ							
FIGUR	F 5.4	Cum	ulative Probability Distribution Plot							
		Juil		· · · · · · · · · /						



LIST OF TABLES

TABLE 2.1	Hydrostratigraphic units within the Study Area5		
TABLE 3.1	Lakes Simulated in the FEFLOW Model		
TABLE 3.2	Initial Hydraulic Conductivity Estimates		
TABLE 3.3	Regional Storage Coefficients		
TABLE 3.4	Well Field Storage Coefficients		
TABLE 5.1	City of Barrie Monitoring Network and Pumping Wells - Water Levels24		
	LIST OF APPENDICES		
APPENDIX C1	Maps		
APPENDIX C2	Modelled Pumping Wells		
APPENDIX C3	Transient Model Results by Monitoring Well		
	LIST OF MAPS		
MAP 1.1	Study Area		
MAP 3.1	2-D Finite Element Mesh		
MAP 3.2	3-D Finite Element Mesh		
MAP 3.3	Boundary Conditions		
MAP 3.4	Recharge Distribution		
MAP 4.1	Streamflow Gauges and Monitoring Wells		
MAP 4.2	City of Barrie Monitoring Network		
MAP 5.1	Spatial Residuals		
MAP 5.2	Calibrated Model Hydraulic Conductivity A1		
MAP 5.3	Calibrated Model Hydraulic Conductivity A2		
MAP 5.4	Calibrated Model Hydraulic Conductivity A3		
MAP 5.5	Calibrated Model Hydraulic Conductivity A4		
MAP 5.6	Simulated Shallow (A1) Equipotential Contours		
MAP 5.7	Simulated Deep (A3) Equipotential Contours		
MAP 5.8	Vertical Hydraulic Gradient		
MAP 5.9	Groundwater Discharge to Surface Water		



1.0 INTRODUCTION

1.1 Overview

The Lake Simcoe Region Conservation Authority (LSRCA) has undertaken a Tier Three Water Budget and Local Area Risk Assessment for the City of Barrie, as recommended within the Tier Two Assessment (Golder and AquaResource 2010). The Barrie Creeks subwatershed (within the City of Barrie) was identified through the Tier Two Water Budget and Stress Assessment analysis as having a moderate to significant potential for stress; as such it qualifies for more rigorous Tier Three review.

Earlier studies in the area (Golder 2004; Golder 2009) focused on delineating wellhead protection areas for the municipalities within south Simcoe County. The characterization phase of this work provided the conceptual foundation for individual numerical models of each municipality as well as for subsequent studies and investigations. A key outcome was the characterization of the complex aquifer system into a refined hydrogeologic framework consisting of eight distinct hydrogeologic units and a groundwater flow model used to delineate wellhead protection areas (WHPAs) for the City of Barrie. This model was a 3D fully-saturated model with static recharge derived from water budget methods and provided a sound understanding of the local flow patterns surrounding the Barrie municipal wells. A regional numerical groundwater model was also developed for the Tier Two study (Golder and AquaResource 2010) in the NVCA, LSRCA and SSEA watersheds, which incorporated the City of Barrie. This model was built upon the combined conceptual models developed during the South Simcoe studies and provides the general regional context for groundwater flow around the City of Barrie. Both of the previous models were focused on regional, rather than local, flow systems and features.

As outlined in the Conceptual Understanding Memo (AquaResource et al. 2011a), the Barrie Study Area (Appendix C.1, Map 1.1) contains the urban well fields within the City of Barrie as the primary focus. The Study Area is slightly larger than the previous Barrie FEFLOW model from the South Simcoe Studies (Golder 2004), and encompasses the modelled capture zones of the well fields of interest, aligned with natural flow divides where possible, and includes portions of Lake Simcoe so that surface water interaction can be accounted for. The model is simulated in unsaturated mode so that the water table can be accurately approximated which is important in this particular Study Area because of the high variability in topography. The goal of the Tier Three assessment is to evaluate the quantitative reliability of the water supply system for the well fields within the Barrie Study Area and to identify potential threats to that reliability. The assessment is centered on a highly refined area surrounding the Barrie Municipal Wells.

1.2 Study Area

The City of Barrie is located at the western end of Kempenfelt Bay of Lake Simcoe, in the center of the Study Area (Map 1.1). The current (2010) population is approximately 135,000 persons (City of Barrie Planning Services), almost all of whom are serviced by the municipal water supply. The municipal water supply is currently based on groundwater; however, a surface water source, on the south shore of Kempenfelt Bay (Lake Simcoe) has recently (August 2011) been commissioned to service the southern pressure zones within the City of Barrie. The majority of the water supply wells lie within the Barrie Creeks subwatershed which was identified in the Tier Two Water Budget and Stress Assessment (Golder and AquaResource 2010) as having a significant potential for stress; the municipal system is required to undergo a more rigorous Tier Three analysis.



The Study Area boundary was delineated for the Tier Three analysis to contain the urban well fields within the City of Barrie as well as the municipal systems in Midhurst (Township of Springwater), and Innisfil Heights and Stroud (Town of Innisfil), given their proximity to the City of Barrie. This boundary encompasses the modelled capture zones of these well fields (as determined by the WHPA model, Golder 2004) and further extends to the natural surface water and groundwater subwatershed boundaries as determined by equipotential and surface water feature maps (see Conceptual Understanding Report, AquaResource et al. 2011a). The complete Study Area covers an area of 800 km² and occupies both the Nottawasaga River watershed and the Lake Simcoe watershed within Simcoe County; however, the primary focus of the characterization study is on the City of Barrie and the immediate surrounding area. The Focus Area, which centers on the City of Barrie well field, is presented on Map 1.1.

1.3 Project Goals and Objectives

The goal of the current phase of work was to develop and calibrate a three-dimensional numerical groundwater flow model that incorporates a refined hydrogeologic model to facilitate a better understanding of the three-dimensional groundwater flow system as part of a risk assessment analysis for a Tier Three Water Budget.

The calibrated groundwater model described in this document has been developed based on the conceptualization of the geology and hydrogeology throughout the region completed by Golder (2004, 2009) as summarized in the Conceptual Understanding Report (AquaResource et al. 2011a). The model was developed using the groundwater modelling code FEFLOW (DHI-WASY 2009) and is appropriate for many applications and uses in water management, including assessment of well capture zones, determination of groundwater under the direct influence of surface water, evaluation of aquifer interconnectivity and interference between supply wells, and calculation of surface to well or surface to aquifer advection times.

Given the local scale, the calibrated groundwater model presented in this document is sufficiently detailed to provide the basis for a Tier Three analysis which includes the following components:

- 1. Calculate a local water budget;
- 2. Analyze flow patterns, water supply and demand;
- 3. Assess risk and evaluate environmental impacts of pumping;
- 4. Map vulnerable areas; and
- 5. Perform uncertainty analysis to assess data and knowledge gaps for future planning including but not limited to:
 - Factors/formations influencing flow;
 - Influence and interaction with surface water features;
 - Understand key uncertainties that influence flow direction.

The groundwater flow model was developed jointly by AquaResource, Golder Associates and International Water Consultants. The team experience provides site specific knowledge and expertise of



the hydrogeologic framework and advanced model expertise to provide a defendable approach to understanding the 3D groundwater flow in a local setting.

1.4 Scope and Approach

This document describes the groundwater model calibration. Section 2.0 provides a summary of the Hydrogeologic Framework defined within the Conceptual Understanding Report (AquaResource et al. 2010). Section 3.0 presents and discusses the model construction. The overall approach to the calibration is presented in Section 4.0 with emphasis on what constitutes a good calibration given the objectives described above, as well as an introduction to the observed data used in calibrating the model. Section 5.0 presents the calibration results and includes a discussion of the model calibration at the well field scale with emphasis on high quality data. Section 6.0 summarizes the limitations of the groundwater flow model and Section 7.0 presents conclusions.

2.0 HYDROGEOLOGIC FRAMEWORK UPDATE

The hydrostratigraphic layer structure was developed in an earlier phase of the project and builds upon previous studies throughout the area, many of which have been modelled in smaller, individual models throughout the Study Area. For additional information on the hydrostratigraphic model, refer to the Conceptual Understanding Report (AquaResource et al. 2011a).

The hydrostratigraphic units developed throughout the South Simcoe and Tier 2 studies consist of eight major overburden units. Of the overburden units, there are four main aquifers (A1-A4) and four main aquitards (C1-C4) that constitute the numerical model layers within those studies. Within the numerical model layer structure, the uppermost main aquifer was further subdivided throughout model calibration of those models, mostly in the upland regions of the current Study Area where thicknesses were in excess of 140 metres. Because of its importance to municipal water supply as well as its thickness within the City of Barrie, the main production aquifer, A3, was subdivided into four layers within those models to increase the vertical resolution. Furthermore, a confining layer (UC) over the uppermost aquifer, A1, was added to accommodate for stream bed conductance and to control excessive drainage in the highlands. It is important to note that the original numerical model in the South Simcoe studies was simulated in fully-saturated mode whereas the current modeling will simulate variably saturated conditions.

2.1 Conceptual Model Modifications

Upon inspection of the surface isopachs and cross-sections and analysis of a preliminary model, it was determined that the UC layer was too thin to be effective as a confining layer and did not correspond with key boreholes (including high quality Ontario Geologic Survey (OGS) boreholes; see Conceptual Understanding Report (AquaResource et al. 2012) in the model area. Conversely, the uppermost aquifer (A1) layer which hosts the predicted water table location as well as numerous private pumping wells was still very thick, despite the subdivision of this layer. The present model for the Tier Three analysis was simulated using unsaturated/saturated conditions which require an increased vertical resolution in order to properly solve for the water table elevations; therefore, the thickness of the A1 unit was too large for this purpose.

When pumping and monitoring wells are added to a FEFLOW model, the well screens are approximated to the closest model slice. In most cases, model layers are designed with careful attention to screen



elevations, in addition to borehole geology, so that the well screen elevations are as representative of field conditions as possible. Errors can be then avoided when the vertical resolution of the layers is appropriate and coincide with screen elevations. This is particularly important within the deep production aquifer where risk analysis and safe drawdown levels will be estimated. However, when a layer is too thick under unsaturated or partially saturated conditions, a secondary problem can occur. Well screen elevations can be erroneously approximated as being completely within the unsaturated portion of the model, resulting in numerical instability and erroneous head solutions. Within the Study Area, wells that are screened in this uppermost aquifer are generally household wells that are shallow and do not penetrate the full thickness of the aquifer unit, therefore the model layer needs to have sufficient vertical resolution so that at least the bottom elevation of the well screen elevations is below the water table.

In the preliminary modelling performed to test the suitability of the conceptual model, hydraulic conductivities were applied to the A1 unit using a Bulk Conductivity method in which borehole geology is used to approximate the bulk hydraulic conductivity in the horizontal direction using the harmonic mean method. The spatial distribution of the bulk hydraulic conductivity revealed that although some strong trends appeared, the inclusion of the shallow, very low K-value conductivities resulted in a very non-Gaussian distribution, which indicates that the layer delineation is too broad and not representative of the natural system.

