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Six Conservation Authorities FEFLOW
Groundwater Modeling Project

Final Report

July 2007

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Prepared for:

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Executive Summary

Introduction

The Six Conservation Authorities (Six CA's) study developed a strategic plan to understand the regional scale geology and hydrogeology within the Six CA's watershed area and how they link to the natural environment. To enhance their understanding a conceptual geological model and a numerical groundwater flow model of the entire Six CA watersheds were developed. The groundwater model will be used as a groundwater management tool to:

1. Examine the impacts of various changes to the natural system on regional groundwater flow;
2. Assess the role of large-scale regional features on regional groundwater flow;
3. Determine groundwater flow rates to evaluate groundwater budgeting; and,
4. Identify pathways and linkages between both local and regional recharge and discharge areas.

Waterloo Hydrogeologic, Inc., A Schlumberger Company (WHI) was retained by the Upper Thames Region Conservation Authority (UTRCA) to develop a three-dimensional conceptual geological model and a three-dimensional hydrogeological (groundwater flow) model that encompass the entire Six CA's watershed.

Objectives

Understanding of the groundwater flow system is gained through the review of available information, the development of a conceptual geological model, and the construction of a three-dimensional numerical flow model that represents the elements of the conceptual geological model. The model is utilized as a tool to further understand and simulate the groundwater flow system. To meet these objectives the following goals were defined for this project:

1. Develop a spatially referenced database for visualization of hydrogeologic information for construction of a numerical flow model.
2. Develop a watershed-scale, three-dimensional, conceptual geological model that builds upon the existing conceptualization and numerical models that have been developed within the watershed.

3. Develop a calibrated steady-state regional groundwater flow model that incorporates details from existing groundwater flow models.

Scope and Major Tasks

The scope of this project was to construct a calibrated groundwater flow model at the regional scale encompassing the Six CA's watershed. The following tasks were completed for both the development of the conceptual model and the hydrogeological model:

1. Identified, acquired and reviewed all available data including previous studies, available digital information and previous groundwater models.
2. Developed a spatially referenced database of hydrogeological information for the study area and completed mapping using GIS to characterize the aquifers and aquitards across the watersheds.
3. Identified regional and local boundaries of groundwater flow (e.g. groundwater/surface water divides) for the conceptual model development, which is consistent with other studies and includes regional and local elements (e.g. surface water features).
4. Construct and calibrate a regional scale three-dimensional hydrogeological model based on the conceptual geological model utilizing the database information and GIS mapping. Calibrate model to average conditions based on static water levels (from water well records) and spot baseflow measurements in area streams between 1915 and 2003.

Previous Work and Existing Data

Regional groundwater study reports were compiled and reviewed, as well as relevant papers in the academic literature. This information was used to develop our understanding of the geologic and hydrogeologic setting in the Six CA study area.

The geologic structure, hydraulic conductivity and layer information were used to develop the conceptual geological model and the numerical groundwater flow model. The local scale models (developed during the Ministry of the Environment (MOE) funded groundwater studies) were used as a reference when defining the regional model characteristics. The comparison of heads and calibration targets as well as discharge rates to rivers and streams were compared between the local and regional models during model calibration.

A number of data sets and maps were utilized in this project to develop the conceptual and numerical groundwater flow models. These included watershed wide thematic maps, parameter distributions and model layers for the geologic and numerical models. The data sources were compiled and analyzed in a relational database and GIS mapping system.

Conceptual Model of the Six CA's Geology and Hydrogeology

The Six CA's watershed includes portions of many counties including Essex, Chatham-Kent, Elgin, Perth, Oxford, Middlesex, Huron, Bruce, Brant, Wellington and Lambton Counties and the Regional Municipality of Waterloo. This watershed is approximately 143 km wide (east to west through London, Ontario) by 300 km long (from Windsor to north Perth) with a ground surface elevation ranging from 472 m amsl in the northern portion of the study area to 170 m amsl at the southern portion where the Thames River enters Lake St. Clair.

The physiographic regions within the watershed are primarily a result of the last glaciation, approximately 25,000 years ago. The present day geologic setting consists of eroded Paleozoic sedimentary bedrock units, overlain by glacial deposits and more recent alluvial deposits.

The bedrock units in the Six CA's watershed consist of Paleozoic sedimentary rocks, composed of limestone, dolostone, and shale that overlie the Precambrian basement. The bedrock units, in the northern to central portion of the watershed, exhibit a regional dip of 0.2 percent to the southwest as is observed across the eastern Michigan Basin and bedrock units in the lower southern portion of the watershed exhibit a regional dip of 0.5 percent to the south, as is observed across the Appalachian Basin (Johnson et al., 1992).

Numerical Groundwater Flow Model

Numerical models are structured tools for integrating a multitude of data (e.g. lithologies, water levels, groundwater/surface water features, or pumping well information) and conceptual ideas to understand groundwater flow paths. This helps the modeller to predict variations caused by changing conditions in light of new data about the system. Models are used throughout the world to evaluate groundwater systems and have been growing in their application since the 1970's. Applications have migrated from simplified models, where geologic complexities were grossly generalized, to more detailed models, which utilize all available data in an effort to represent the hydrogeologic system as accurately as possible. In our experience, incorporation of geologic/hydrogeologic detail produces a more realistic model and a more useful tool. Despite these efforts, natural uncertainty will be inherent in the model predictions since nature's complexities, hidden beneath the ground surface, are at a finer scale than the model can represent.

The location, extent and finite element mesh of the model domain encompasses the entire Six CA's watershed. The model domain is approximately 143 kilometers in width (East-West) and approximately 168 kilometers in length (North-South).

The mesh is refined in areas where it is important to have an enhanced definition of the potentiometric surface. This includes rivers (Thames, Maitland, Ausable, Avon, Sydenham Rivers and their tributaries), and large pumping wells (identified in the PTTW dataset). The model domain was subdivided into the six defined sub-basins, which allows us to calculate detailed water budgets in sub-basins and future model refinements.

The model was calibrated to observations of hydraulic heads in MOE water well records and to observations of groundwater discharge (from baseflow estimation) to the rivers and their tributaries. Model calculated hydraulic head and baseflow measurements closely match observed values within an acceptable statistical range (ASTM, 1995) while reproducing observed flow directions. The overall mass balance error was less than 0.1 percent, which is considered acceptable. The calibration was achieved using input parameter values within the expected range or measured range for the groundwater system in the Six CA's watersheds.

Summary and Recommendations

This report presents the analyses and development of the numerical groundwater flow model. The model represents the full three-dimensional regional groundwater flow system and extends deep into the underlying bedrock to incorporate interaction with the deeper groundwater system. Through this approach, the Six CA's can use the numerical model to evaluate the interaction of groundwater and surface water (water balance) and assess the potential influence of additional stresses (e.g. land use changes, pumping etc.). In addition, this model can be updated as new information becomes available and refined as necessary to focus calibration and prediction capabilities in local areas of concern.

Recommendations related to the further development and uses of the groundwater flow model as a groundwater management tool are as follows:

1. Maintain a detailed analysis of PTTW Average Annual Extraction Rates to provide information for the model to understand the influence on the regional water balance.
2. The model should be updated to include any additional municipal pumping wells in the study area. It can also be used to test modeling scenarios that seek to understand how additional pumping wells will stress the groundwater system.
3. Update the model at regular intervals using detailed geological cross-sections and any other new information that becomes available.
4. Review the model at smaller scales (scale of future simulations; ie., sub-watershed scale) to verify the representation of the model layers and assess the need for localized refinement.
5. Examine interaction between the groundwater model and surface water models (