In summary, the layer structure of the upper two layers required refinement and improvement due to the following:

- The Upper UC layer did not reflect borehole geology
- The expected location of the water table is within the interpreted A1 sequence within the highlands of the model where it is the thickest. Extra refinement within this unit would be more appropriate.
- Pumping and monitoring wells which are added to the FEFLOW model will be applied on the closest model slice. Therefore, theoretically, a well that should be screened to a 12-metre depth in the thickest area of A1 may only have the choice of being placed at either 0.20 m (Top of A1) or 70 m (Middle of A1) depth
- Bulk hydraulic conductivity within the uppermost modelled aquifer was too vertically heterogeneous suggesting that some important confining areas of the sequence were not adequately represented.

Cross sections were created in key areas of the model to assess where the UC layer would best be approximated. These cross sections were also drawn through OGS boreholes to ensure the model layers were still true to these very high quality interpretations. In the highlands, the most efficient way to approximate the new Top of A1 surface was to subtract the Top of C1 from the 100m Digital Elevation Model (DEM) and divide in half, as the bottom of most of the shallow A1 wells screened within A1 is located around this elevation. This half-way point is supported with borehole geology. In the lowlands, it was determined that UC should not exist at all. In the case of a hydrogeological unit not existing in a numerical model layer, it is standard to apply a minimum model thickness of 0.10 m to maintain layer continuity. However, when the thickness of A1 was divided in half in these areas, the average thickness is approximately 25 cm; therefore, it was sufficient to place the bottom of the UC/Top of A1 unit directly halfway between the Top of C1 and the DEM for the entire model domain. Once this was completed, the



cross sections showed a good match with boreholes within the upland regions. The majority of the boreholes remain completed within the aquifer unit and most borehole geology shows some confining layers within it in most places within the highlands. Within the lowlands, the change has little effect as the uppermost layers UC and A1 were already at minimum thickness. These modifications resulted in improved refinement near the predicted water table elevation, better borehole representation, and realistic elevations for pumping and monitoring well screen depth placements.

2.2 Conceptual Model Overview

Table 2.1 presents a summary of the hydrostratigraphic units in the Study Area, including a description of the hydrostratigraphic unit name, and the specific geologic units identified within the hydrostratigraphic unit.

TABLE 2.1 Hydrostratigraphic units within the Study Area

Model Layer	Unit Name	Unit Description
Layer 1	SrfG	Represents conductance in stream beds, mapped surficial geology. 0.10-3 m in thickness.
Layers 2, 3	UC	Represents confining layer over A1, mostly present in upland area such as the Oro Moraine, where missing then A1 properties used
Layer 4	A1	Uppermost aquifer, present in upland areas. Frequently exists as surficial and unconfined, stratigraphically equivalent to the Oak Ridges Moraine, generally is associated with coarse-grained glacial and interglacial sediments mapped as ice-contact stratified drift.
Layer 5	C1	Upper Aquitard
Layer 6	A2	Intermediate Aquifer, stratigraphically equivalent to interstadial units within the Northern Till. Within the lowland areas it is often the uppermost coarse-grained unit, commonly used for private water supplies, as well as some of the smaller municipal water supply wells (i.e. Innisfil)
Layer 7	C2	Intermediate Aquitard, providing protection to the municipal aquifer
Layer 8, 9, 10, 11	А3	Main municipal production aquifer, stratigraphically equivalent to the Thorncliffe deposits in the Upland regions. Represents the bulk of the Barrie-Borden channel aquifer.
Layer 12	C3	Lower Aquitard
Layer 13	A4	Lower aquifer, thin and sometimes combined with A3 in the Barrie City Core, where C3 is thin or absent
Layer 14	C4	Lower Aquitard, also represents weathered bedrock

This hydrostratigraphic structure provides the basis for the layer structure of the numerical model.

2.3 Hydrogeologic Unit Mapping

A set of surfaces for the tops of each of the hydrostratigraphic units applied as layers in the groundwater model were developed based on interpretations from Golder (2004, 2006, 2009). A 5-meter resolution Digital Elevation Model (DEM), the depth to bedrock dataset (Golder 2009), and regional water well database (WWIS) top of bedrock picks provided supplemental information. The developed surfaces are as follows:

1. Top of SrfG: represented with 5 meter DEM



- 2. Top of UC: calculated from DEM 3 m, where this unit is present*
- 3. Middle of UC: calculated from ((DEM Top of A1)/2), where this unit is present*
- 4. Top of A1/Bottom UC: calculated from ((DEM Top of C1)/2), where this unit is present*
- 5. Top of C1/Bottom A1: representative elevation as determined by borehole interpretation**
- 6. Top of A2/Bottom C1: representative elevation as determined by borehole interpretation**
- 7. Top of C2/Bottom A2: representative elevation as determined by borehole interpretation**
- 8. Top of A3/Bottom C2: representative elevation as determined by borehole interpretation**
- 9. Top A3 Sublayer: calculated from ((Top of A3 (Top of A3-Top of C3)/4)
- 10. Top A3 Sublayer: calculated from ((Top of A3 (Top of A3-Top of C3)/2)
- 11. Top A3 Sublayer: calculated from ((Top of C3 + (Top of A3-Top of C3)/4)
- 12. Top of C3/Bottom A3: representative elevation as determined by borehole interpretation**
- 13. Top of A4/Bottom C3: representative elevation as determined by borehole interpretation**
- 14. Top of C4/Bottom A4: representative elevation as determined by borehole interpretation**
- 15. Top of Bedrock/Bottom A4: representative elevation as determined by borehole interpretation**

*In the case of an absent unit, the surface was calculated to be 0.10 m below the upper surface so that a minimum layer thickness is maintained for numerical purposes.

If the hydrogeologic units pinch out, numerical model layers decrease to a minimum thickness of 10 cm, to maintain layer continuity. GIS polygons are used to ensure that the model properties applied within these areas represent that of the next adjacent lower layer that has a thickness exceeding 10 cm (i.e. if C2 is absent, properties from A3 are used. If A3 is absent as well, C3 is used, etc.).

2.4 3-D Hydrogeologic Unit Model

Hydrostratigraphic picks were generated at the interpreted upper surface of each hydrostratigraphic layer (Table 2.1). The generated surfaces represent the top of hydrostratigraphic units. Continuous surfaces of picks were generated in Surfer 8.05 (Golden Software 2009) using a linear kriging algorithm to a 100 m resolution. Kriging was chosen as it a) is an exact interpolator that will retain defined values at specified points (i.e. picks), and b) incorporates anisotropy and underlying trends in an efficient manner.

The generated numerical model surfaces were restricted to the boundaries of the Study Area.

Surfaces were imported into Leapfrog Hydro 3-dimensional visualization (Leapfrog Hydro 2012) where a 3-D hydrogeologic block model was created to visually inspect the vertical and lateral distribution of model layers based on the generated surfaces.

3.0 GROUNDWATER FLOW MODEL

The preliminary groundwater flow model for the study site was developed using FEFLOW, a commercially available finite element groundwater modeling code developed by DHI-WASY (2009). The groundwater flow model is based on the hydrogeologic framework described in Section 2.0 and based on the surfaces of the 3-D Conceptual Model that define the hydrostratigraphic units.

FEFLOW was selected as the modelling code for use in this area because of its advanced capabilities that include the following:



^{**}See Conceptual Understanding Report (AquaResource et al, 2010) for more details.

- 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 slopes of the Upland Areas;
- Efficiency of localized mesh discretization; requires 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 (allows simulation of shallow aquifer within the context of the regional model);
- 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 simulation that facilitates more accurate simulation of the shallow subsurface and decreases numerical issues.

Given these considerations, FEFLOW was selected for use in completing the groundwater modelling for the Study Area.

3.1 Modelling Process

The numerical modelling process for the Tier Three Assessment consisted of three stages:

3.1.1 Model Set Up

Groundwater flow is simulated by applying boundary conditions at the locations were water enters or leaves the groundwater flow system (e.g., recharge, discharge to streams, pumping wells) and is subjected to a variable hydraulic conductivity, storage, and porosity field. For the purpose of a Tier Three analysis, the FEFLOW model was built in unsaturated mode to allow the benefit of water table approximation.

Both the surface water model (MIKE SHE, AquaResource et al. 2011) and groundwater model were designed for the purpose of calibrating each model simultaneously by exchanging information between them. In both models, analogous layer structures were designed, identical pumping data and groundwater monitoring wells were used, and external groundwater boundary conditions were applied.

Upon construction of both models, a recharge distribution was supplied to the FEFLOW model from a preliminarily calibrated MIKE SHE model.

3.1.2 Steady-State Calibration.

During the steady-state calibration, the model input parameters and boundary conditions were adjusted to obtain a reasonable fit to the range of head and baseflow values. Throughout the FEFLOW calibration, feedback was supplied back to the MIKE SHE model via new groundwater parameters (i.e. adjusted conductivity), the MIKE SHE model was recalibrated to the new parameters and a new recharge distribution was created for input to FEFLOW. This iterative process was repeated until both models were considered to be calibrated.



3.1.3 Transient Calibration/Long Term Verification

Long-term model verification is another step in the model calibration process whereby the calibrated model output is compared to a different set of field observations than those observations used to calibrate the model. In this assessment, a transient simulation was undertaken to examine the model predicted and observed responses to municipal pumping within the City of Barrie. This step aimed to simulate the head response resulting from groundwater extraction from all well fields within the City of Barrie between 1997 and 2010. The model was set up with average monthly recharge (obtained from the results of the MIKE SHE model) and average monthly groundwater extraction from each of the City of Barrie municipal wells. The 13 year simulation was divided into a total of 165 monthly stress periods, and as noted above, the groundwater pumping and recharge were considered constant throughout each of the stress periods. These stress periods, along with their pumping rates, are presented within the Conceptual Understanding Report (AquaResource et al. 2011a).

Model input parameters from the steady-state calibration were used as initial conditions to simulate the transient conditions. Input parameters (hydraulic conductivity and storage estimates) were modified until a reasonable match was achieved between the model simulated and observed hydraulic head measurements to represent observed water level changes during the tests. Changes to input parameters made during the transient calibration were incorporated back into the steady-state model to ensure the same input parameters were present in the two models.

3.1.4 Sensitivity Analysis

An assessment of the sensitivity of the model input parameters was conducted to provide a basis for a discussion on the uncertainty associated with the modelling and the model results.

This section of the report outlines the groundwater model set up, the steady-state and transient model calibration. The application of the sensitivity analysis to quantify uncertainty in the risk assessment is discussed in the main report.

3.2 Model Domain

Three main aspects were considered during the delineation of the model domain and creation of the finite element mesh. First, domain boundaries must extend adequately away from areas where predictions are necessary so that these areas are not strongly influenced by the model boundaries. For this site, the model domain needed to be such that the present and possible future extents of the capture zones of the municipal wells are sufficiently distanced from the model boundary. The second consideration is to identify physically-based boundary conditions around the perimeter of the model. Therefore, the model boundary was extended to the natural boundaries of the groundwater flow system. This was accomplished by examining the potentiometric surfaces and water levels within the watershed, paying particular attention to watershed boundaries. Lastly, while balancing these first two considerations, the size of the domain must also be taken into account so that it can contain an appropriate level of resolution while still remaining computationally practical.

The resulting numerical model domain encompasses the City of Barrie as well as portions of the Townships of Essa, Oro, and Springwater (Map 1.1). The model domain was designed to encompass the entire Barrie Creek subwatershed as well as adjacent subwatersheds that may possibly contribute to interbasin flow. In addition, the model extends into Lake Simcoe to simulate recharge/discharge directly



to and from groundwater. The model domain is approximately 14.5 km in width (west-east) and it extends approximately 13 km in length (north-south) covering an area of 800 km².

3.3 3-D Finite Element Mesh

An important consideration during the development of the model is that the finite elements be aligned with important features in the model including locations of all wells, streams, ponds, and the well field focus area. As a result, boundary conditions can be applied to their exact locations either for present or future applications. Additionally, the mesh can be discretely refined to a higher resolution along these features. This method of variable mesh refinement allows for a numerical mesh that is both efficient for calculations but also practical for capturing local detail where needed.

The Study Area boundary, as well as the boundary of Lake Simcoe within the Study Area and the boundary of the well field Focus Area, provide the basis for the initial mesh design. The study boundary topology was normalized to a resolution of approximately 100 m and the Lake Simcoe boundary topology was normalized to a resolution of approximately 50 m. Within the ambient regions of Study Area (i.e. areas without significant features), the average element length is approximately 200 m and within the ambient regions of the Well Field Focus Area, the average element length is approximately 100 m.

The 2-D model finite element mesh is presented in Map 3.1. The mesh was refined in areas where it was important to have an enhanced definition of groundwater flow and the potentiometric surface. Features that were incorporated into the mesh design included wells, streams and lakes. A total of 124 wells were included in the mesh design, including present and future pumping wells, and private wells. The well locations were refined to a resolution of 15 m. Prominent streams and ponds were also included in the mesh design. To avoid poor mesh geometries that can lead to numerical instability, these features were first simplified to 50 m segments outside of the Focus Area and 20 m within the Focus Area. The simplified river segments were then incorporated as line features within the mesh design so model nodes were exactly located along mapped streams. Ephemeral or channelized streams were included for future use; however, only perennial streams and ponds as determined by air photo analysis are currently represented explicitly within the model.

This 2-D mesh was extended into 3-D by the addition of the surfaces described in Section 2.0, resulting in a total of 2,968,644 elements and 1,604,160 nodes. Images of the final 3-D mesh are presented in Map 3.2. The inset on Map 3.2 shows an example of the mesh refinement surrounding the municipal wells.

3.4 Boundary Conditions

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

 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 for the simulation of lakes, rivers, or other surface water bodies.



• Specified Flux boundary conditions are assigned to represent a known flux across a surface, into the model domain. These types of boundaries are often used to simulate recharge entering the model through the uppermost layer of the model. Wells are also special types of flux boundaries.

Map 3.3 illustrates the spatial distribution of boundary conditions assigned in the FEFLOW groundwater model. Sections 3.4.1 through 3.4.4 provide a discussion on the boundary conditions applied in the model.

3.4.1 External Regional Flow Boundary Conditions

As mentioned above, the model domain was delineated to correspond to natural groundwater flow boundaries (groundwater divides). To determine appropriate lateral boundary conditions for the model, water level contours were reviewed (AquaResource et al. 2011a). Where water level trends suggested that natural flow boundaries exist (groundwater divides), no-flow boundaries were applied. In other cases, where the deeper groundwater flow regime did not exhibit the same boundaries as the shallow regime, boundary conditions were required to allow in/outflow along these deep features. These boundary conditions were set at specified head according to measured water levels in the area and monitored throughout calibration to obtain the observed gradient across the boundary.

Since a larger watershed scale model was completed prior to the completion of this assessment, cross-boundary flows from the adjacent models from those models could be used for comparison purposes to the current model. This comparison is helpful because the watershed scale model contains hydrogeologic information beyond the boundary of the current model and observed water levels beyond this boundary were used for calibration of that model. This comparison showed compatibility between the two models, in both flow direction and magnitude.

Map 3.3 shows the location and type of boundaries applied on the perimeter of the model domain. Inflow and outflow to the model through lateral boundaries has been incorporated into the model for both the shallow and deep aquifer flow systems. In the shallow aquifer (A1), most of the model boundary cross cuts the equipotentials (Map 3.3), indicating that groundwater flow divides exist in the model at these locations. Initially, no lateral boundaries were applied to the shallow system. However, the initial phases of calibration and further inspection into observed water levels in the area showed that that the northeast boundary is in an area where flow may be entering into the model; therefore, a variable Type 1 boundary condition was interpolated and also shown in Map 3.3.

For the deep layers, the inflow or outflow has been estimated based on equipotentials within the A3 Unit (Map 3.3). Where there has been no external boundary condition applied, the boundary is considered no-flow. Water levels around the western boundary indicate that there is interbasin flow occurring under the Minesing Wetland where the deep discharge to the Wetland occurs slightly west of the model boundary.

3.4.2 Surface Water Boundary Conditions

Selected rivers and streams were simulated in the model using specified head boundary conditions. In addition, large lakes including Lake Simcoe were also simulated in the model. The application of boundary conditions in the model to simulate these features is discussed below.



3.4.2.1 Rivers and Streams

Groundwater discharge from overburden occurs along streams, wetlands, and ponds. These surface water features have potential to be impacted from anthropogenic activities, such as excessive groundwater pumping. Perennial surface water features are represented in the FEFLOW model using specified head or head dependent flux boundaries. Perennial streams and ponds were initially identified using the Strahler number (1), but confirmed and modified by air photo analysis and field observations and represented in the FEFLOW model (Map 3.3).

Specification of stream and river boundaries using specified head boundary conditions requires the application of a value for the river stage (elevation). The stage elevation was taken from water levels represented in the 5 m Digital Elevation Model (DEM). Prior to assigning river boundary conditions in the model, the stream network was inspected using a GIS software package to ensure the river stage specified in the model was decreasing in the downstream direction. The boundary conditions applied to the model are therefore referred to as "hydraulically-corrected". As well, the degree of conductance through the river/ lake bed with the underlying groundwater system is assigned by using a thin model layer under the water body and applying a hydraulic conductivity appropriate for the mapped surficial geology to ensure that discharge to the water body is realistic. The stream conductance applied at the base of all stream and river segments (in the first layer of the model, Layer SrfG as described in Section 2.0) was variable depending on the surficial geology that the rivers or stream passes through, the flow characteristics of the river (e.g., sinuous versus straight paths), as well as the mapped thermal regime. In general, streams that travel with relatively straight courses and were mapped to contain coldwater fish species (NVCA and DFO 2009; LSRCA 2010) were given a high conductance value. Those streams that meander significantly through clay plains and are reported to have mixed or warmwater thermal regimes (NVCA and DFO 2009; LSRCA 2010) were given a low streambed conductance. While this conductance value does not greatly impact the surface water/groundwater interaction in lower hydraulic conductivity sediments, it is designed to control the interaction between surface water and groundwater in areas where the streams are interpreted to cut through coarse grained sediments. This is adjusted throughout the model calibration as warranted based on observed data.

3.4.2.2 Lakes and Wetlands

Lake Simcoe (Kempenfelt Bay and Cooks Bay) was simulated in the model using specified boundary conditions applied in the upper overburden layers with a head elevation set to 218.8 masl. The available bathymetry of the Lake was incorporated into the model so that boundary conditions of the lakes could be set in the deeper layers that they exist within, and so that the locations where the hydrogeologic layers intersect the lake basin (i.e. where surface water/groundwater exchange occurs) is realistic.

There are a total of three lakes mapped within the Study Area that were large enough to be simulated in the groundwater flow model (Map 3.3). To accurately simulate the flow into and out of these elements, only large lakes that were verified through air photo analysis were simulated. The threshold of 0.02 km² was applied as the FEFLOW elements regionally are approximately 0.02 km². In some areas, smaller riparian-type water bodies that were connected to larger systems such as streams and larger lakes were included with those features as boundary conditions in the model. Table 3.1 below outlines the lakes that were simulated in the groundwater model. The remainder, smaller water bodies that were not included that may have groundwater discharge were included as calibration verification points.



Lakes are simulated in the groundwater model using specified head boundary conditions. The application of these boundary conditions assumes there is good hydraulic connection between the lake and the underlying groundwater system. As with the rivers and streams, the lake stage elevation was taken from the 10 m DEM.

TABLE 3.1 Lakes Simulated in the FEFLOW Model

Lake Name	Surface Area (km²)	Stage Elevation (masl)				
Lake Simcoe*	57.0	218.8				
Little Lake	2.3	227.8				
Hendrie Lake	0.1	188.6				
* only includes portion within model boundary						

3.4.3 Recharge

Groundwater recharge refers to the amount of water that infiltrates through the unsaturated zone and ultimately reaches the water table. The rate of groundwater recharge is dependent on a number of factors including precipitation, land use and vegetation, surficial soil type (geology), physiography, and ground surface topography. Recharge is enhanced in areas where the ground surface is hummocky and water does not runoff to nearby creeks and rivers.

Recharge rates used in the groundwater model were obtained from the surface water model MIKE-SHE which is described within the Recharge Estimation Memo (AquaResource et al. 2011b). The recharge rates provided by MIKE SHE were modified slightly for the input to the groundwater model; for instance, negative recharge values (i.e. discharge conditions) were assigned a value of 0, and the unsuitably high recharge was capped to a maximum of 450 mm/yr. The total amount of recharge to the model (Map 3.4) is 455, 250 m³/day, which represents an average recharge of 225 mm/year. Estimated recharge rates and distribution were adjusted locally in a pseudo-coupled approach during the calibration process of both the groundwater and surface water models to address discrepancies between observed and simulated data.

3.4.4 Pumping Wells

In FEFLOW, groundwater extraction wells are typically represented using the constant flux boundary condition using one-dimensional vertical line elements superimposed on the three-dimensional finite element mesh. As such, the entire pumping rate is applied to the bottom node of the line element; fluxes into the well from all nodes along the well screen (vertically) are computed based on the transmissivity associated with each calculation point. In this manner, flux contribution to a well from multiple stratigraphic layers is automatically calculated. This is particularly important for wells that penetrate multiple geological sequences.

As noted in Section 3.3 above, the mesh was refined around the pumping wells to more accurately simulate the groundwater flow patterns surrounding the wells and to reduce model instability caused by high-velocity flow. The wells that are simulated under steady state conditions, along with their average daily pumping rates, are presented in Appendix C2. A total of 124 pumping wells are represented, however some wells are standby wells with combined pumping rates with their system. The locations of all pumping wells represented in the model can be seen in both Maps 1.1 and 3.1, and a close up of the wells can be seen on Map 4.2. The reported or estimated pumping rates for 2008 were applied in the



model as these are more accurate for examining existing water demands than using the maximum permitted rates for the purpose of calibration.

3.5 Model Properties

The primary hydrogeologic properties assigned within the FEFLOW model for simulation of steady-state (average annual) conditions includes the hydraulic conductivity, porosity and unsaturated zone pressure-saturation properties. Hydraulic conductivity is a property of sediment or rock that describes the relative ease with which water can move through pore spaces or fractures and can have a significant impact on the model calculated hydraulic head distribution. Porosity refers to the volume of void space per unit volume of geologic materials and is used in velocity calculations. Therefore, porosity estimates are only used for particle tracking calculations. Since this study requires transient simulations for the drought assessment, storage is also estimated.

3.5.1 Hydraulic Conductivity

Hydraulic conductivity is the primary variable that controls the calculated hydraulic head distribution throughout the model domain (based on boundary condition values). In developing a groundwater model, initial estimates of hydraulic conductivities are specified and refined through the calibration process to achieve an acceptable fit to observed data. Initial conductivity estimates are based on the conceptual understanding of the geologic/hydrostratigraphic units and their hydrogeologic properties. Where data from pumping tests is available, these data can help to constrain the conductivity estimates within particular geologic formations. When such data is not readily available, conductivity values are often estimated from literature values for materials with a similar lithological description, or from previous studies conducted in the area. In this study, a combination of site specific, measured hydraulic conductivity and lithology-estimated conductivity values are applied. It has been assumed that all model layers contain fresh water (low TDS and salinity).

The majority of hydraulic conductivity estimates within the Focus Area were extracted from the previous groundwater protection studies (Golder 2004, 2006) as well as more recent well field assessments. Outside of the Focus Area, lithology from boreholes was used to derive an initial conductivity estimate. Those estimates were interpolated in each of the interpreted hydrostratigraphic layers and generalized to produce hydraulic conductivity distributions. This method produces a heterogeneous distribution of hydraulic conductivities across the model layers where the heterogeneity represents spatial lithology changes. The hydraulic conductivity distribution within each unit was then demarcated into representative zones, called Kzones, and assigned an average conductivity value based on either the borehole lithology or measured values from hydraulic testing.

The initial conductivity distribution in the model ranged from $5x10^{-3}$ m/s for coarse-grained gravel deposits, to $1x10^{-7}$ m/s for fine-grained deposits. Average initial hydraulic conductivity estimates for each unit are presented in Table 3.2. These estimates are consistent with those used within the South Simcoe Studies (Golder 2004), and are refined through additional data collection associated with ongoing studies and model calibration. It is important to note that these are non-weighted averages of the boreholes within each model layer; the average conductivity within the confining units may be offset by the high conductivities within the model layer, in areas where the predominant geological layer does not exist. The vertical hydraulic conductivity was set to be 1:10 of the horizontal.



TABLE 3.2 Initial Hydraulic Conductivity Estimates

Unit	Mean Hydraulic Conductivity (m/s)
UC	1.66E-06
A1	1.12E-04
C1	2.43E-07
A2	1.44E-04
C2	3.40E-07
А3	5.40E-03
C3	3.68E-07
A4	8.49E-05
C4	1.75E-07

3.5.2 Unsaturated Flow Parameters

In order to enhance the model's ability to represent groundwater flow on a site scale, saturated and unsaturated flows were calculated simultaneously using Richard's equation (Variably Saturated Mode). In this mode, the mesh and properties remain fixed and the parameters applied vary depending upon the saturation state within each element. Although this method requires specification of unsaturated zone parameters which are typically not well known, the purpose of unsaturated zone simulation is to represent the realistic position of the water table and not dynamic unsaturated responses. Therefore, simplified constitutive relations (e.g. material specific K-saturation relationships) were simulated for this model.

The most common way to simplify the relationship is to assume the function that relates the saturation and the relative hydraulic conductivity is linear which was completed for the Van Genuchten Modified relationship model. This simplification avoids some of the non-linearities within the unsaturated zone and allows an iterative solution of the water table position to be efficiently achieved (Vogel et. al. 2001; Beckers 1998; Huyakorn et al. 1986).

3.6 Transient Model Setup

Long-term model verification is another step in the model calibration process whereby the calibrated model output is compared to a different set of field observations than those observations used to calibrate the model. In this assessment, a transient simulation was undertaken to examine the model predicted and observed responses to municipal pumping within the Study Area. This step aimed to simulate the head response resulting from groundwater extraction from all well fields within the City of Barrie between 1997 and 2010. The model was set up with an average monthly recharge and average monthly groundwater extraction from each of the City of Barrie municipal wells. The 13 year simulation was divided into a total of 165 monthly stress periods, and as noted above, the groundwater pumping and recharge were considered constant throughout each of the stress periods. These stress periods, along with their pumping rates, are presented within the Conceptual Understanding Report.

3.6.1 Aquifer Storage

Groundwater storage is defined as the quantity of water released from an aquifer system due to a unit change in the water level. The size of the storage coefficient is dependent on whether the aquifer is



unconfined or confined. In a confined aquifer, water derived from the storage is relative to the expansion of water as the aquifer is depressurized and the compression of the aquifer. In a confined aquifer, 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). Because of these variables, the storage coefficient of most confined aquifers range from 10^{-5} to 10^{-3} . Conversely, in an unconfined aquifer setting, the predominant source of water is from gravity drainage and the expansion of water and compaction of rock is negligible. Thus, the storage coefficient is approximately the value of the specific yield and ranges from 0.1 to 0.3 (similar to the porosity). Note: steady-state and do not require the specification of storage parameters.

The initial storage coefficients within the model are shown in Table 3.3. However, within the focus area, storage was specified via zones based on pumping test analyses, where available and is shown in Table 3.4. Within the area of wells 17 and 18 (See Map.4.2 for well locations), storage was generally found to be within the 10^{-4} to 10^{-5} range (IWS 2001), confirming excellent aquifer conditions in this area. Within the vicinity of Well 6 (nonoperational well as of 2001), as well as Wells 9 and 13, storage was determined to be around 10^{-2} , suggesting semi-confined leaky artesian conditions (IWS 2001). Amongst the Lakeshore wells (Wells 11, 12, 14, and 15), confined artesian conditions were found with a storage coefficient of 10^{-4} with restricted flow or connection to the lake due to the confining layer (IWS 2001); however, earlier pumping tests for well 12 were at 1.6×10^{-3} and lower (IWS 1985).

TABLE 3.3 Regional Storage Coefficients

Geologic Description	Specific Storage (1/m)
Sand and Gravel	10 ⁻⁴
Silt	10 ⁻⁵
Clay	10 ⁻⁶
Till	10 ⁻⁶

TABLE 3.4 Well Field Storage Coefficients

	Well Name	Specific Storage (1/m)	Source
Pressure Zone 1 –	12 (Centennial Park)	1 × 10 ⁻⁴	IWS, 1985
Lakeshore Wells	14 (Heritage Park)	1×10^{-4}	IWS, 1985
	15 (Centennial Park)	1×10^{-4}	IWS, 1985
	11 (Heritage Park)	1 × 10 ⁻⁴	IWS, 1985
Pressure Zone 1 -	3A (Anne Street)	5 × 10 ⁻⁴	IWS, 2011
Core	4 (Perry Street)	5×10^{-4}	IWS, 2011
	5 (John Street)	5 v 10 ⁻⁴	IWS, 2011
	6 (Wood Street, non-operational since 2001)	10 ⁻²	IWS, 2001
	7 (Tiffin Street)	$10^{-3} - 7 \times 10^{-3}$	IWS, 2011
	17 (Cross Street)	10 ⁻⁵	IWS, 2009
	18 (Cross Street)	10 ⁻⁵	IWS, 2009
Pressure Zone 2 -	9 (Johnson Street)	2×10^{-1}	IWS, 2001
North	13 (Johnson Street)	2 × 10 ⁻¹	IWS, 2001
	16 (Brownwood)	$10^{-3} - 5 \times 10^{-4}$	IWS, 1995
Pressure Zone 2 - South	10 (Huronia Road, Decommissioned as of date)	10 ⁻⁴ - 10 ⁻⁵	IWS, 1999



4.0 CALIBRATION APPROACH

Calibration is the process of adjusting the model representation of the physical system, by adjusting parameter value distributions and/or boundary conditions to minimize the difference between simulated and observed values for hydraulic head or groundwater discharge. A steady-state calibration implies long term average conditions are modelled. A transient calibration entails using temporal data over a discrete period of time to compare model response to changing conditions (i.e. pumping, recharge).

The approach for the model calibration includes these general steps:

- 1. Initial model simulation using estimated conductivity values, boundary conditions and a preliminary average annual recharge estimate obtained via surface water modelling,
- 2. Modification of model properties (such as hydraulic conductivity) and boundary conditions (such as interbasin flow) through scaling factors for broad regions to improve regional calibration,
- 3. Provide qualitative and quantitative feedback from the groundwater model to the surface water model (i.e. changes in model properties or boundary conditions)
- 4. Local refinement and review of model properties and boundary conditions, including revisions to the surface water model produced recharge estimate, to improve the local model calibration,
- 5. Evaluation of the model flows and calculated baseflows followed by refinement of boundaries and hydraulic conductivity values at streams and rivers to interaction with streams,
- 6. Additional identification of streams that are channelized, ephemeral or in an area known to have perched water table conditions. Update and refine to improve calibration,
- 7. Completion of transient simulations, local refinement.

During the model calibration process, the model input parameters are changed, the model is run, and the results are reviewed. The approach in this study was to initially focus on the ability of the model to represent regional flow conditions. This is done in steps 1 and 2 listed above by completing an initial model simulation and then adjusting the hydraulic conductivities in the model layers by a scaling factor. This will result in a model that is able to represent the regional flow system well, but locally additional refinement will be necessary, which is accomplished by steps 3-5. Step 6 will verify any outstanding questions regarding material properties, in particular, storage.

Typically, when calibrating a groundwater flow model, hydraulic conductivity and storage is specified for discrete hydrogeological units (i.e., aquifers and aquitards), where the value of the property would encompass many elements and one or more layers. However, as model layers are very heterogeneous, adjusting properties manually on an elemental basis would be impractical. To overcome this challenge, the model area was subdivided into regions or polygons with similar hydrogeological properties and assigned a uniform hydraulic conductivity value and a specific storage value. The values applied to these regions were modified through the calibration process. Locally, hydraulic conductivity and storage were adjusted as needed to satisfy calibration targets and additional zones were added as warranted. Throughout this process, checks are conducted with borehole lithologies from drill logs and background reports containing hydraulic test results, to maintain geological veracity.



4.1 Steady-State Calibration Datasets

The ability of the model to represent actual field conditions is judged based on the available observation data. Establishing an observation data set is essential to the development of a defensible groundwater model. Special considerations need to be applied to achieve a calibration dataset that is consistent with the chosen calibration pumping period and addresses the varying quality of observation data throughout the model area.

Observed water levels (hydraulic head data) and groundwater discharge estimates are often used as targets when calibrating steady-state groundwater models. The sections below outline the calibration targets used in the groundwater flow model and the approach taken in this study to calibrate the groundwater flow model.

4.1.1 Surface Water Data Set

In order to estimate groundwater discharge, streamflow records can be used to determine baseflow within the Study Area. It is assumed that baseflow is predominately groundwater discharge within the Study Area, and therefore baseflow estimates are appropriate calibration targets. This calibration measure is important because it helps to eliminate some of the non-uniqueness associated with a specific model calibration. Recognizing the uncertainty in estimated groundwater discharge rates, the calibration approach relies on an estimated range, as opposed to a single value. Calibration efforts focus on those areas where the difference between the observed and simulated conditions is highest. For those areas, model layer structure modifications as well as local hydraulic conductivity modifications can be used to improve the local calibration to baseflow.

Streamflow records within the 1980-2009 periods were used from 3 gauges operated by Water Survey of Canada (WSC). The distribution of these gauges is illustrated on Map 4.1. A baseflow separation exercise was performed on the continuous streamflow data to obtain estimates of baseflow. The baseflow separation routine used in this analysis is the Baseflow Separation Program, included with the Soil and Water Assessment Tool (SWAT) hydrologic model (See Section 5.1, AquaResource et al. 2011a). This routine employs a digital filtering technique meant to replicate by-hand hydrograph separation. This program, previously known as BFLOW, was found to be the most appropriate (Bellamy et al. 2003) and has been selected as the optimum baseflow separation technique for studies completed for a variety of Conservation Authorities, including Ausable Bayfield, Maitland Valley and the Grand River. The program outputs three different daily baseflow estimates. Recognizing the uncertainty in estimated groundwater discharge rates, the calibration approach utilized a range in baseflow estimates, as opposed to a single value.

4.1.2 <u>Hydraulic Head Data Set</u>

In calibrating a groundwater model, observed water levels are used for the entire Study Area, as long as those wells are reported to be of good reliability. Their locations, elevation and construction details should generally be known with a high level of confidence.

The goals for establishing a calibration data set for this model were as follows:

• Identify and use wells that have location and elevation reliabilities that are considered acceptable as a standard data set



- Identify and use groundwater level targets from wells that reflect the temporal calibration pumping conditions
- Identify and weigh 'High Quality' calibration targets
- Achieve a spatial distribution of calibration targets that adequately covers the entire model domain

After a dataset has been established, each calibration point will be assigned to the appropriate model layer based on the hydrostratigraphic unit across which the well is screened.

A total of 2260 well water levels (obtained from the MOE WWIS) distributed across the entire Study Area was used to calibrate the steady-state model. All data from those wells are considered to be of acceptable reliability (UTM reliability codes less than 5), and range from 1980-2010. Map 4.1 illustrates the boreholes within the Study Area. These static water level observations offer the significant benefit of having model calibration targets that extend across the entire model domain, however, there can be high uncertainty associated with the individual observations. These uncertainties arise from errors in the reported location of the wells and the measurement techniques used were not designed to provide reliable scientific information. As a result, 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 discrete location in the present day.

4.1.3 High Quality Datasets

Equipotential Surface Review Wells

A subset of high quality water levels were also selected for calibration targets, as indicated in Map 4.1 and Map 4.2. This high quality dataset of observed water levels was extracted from a concurrent study conducted by Golder (2009) to more accurately map flow directions in the immediate vicinity of municipal production wells throughout South Simcoe County, and therefore were weighted higher than the remainder of the total water levels within the calibration process. Within the Golder studies, this well data was reviewed and deemed of higher quality when 1) the elevation and locations were verified with GPS/Land Survey and 2) the water levels were assessed or measured by a professional geoscientist. In most cases, this led to water levels measured or verified for the purpose of other groundwater studies being assigned as high quality.

City of Barrie Monitoring Well Network

Because this project focuses on local area risk, high quality wells within the Focus Area were given priority consideration throughout calibration of the model. These wells consist of regularly-monitored test or sentinel wells as well as municipal pumping wells and are shown on Map 4.2, as these wells have a time series of water levels, from which average values can be inferred.

4.1.4 Transient Calibration Dataset

An important component of calibration in the Tier Three review is the consideration of transient conditions. The transient calibration builds upon the insights gained in the steady-state calibration with the goal of refining model parameters local to the well field. Such refinement provides more reliable prediction of well sustainability (drawdown) and potential interference with other wells and/or surface water bodies. Calibration to transient hydraulic responses facilitates refinement of model storage parameters as well as hydraulic conductivity. The transient data provides an additional important



constraint on the analysis and can greatly enhance the understanding of lateral and vertical aquifer interconnections.

The final stage in the calibration process was to run the groundwater model transiently between 1997 and 2010. The calibration targets include the high quality wells outlined in Section 4.1.3 above, and they are also illustrated on Map 4.2.

4.1.5 Calibration Measures

To ensure that the model reflects observed conditions, the simulated conditions are compared with observed conditions, including water levels, baseflows and known discharge areas. Qualitative assessment of predicted and observed water levels can provide an assessment of the model calibration; however a quantitative assessment is usually also helpful. Quantitative measures of calibration are based on residual values (the difference between simulated and observed water levels at a point) and include:

- Residual mean (average of all residuals)
- Absolute residual mean (average of the absolute value of all residuals)
- Root mean squared error (square root of the sum of the squares for all residuals)
- Normalized root mean squared error (root mean squared error divided by model water level range)

For this modelling effort, the normalized root mean squared (NRMS) error and the absolute residual mean (ARM) error are considered the most important. The NRMS is used to evaluate the overall calibration of the model, while the ARM is used to evaluate the calibration in more localized areas, such as within the vicinity of the plume. The distribution of residuals (error between model and observed heads) should also be considered. The distribution of residuals presented as a histogram can show if there is a bias in the calculated heads, with the goal of having a bell-shaped distribution of residuals. Cumulative probability plots can show similar effects, indicating whether or not the majority of the residuals approximate a normal distribution, suggesting that the residuals are distributed randomly.

Given the expected end uses and our ability to characterize the groundwater flow system within the Study Area, a well calibrated model should exhibit the following traits:

- Normal distribution of residuals (difference between measured and observed groundwater levels) with the greatest number of residuals very close to 0 m.
- Normalized root mean squared error less than 5% for groundwater level residuals. This is common
 calibration target used in groundwater models and indicates a good match between observed and
 calculated water levels.
- Mean absolute error for groundwater level residuals for the different well fields to be less than 5 to 10 m or within the range of annual groundwater fluctuations and measuring error for the different groundwater levels.
- Predicted equipotentials are similar to equipotential maps generated using monitored data with similar flow directions and gradients where high quality information is available.



- Discrepancies between model predicted and field estimated baseflows to be within a factor of two of each other.
- Transient hydrographs comparing both the observed temporal water levels and simulated temporal
 water levels to ensure response due to changes in pumping and/or recharge are reflected within the
 model.

5.0 CALIBRATION RESULTS

5.1 Quantitative Assessment

5.1.1 Calibration to Baseflow Estimates

Streamflow records within the 1980-2009 periods were used from 3 gauges operated by Water Survey of Canada (WSC). Recognizing the uncertainty in estimated groundwater discharge rates, the calibration approach utilized a range in baseflow estimates, as opposed to a single value. 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 1980-2009 period.

It is important to note that whereas baseflow separation routines may separate quick stream response from slow stream response, the association of baseflow to groundwater discharge is not absolute. Baseflow is the release of water from storage contained within the upstream drainage area that drains to a particular stream gauge. This water released from storage could originate in aquifers, and hence is termed groundwater discharge, but also could originate from wetlands or reservoirs. Other anthropogenic impacts such as sewage treatment plant discharges or water diversions may contribute a portion of baseflow as well. Recognizing this, as well as the effects of natural seasonal and climatic variability, there is a higher degree of uncertainty associated with baseflow calibration targets. Regardless, for this study it has been assumed that baseflow predominately represents groundwater discharge within the Study Area, and that baseflow estimates are appropriate calibration targets.

The match between observed and simulated baseflow is presented in Figure 5.1. Simulated baseflow from the steady-state groundwater-flow model is calculated by adding up the total groundwater discharge to stream boundary conditions for all calculation locations upstream of the observed location (i.e., stream gauge). The stations are listed from left to right in order of the relative groundwater discharge, with those on the left representing headwater streams and those on the right representing major river segments.

Care was taken to match simulated and observed discharge wherever possible. In general, the fit to observed flows along large stream reaches is considered good, the baseflows are within the same order of magnitude as the observed values. Predicted baseflows in Willow Creek are slightly underestimated, most likely due to uncertainty in the thick shallow aquifer system in the Upland regions to the east. It is not likely that the mismatch between observed and simulated baseflows is due to local numerical errors in the flows calculated with the groundwater flow model. Numerical errors within the code are minimal at the scale of baseflow under examination (and if they were present to a large degree, it would be more obvious in a stream of smaller flow volumes, such as Lovers Creek, rather than a large catchment such as Willow Creek). It is more likely that the mismatches are due to limitations of the present understanding of the groundwater flow system, in particular uncertainties in the representation of the water table within the upland regions of the Oro Moraine. Recognizing the uncertainty associated with



the baseflow calibration target values, the overall match to observed baseflow is considered reasonable and this suggests that estimated recharge rates are of a reasonable magnitude.

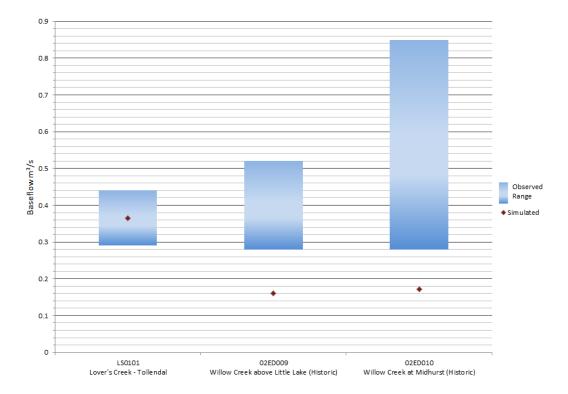


FIGURE 5.1 Comparison of Simulated and Observed Baseflow (m³/s) for 1980-2010

5.1.2 Calibration to Hydraulic Heads

Figure 5.2 presents the scatter plot of observed and simulated hydraulic heads for the calibration target points. Good agreement between simulated and observed water levels was achieved. Although some small local trends can be seen, calculated water levels appear to be scattered randomly about the line of perfect fit. This distribution suggests that there is no large systematic bias in the model results. This regional match of observed and simulated water levels suggests that the numerical model represents the regional scale groundwater flow pattern to an acceptable degree. Calibration statistics for the hydraulic head calibration measures are further explained below.

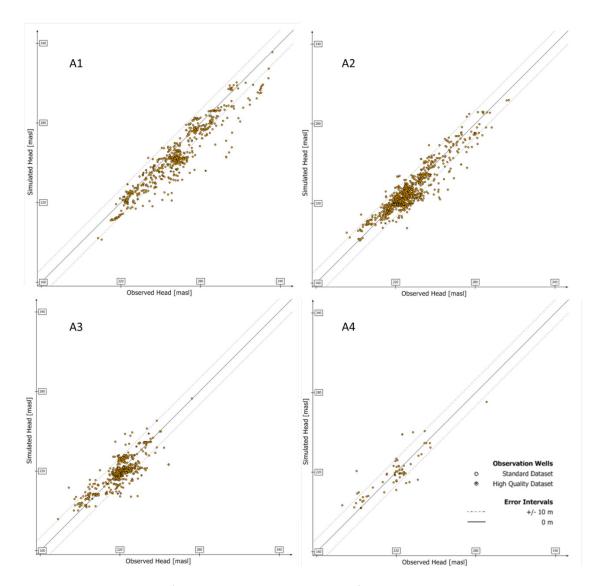


FIGURE 5.2 Scatter Plot of Calibration Residuals by Aquifer

Normalized root mean squared (NRMS) error = 3.6%. This percentage value allows the goodness-of-fit in one model to be compared to another, regardless of the scale of the model. This percentage value allows the goodness-of-fit in one model to be compared with another model, regardless of the scale. Typically, a model is considered representative with a 10% NRMS (Spitz and Moreno, 1996); however, the NRMS error is dependent on the range of observed water levels.

Root mean squared (RMS) error = 7.8 m. The RMS is similar to a standard deviation, providing a measure of the degree of scatter about the 1:1 best-fit line. The measure indicates that the majority statistical population of predicted water levels would fall within 7.8 m of the observed value. An error of ±5 m is generally accepted, in our experience, to be inherent in the use of water well record data, reflecting inaccuracies in well elevation and measurements. Additional error stems from the simplified representation of local flow conditions, particularly outside of the Focus Area (i.e. Alcona area) that were not a particular focus for the calibration efforts.



Mean Error = -2.2 m. The mean error is a measure of whether, on average, predicted water levels are higher or lower than those observed (ideally it should be close to 0). This statistic indicates that on average, the simulated water levels are low by 0.42 m, indicating that a good balance has been achieved between water levels higher and lower than simulated. This further indicates that the regional trends in water levels are well simulated.

Mean Absolute Error = 5.7 m. The mean absolute error is a measure of the average deviation between observed and simulated water levels. The mean absolute error of 5.3 m is less than the population statistic (RMS). An error of ±5 m is generally accepted to be inherent in the use of water well record data, reflecting inaccuracies in well elevation and measurements. Consequently the value achieved within this model is only marginally above the expected noise in the data.

As previously discussed, calibration efforts were focused on the Well Field Focus Area, and particular attention was paid to the high quality monitoring wells mentioned within Section 4.1.3. Within the Focus Area, the statistics described above show that the simulated groundwater flow levels are reasonably reflecting observed data. Considering only the high quality dataset, the calibration statistics are as follows: RMS = 4.1 m, ME = -1.8 m, and MAE = 3.5 m. The range and magnitude of error within the higher reliability wells is much smaller than with the standard data set which incorporates all observed data, including the high reliability wells.

Map 5.1 illustrates the spatial distribution of calibration residuals (simulated - observed hydraulic head) match between the observed and calculated hydraulic head measurements for all water level calibration targets. As this figure illustrates, the residual values are scattered about the simulated values. Where oppositely coloured symbols are next to one another, this reflects the uncertainty in the underlying data, whereas areas with local trends indicate that local conditions are not well represented. Within the Focus Area, trends have been removed through the steady state calibration. Small pockets of trends outside of the focus area remain and are generally located within the unsaturated, upland areas where the simulated water table is approximate, and perched water table systems are not represented within the model. Because of the thickness of the upper aquifer, it is difficult to achieve the level of vertical refinement (i.e., more layers) that is necessary for a more realistic approach to estimating the water table location within unsaturated flow modeling while remaining to be practical on a regional level for stress assessment purposes.

In the case where a perched water table was suspected, observed water levels were compared spatially with regards to one another in order to confirm the presence of the perched system. Data points that were confirmed to be within a perched system, either from local knowledge or because of stark contrasts between water elevation depths within the shallow system within a relatively small area, were included in Map 5.1 for visualization purposes, but were removed from the statistical calculations.

Within the Focus Area, care was taken to prioritize the City of Barrie monitoring network as a local calibration target. Because water levels from the WWIS system are taken from a discrete point in time which may not correspond with the pumping rates (2008), these targets were replaced with a range and a typical value for calibration purposes. These wells are considered a more reliable data source than the MOE static water levels and as such, the model calibration focused on fitting the model predicted heads within the range of observed values. The typical observed value, Do, was derived from the transient water level data which included 1997-2010. Water levels were taken, targeting the 2008-2009 range, where available, during pumping conditions. These values, as well as the simulated water levels for



these wells, are shown (Do) in Table 5.1. This table represents a subset of high quality wells where water levels (static from time of drilling) from the WWIS dataset were updated with SCADA data.

TABLE 5.1 City of Barrie Monitoring Network and Pumping Wells - Water Levels

	Depth to WL (m)		D. D.				
Well Name	Paired With	MOE	Simulated (Ds)	Typical Obs. (Do)	Obs. Range	Ds-Do (m)	Date Range/Comments
TW9/59	Well 4	5700248	7.8	11.0	5.4-18.4	-5.7	2008-2009
TW1/60	Well 5	5700253	15.2	14.0	12.0-16.0	1.2	2008-2009
Well_5		5700271	15.5	15.9	11.9-17.9	-0.4	2008-2009
Well_6		5706146	12.8	10.8	6.8-16.8	2.0	2008-2009
Well_7		5709125	18.1	18.1	14.1-21.1	0.0	2008-2009
TW1/74	Well 10	5711576	24.4	27.2	25.2-32.2	-2.8	2008-2009, observed water levels range from 19 m to 27 m depth
Well_8		5711799	9.2	6.3	3.3-30.3	3.0	1991-2001 Non pumping used, no data after Jan 01
TW1/75	Well 9	5712119	39.1	34.0	29.0-34.0	5.1	1997-2004, No Data after Jan 03, Value picked from earlier years due to decreasing well quality
Well_9		5712496	39.7	39.3	29.3-40.3	0.4	1997-2007 Used, No data after April 2007
Well_10		5714078	26.5	33	23.0-55.0	0.5	2008
Well_12		5717393	3.7	6.8	1.8-21.8	-3.1	2008-2009, wide spread in data
TW1/81	Well 12	5717394	3.7	6.4	1.4-9.4	-2.7	2008-2009
TW1/83	Well 11	5718640	10.1	8.1	3.1-11.1	1.9	2008-2009, wide spread in data
Well_11		5719264	11.9	8.2	5.3-30.3	3.8	2008-2009, wide spread in data
TW3/88	Well 13	5723009	39.6	34.3	29.3-38.3	5.3	2008-2009
TW1/91	Well 3A	5728346	8.6	9.6	7.6-19.6	-1.0	2008-2009
Well_4		DHL0195	11.1	12.0	5.0-18.0	-0.8	2008-2009
Well_17		5737406	18.0	17.0	7.0-25.0	1.0	2008-2009
Well_18		5739442	17.0	16.5	12.5-24.5	0.5	2008-2009
Well_3A		5732108	11.6	19.8	7.8-39.8	-8.2	2008-2009
Well_16		5733545	31.3	26.6	17.6-31.6	4.6	2008-2009
Well_15		5728705	4.4	10.4	0.4-12.4	-6.0	2008-2009
Well_14		5727877	8.0	13.0	-2.0-23.0	-5.0	2008-2009
Well_13		5724686	40.1	44.3	26.3-45.3	-4.2	2009
TW2/60	Well 8	5700255	9.1	6.0	2.0-17.0	3.1	1997-2001 used but corresponds to replacement well TW4/72
TW2/66	Well 6	5700287	13.8	10.0	7.0-15.0	3.8	2008-2009
TW3/60	Well 7	5701702	18.0	16.0	13.0-19.0	2.0	2008-2009



Well Name	Paired With	MOE	Depth to WL (m)		Ds-Do	Date Range/Comments	
TW3/81	Well 15	5717579	3.4	7.9	0.9-9.9	-4.5	2008-2009
TW3/90	Well 14	5727319	6.6	5.6	3.6-10.6	1.0	2008-2009
TW2/95	Well 16	5732632	30.6	25.6	18.6-28.6	5.0	2008-2009
TW1/02	Well 17 18	5736793	18.9	16.5	13.5-23.5	2.4	2008-2009
TW2/02	Well 17 18	5736794	17.4	17.0	15.0-22.0	0.4	2008-2009

The observed water levels were loosely compared to the typical measured value throughout the calibration. Overall, the comparison (Ds-Do) in Table 5.1 produced satisfactory results, such that the simulated water level was within the range of observed water levels. However, many of the wells had a wide range in observed water levels throughout the time period (1997-2010) due to changes in pumping conditions (including decreased pumping or non-pumping conditions). Therefore, it is also useful to compare the calculated water levels to the entire range. Figure 5.3 is a graph that illustrates the range in observed water levels within the high quality monitoring wells within the Study Area. As the figure illustrates, the model is predicting heads for most wells that lie within the range of the observed water levels or within an acceptable margin of error (1- 2 m), indicating the model is well calibrated to this dataset. A discrepancy of 1 to 2 m was considered acceptable because there may be discrepancies in the reference elevation (stick up, concrete pad, ground elevations) from which water levels are taken. One exception to the well matched simulated heads is Well 1/75. In this case, the well was decommissioned in 2003, while the steady state model uses 2009 pumping rates. Therefore, the observed hydrograph for Well 1/75 is not representative of current conditions.

Some monitoring wells exhibit a large range of observed water levels and this is due to their close proximity to the municipal pumping wells, which turn on and off at different times. Some pumping wells also exhibit a large range, in particular, wells 3A, 10, 11 and 14, all of which have experience some declining well performance and rehabilitation during the observed time range (1997-2010).



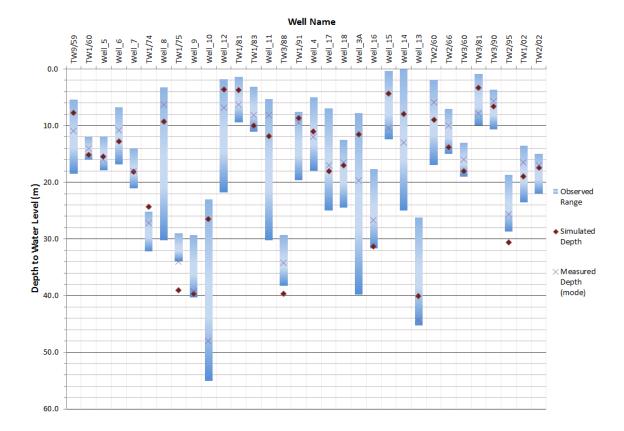


FIGURE 5.3 Calculated Vs. Observed Range of Head within the City of Barrie Monitoring Network

A cumulative probability distribution of the model results is show in Figure 5.4. The residuals approximate closely a straight line on the normal distribution plot. This confirms that the local mismatches between the observed data and the model are random, and that there is no systematic bias in the model results. Spitz and Moreno (1996) and Hill (1998) suggest that the residuals from a calibration should be normally distributed, with a mean of zero. This infers that the largest portion of the residuals plotted on a probability plot should approximate a straight line, with the residual corresponding to 50% close to zero (Neville pers. comm. 2011). The results from the model calibration satisfy this criterion.



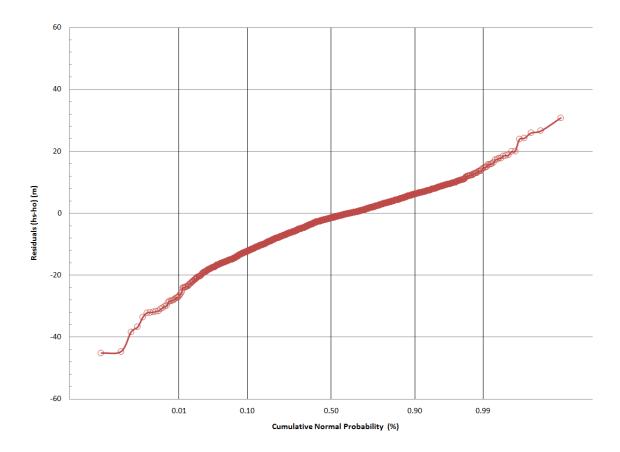


FIGURE 5.4 Cumulative Probability Distribution Plot

5.1.3 <u>Transient Calibration Results</u>

As noted above, the high quality monitoring wells within the City of Barrie were used to examine the model's ability to simulate the groundwater system's response to municipal pumping. Figures C.5.1 to C.5.13 in Appendix C3 illustrate the results of the long term (1997-2010) model simulation, in terms of relative drawdown. There is good agreement between the observed and model predicted heads for the majority of the wells examined in the calibration, particularly to the maximum water levels in the observation data. Some of the municipal 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; the average monthly pumping rates produce model predicted water levels that are dampened when compared to observed water levels. Additionally, this appears to be the case in wells known to have been rehabilitated throughout the calibration period, as these wells have a history of poor performance. In the case of poor well performance, minimum observed water levels cannot be reproduced within the model. Finally, when calibrating a model to two wells located very close together who exhibit different magnitudes of response, a compromise must be made to optimize the goodness of fit to the hydrographs of both wells.

City Core Wells (Wells 3A, 4, 5, 7, 17 and 18)

The model predicted (line) and observed drawdown levels (points) reported in monitoring well TW1/91 and Well 3A are presented on Figure C.5.1. The monitoring well lies 14 m south of Well 3A. While the observed water levels of the pumping well vary approximately 30 m over the period of analysis (1997-



2010), the observed water levels of the test wells vary approximately 8 m. The simulated drawdown shows an excellent match to the observed drawdown in the test wells, mimicking observed highs and lows. The pumping well, which has experienced some decline in performance (See Conceptual Understanding Report, Section 3.2.4), shows a good match between the simulated and observed drawdown; however, some well loss and extreme highs and lows are unaccounted for within the model.

The model predicted (line) and observed drawdown levels (points) reported in monitoring well TW9/59 and Well 4 are presented on Figure C.5.2. The monitoring well lies 40 m south of Well 4. Both the test well and the pumping well show a data spread of about 10 m. The simulated drawdown shows a good match to the observed drawdown in the test wells, mimicking observed highs and lows. The pumping well shows a reasonable match between the simulated and observed drawdown. The extreme high and low measurements are unaccounted for within the model; however, these points represent a very small population of the dataset.

The model predicted (line) and observed drawdown levels (points) reported in monitoring well TW1/60 and Well 5 are presented on Figure C.5.3. The monitoring well lies 10 m east of Well 5. Both the observed water levels and the well water levels vary approximately 10 m over the period of analysis (1997-2010). The simulated water levels show a similar response to pumping as the observed water levels in the test wells.

The model predicted (line) and observed drawdown levels (points) reported in monitoring well TW3/60 and Well 7 are presented on Figure C.5.4. The monitoring well lies 7 m southwest of Well 7. Similar to wells TW1/60 and Well 5, the observed drawdown of both wells varies approximately 10 m over the period of analysis (1997-2010). The simulated drawdown shows a similar response to pumping as the observed drawdown in the test wells.

The model predicted (line) and observed drawdown levels (points) in monitoring wells TW1/02, TW2/02, Well 17 and Well 18 are presented on Figure C.5.5a and C.5.5b. While the observed drawdown of both pumping wells varies approximately 10 m over the period of analysis (1997-2010), the observed drawdown of the test wells vary approximately 6 m. The simulated drawdown shows a good match to the observed drawdown in the test wells. The extreme high and low data points have not been well matched, but these represent a relatively small population of the actual data, which means they are discrete, very local responses unable to be accounted for by the model.

Well 6 (Figure C.5.6) was also simulated until its shutdown in 2001. The results show a good match with observed response to pumping as well as the shutdown in 2001.

Lakeshore Wells (Well 8, Wells 11/14, Well 12, and Well 15)

The model predicted (line) and observed drawdown levels (points) reported in monitoring well TW 1/83, TW3/90, Well 11 and Well 14 are presented on Figures C.5.8a and C.5.8b. TW1/83 is 3 m northeast of Well 11, and TW3/90 is 25 m southeast of Well 14. The observed drawdown of the pumping wells vary greatly, with a wide spread in data due to well loss, declining well performance (see Conceptual Understanding Report, Section 3.2.4), and very local drawdown. As a result, both wells have been rehabilitated several times, and Well 11 has been offline since 2009. As a result, calibration focused on the response of the test wells nearby. The drawdown trends in the observed water levels are represented quite well by the model.



The model predicted (line) and observed drawdown levels (points) reported in monitoring well TW1/81 and Well 12 are presented on Figure C.5.9. The monitoring well lies 7 m southwest of Well 12. While the observed drawdown of the pumping well vary approximately 20 m over the period of analysis (1997-2010), the observed drawdown of the test wells vary approximately 6 m. The simulated drawdown shows an excellent match to the observed responses in the test wells, mimicking observed highs and lows. In the pumping well, the high and low water levels have not been well matched.

The model predicted (line) and observed drawdown levels (points) reported in monitoring well TW3/81and Well 15 are presented on Figure C.5.10. The monitoring well lies 7 m southwest of Well 15. While the observed water levels of the pumping well vary approximately 20 m over the period of analysis (1997-2010), the observed water levels of the test wells vary approximately 10 m. The simulated drawdown shows a good match to the observed response in the test wells, mimicking general trends.

Well 8 (Figure C.5.11) was also simulated, and water levels were compared for both the pumping well and its paired monitoring well, TW2/60. The results show a well matched seasonal response until the wells were decommissioned in 2001; however, the minimum water levels have not been represented adequately within the model. Well 8 was decommissioned due to poor well operating conditions, it has been assumed that the poor match can be attributed to this.

Barrie South (Well 10)

Although Well 10 has been decommissioned, effort was made to also calibrate the model to its water levels throughout the time period. The model predicted (line) and observed drawdown levels (points) reported in monitoring well TW1/74 and Well 10 are presented on Figure C.5.12. The monitoring well lies14 m north of Well 10, and the water levels vary approximately 10 m over the period of analysis (1997-2010). The simulated drawdown shows an excellent match to the observed responses at TW1/74; however, the magnitude of the response is overestimated. Well 10 presents two distinct ranges for depths – with a wide range between them of approximately 20 m. The upper range was asserted to be appropriate for calibration, because of its correspondence to the water levels found in the monitoring well, TW1/74.

Barrie North (Wells 9/13 and Well 16)

The model predicted (line) and observed drawdown levels (points) reported in monitoring wells TW1/75, TW3/88, Well 9 and Well 13 are presented on Figure C.5.7. TW1/75 is approximately 10 m southwest of Well 9, and TW3/88 is approximately 10 m south of Well 13. The monitoring data for both pumping wells show two distinct groupings which appear to relate to pumping and non-pumping conditions. The model was calibrated to the water levels measured during pumping conditions, which also correlate to the trends and values of the water levels of the test wells, which are close by and screened within the same aquifer. The response trends in the observed drawdown are well represented within the model.

The model predicted (line) and observed drawdown levels (points) reported Well 16 is presented on Figure C.5.13. Well 16, which did not begin pumping until 2000, shows observed water levels with a range of 10 m. The model simulated water levels for both wells show a good match to the observed relative water level and there were excellent matches to observed lows.



5.2 Qualitative Assessment

The following sections outline the qualitative measures used to assess the model calibration. Models are non-unique and as such, field based parameter values are beneficial to assess the reasonableness of the input parameters. In addition, model-predicted water levels are compared and contrasted with the observed water level maps produced by contouring the water levels reported in the MOE water wells and the available higher quality data sets.

The following section outlines final model parameters within the municipal aquifer, as well as the model predicted water levels in the shallow (A1) and deep (A3) systems 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 City of Barrie high quality monitoring wells.

5.1 Model Input Parameters

Most of the wells are simulated in the model to be drawing from permeable sand, gravel and cobble units that lie within buried channel sediments. The hydraulic conductivity and transmissivity values of the sediment within the municipal aquifer material do not vary widely. Table 5.2 shows that the modelled transmissivity values are consistent with range of values determined from pumping tests referenced. Calibrated model conductivity in general was calibrated to be slightly higher than field based data; the small discrepancy comes from two sources. One, the model is calibrated on a zone basis, which applied an average K rather than a localized K. Second, model layers will always be more generalized than what is found in the field. Modelled Conductivity can be seen on Maps 5.2 to 5.5 for each aquifer unit.

Table 5.2: Modelled and Field-Based Bedrock Conductivity and Transmissivity Values

	Field Mea	sured	Modelled			
Name	T (m²/s)	K (m/s)	T (m²/s)	K (m/s)		
Well No. 3A	3.3E-02	1.45E-03	2.8E-02	1.60E-03		
Well No. 4	1.4E-02	9.03E-04	1.8E-02	3.50E-03		
Well No. 5	2.5E-02	6.60E-04	9.4E-03	1.60E-03		
Well No. 7	3.9E-02	1.45E-03	4.0E-03	1.23E-03		
Well No. 9	2.9E-02	3.94E-04	1.5E-02	1.63E-03		
Well No. 11	1.4E-02	4.24E-04	1.7E-02	3.50E-03		
Well No. 12	1.2E-02	3.01E-04	1.3E-03	1.60E-04		
Well No. 13	3.0E-02	4.28E-04	1.8E-02	1.60E-03		
Well No. 14	1.6E-02	5.63E-04	1.4E-03	1.61E-04		
Well No. 15	2.1E-02	8.68E-04	9.3E-03	1.63E-03		
Well No. 16	1.7E-02	7.75E-04	4.3E-03	5.02E-04		
Well No. 17	2.9E-02	6.71E-04	8.2E-03	1.63E-03		
Well No. 18	3.2E-02	7.35E-04	9.5E-03	1.63E-03		

5.2.1 <u>Simulated Shallow Aquifer (A1) Equipotential Contours</u>

Map 5.6 illustrates the predicted water level contours produced in the steady state groundwater flow model. As illustrated on the figure, water table contours generally mimic the ground surface



topography, and flow converges towards the higher order streams and wetlands. The groundwater elevation contours compare well with the observed water level contours illustrated on Map 4.3, in the Conceptual Understanding Report, in that flow gradients both in terms of direction and magnitude are similar, especially considering flow driven towards the Barrie city core. There are some local differences, the shape of the contour intervals within the simulated water levels are much smoother, indicating that there is local characterization that has not been captured, particularly in the highest areas of the Oro Moraine, and an area along Banks Creek south of Stroud.

The largest gradients (tightly spaced contours) are observed at regional discharge locations, which include the Nottawasaga River, the steep topography around Little Lake and along the flanks of upland regions. The lowest gradients are observed within the Minesing Wetland as well as in the flat regions within the centre of upland areas.

5.2.2 Simulated Deep Aquifer (A3) Equipotential Contours

Map 5.7 illustrates the deep aquifer water level elevation contours within the Study Area. The water level contours are similar to the shallow water levels however the deep water levels exhibit a more subdued expression. The water level contours converge within the bedrock valley associated with the modern day Nottawasaga River, and on regional groundwater discharge features such as Kempenfelt Bay. Flow is noted to be influenced by the Nottawasaga and the Minesing wetland complex where there is a hydraulic connection with the deeper system. As with the shallow system, although the simulated equipotentials reflect the same flow gradients as the observed equipotentials, some local features within the simulated results are absent.

5.2.3 Vertical Hydraulic Gradient

Map 5.8 illustrates the direction of the simulated vertical hydraulic gradient across the Study Area, calculated as the difference between the water table elevation surface and deep potentiometric surface. The map is shaded to show the upwards (blue) and downwards (green) gradients. Upwards gradients are predicted to exist along the Nottawasaga River and its tributaries and some wetland complexes; a reflection of groundwater discharge to those areas. The largest areas of groundwater discharge are in portions of the Minesing Swamp, consistent with the existing knowledge of the wetland, as well as Little Lake and Lake Simcoe. The highest downwards gradients are present along the crest of the Oro Moraine and along the flanks of the upland areas on either side of the Barrie city core where shallow overburden groundwater recharges the underlying aquifers.

5.2.4 Groundwater Discharge to Surface Water

Map 5.9 illustrates the location and magnitude of the simulated groundwater discharge zones along creeks and rivers incorporated within the groundwater flow model. On this figure, the darkest blue circles represent the river reaches with the largest groundwater discharge. Conversely, water shown in pink on the figure is simulated as recharging the groundwater system. These would be considered losing stream reaches. A comparison of the discharge mapping from the model with maps produced by the Fisheries Habitat Plan (NVCA and Fisheries and Oceans Canada 2009) and LSRCA (2010) shows that most coldwater and coolwater fishery stream reaches, both of which are known to be groundwater discharge areas, are well represented within the model. Some of the extreme upper reaches of the streams, particularly those close to or above the simulated water table, are not as well represented due to a lack of local refinement, especially in areas where the stream is thought to be fed by perched aquifer conditions. During the calibration process, stream segments that were simulated to be recharging the



aquifer were compared to coldwater mapping and given a low conductance value, if warranted, such that the volume of water recharging along streams is minimal and does not negatively impact the overall water budget.

5.3 Overall Groundwater Model Calibration Assessment

The ability of the groundwater model to simulate the flow system in the Study Area was evaluated both qualitatively and quantitatively. Qualitatively, the simulated groundwater level contours and vertical hydraulic gradients are consistent with observed conditions. The elevations of regional wetlands were also overlain with model results to ensure modelled water levels were representative of these wetland elevations. Modelled stream discharge was compared to mapped coldwater regimes. Quantitatively, simulated hydraulic head and baseflow measurements closely match observed values within the acceptable statistical range, while reproducing observed flow directions and gradients. 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, the simulated heads at most of the City's monitoring network were close to observed values and the model accurately predicts the flow system response to stresses due to pumping of the municipal aquifer. Model predicted groundwater levels over the 13 year period (1997-2010) are very similar to the measured hydraulic heads in monitoring wells over the same period within the city core suggest the model is well calibrated to transient conditions. And finally, simulated groundwater discharge rates agree favourably with a majority of the baseflow estimates.

The calibration was achieved using input parameter values that are within the expected range or measured range for the groundwater system in the area. Local knowledge of the Study Area was also beneficial in this regard, and helped guide the calibration effort. 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.

6.0 GROUNDWATER FLOW MODEL LIMITATIONS

All models developed to represent natural systems are simplifications of the natural environment and the hydrologic processes within that environment. One can never understand all the complexities of the physical system to incorporate all details into a numerical context. In reality, most of the scientific approach involves representing physical conditions observed using approximations of larger-scale functionality; hydraulic conductivity is an example of this. This approximation does not negate the ability of scientists and practitioners to utilize numerical models as tools to help understand and manage natural systems; we do however need to recognize the limitations of such tools when interpreting model results.

Many elements of the groundwater modelling process using any modelling code are subject to uncertainty. Although the calibration process is performed in an attempt to provide a realistic representation of physical conditions and to reduce uncertainty, the model results and water budgets reflect the uncertainty in the model input parameters.

The following sections summarize some of the uncertainties associated with the modelling process and discuss some of the potential impacts of this uncertainty.



6.1 Scale

The groundwater flow model is designed to incorporate the key hydrogeologic features of the regional Study Area and localized features of the Focus Area around the City of Barrie well field. Thus the model has been designed to evaluate the flows through the system incorporating key identified features and characteristics as understood through the characterization process and through local experience. The implication is that features at a smaller scale may not be adequately represented outside of the Focus Area to support more local assessments and additional refinement and characterization is required to examine those areas. This is especially true for this Study Area, which contains several relatively small scale features such as sharp topographic changes, and numerous streams and wetlands.

6.2 Characterization Data

One uncertainty in groundwater models is the lack of high quality subsurface data. For this model, an attempt was made to reduce this uncertainly through the generation of hydraulic conductivity fields, based on the lithology recorded at individual boreholes and available aquifer testing data, combined with the development of a conceptual geologic model. However, very small scaled features within the shallow system of the upland areas are not well understood, as most hydrogeologic investigations within the Study Area focus on the deep aquifer system. This includes, but is not limited to, perched water table conditions. Properties within some of the confining aquitards are also not well known, and can only be inferred from borehole lithology or head differences across the layer, rather than hydraulic testing within that layer.

6.3 Calibration Data

The scale of the calibration effort is consistent with the scale of the model. The model was designed and calibrated to both regional-scale features that control groundwater flow at the subwatershed level, as well as local feature surrounding the municipal well fields. Accordingly, the calibration procedure implemented for this study grouped parameters spatially, and varied them in proportion to one another. During that procedure, calibration focused on spatial trends in observed water levels and discharge estimates. Calibration targets that included water levels reported in the MOE water well database and baseflow calibration targets, as discussed below:

• Water levels from MOE Water Well Records: In our experience, the expected range of uncertainty associated with water levels from water well records is on the order of 5 m. This is due to inaccurate water level measurements, inaccurate reference point elevations or measurements taken in poorly developed wells. This can include for example: variability of the water level relative to the time of measurement (i.e., seasonal or annual differences); measurement timing (i.e., levels may not have recovered to static conditions); measurement error or recording errors; well location errors; and measurement point elevation errors. Errors in elevations, either ground surface, screen information or water levels can also result in monitoring data being assigned erroneously to particular units. As a result, it is common to see scatter with this type of data, such that individual values have an associated degree of uncertainty, but the trends illustrated by multiple data points are expected to be realistic. Since natural fluctuations in groundwater levels are generally minor (~2 m or less where stress conditions are consistent), carefully measured water levels are considered to be more certain than most other calibration targets.



• Groundwater Discharge Estimates: Groundwater discharge is expected to be a component of the baseflow in most stream / river courses; the remainder of the baseflow is contributed from upstream wetland or other storage mechanisms. As the proportion of groundwater discharge to wetland discharge is rarely known, this is one source of uncertainty. Further, baseflow discharge is estimated using streamflow recession approaches which are empirical and interpretive. Further, baseflow estimates are generally determined from a limited time period of available streamflow record yet are assumed to be representative of an average "static" condition, although static baseflow conditions do not exist. The approximation from highly variable natural and seasonally fluctuating river conditions results in uncertainty such that calibration of groundwater discharge to baseflows is generally targeted to be within the range of observed baseflow estimates.

6.4 Limitations of the Modelling Approach

In addition to the characterization and calibration uncertainty, the numerical representation and simulation of groundwater flow systems also contains limitations. Model simulation uncertainty comes from both the approximate solution of the equations using the finite element method, as well as the limitations surrounding finite discretization and assumptions of steady-state.

- Galerkin Finite Element Solution: The Galerkin finite element method employed by FEFLOW solves
 the system of equations using an iterative solver that attempts to minimize the residuals globally; it
 is expected that some numerical error can exist internally within the model domain, although this is
 generally minor. Strict convergence criteria (i.e., 1e-3m) and water balance criteria (< 1% error) were
 applied to minimize residuals throughout the model.
- Finite Discretization: Practically, the solution of the equations is limited to calculation of groundwater head and flows at a finite number of points; the higher the number of points (smaller the elements), the more computer power and time needed. More precision is achieved when using a higher number of calculation points, particularly in areas of larger water level changes. With any scale of model, there is a balance between the level discretization (distance between calculation points) and the required computer power to efficiently run and calibrate the model (also financial budget). The practical limitation of discretization therefore presents some uncertainty in the water budget results. This limitation is especially important because it affects the majority of both the adjustable model parameters, as well as the trends in observed data, where many monitoring wells could be contained within one model element. In a model of this scale, balance needs to be struck between the level of detail needed, the data available, and the computational effort that is still needed to be practical for stress assessment purposes.
- Steady-State Solution: Similarly to the spatial discretization, the time discretization chosen for modelling affects the computer power and time (budget) required to calibrate and apply a numerical model. As a result, one simplifying assumption that is commonly made is that the groundwater flow system can be adequately represented using a steady-state simulation approach. Hydraulic stresses are often time-averaged and associated with water level targets averaged over the same temporal period. In addition, since groundwater systems respond at relatively slow rates (months, years, decades) particularly at the regional scale, a steady-state approximation is reasonable and provides general understanding. This assumption may however create differences between the simulated conditions and conditions observed in the field at any one particular time. For these reasons, transient simulations are conducted in an attempt to reduce uncertainty in hydraulic properties such as conductivity. However, this effort improves representation within the



area local to the transient calibration wells (in this case, within the Focus Area) and outside of this region, uncertainty can still persist.

As noted above, there are a number of limitations in the numerical modelling process that lead to uncertainty in model predictions. The uncertainty due to the modelling process however, is considered to be relatively minor compared to the uncertainty in the physical characterization and calibration process. Overall, the discussed model limitations and uncertainty do not detract from using the numerical flow model developed for the stated objectives of the Tier Three Risk Assessment.

7.0 SUMMARY AND CONCLUSIONS

A FEFLOW groundwater flow model was developed for the Study Area. The model layers were developed from an established conceptual model that was based on deep borehole logs, and high quality logs reported in various hydrogeology studies completed within the Barrie area.

The model was calibrated using the recharge estimates provided by the calibrated Mike SHE surface water model. Both models were calibrated iteratively, so that they used the same information and could provide feedback from one model to the other. The model calibration focused on matching the range of observed water levels in 32 high quality monitoring wells, other high quality observation data that has been verified through other studies and to the static water levels reported in the MOE water well database. The model was also transiently calibrated to long term municipal pumping and observation data in the high quality monitoring data. The calibration results show that the model is well calibrated to current and historical conditions and is considered suitable for use in predictive scenarios. Knowledge of data gaps acquired through the model building and calibration process can be applied in an uncertainty assessment within the context of the predictive scenarios.

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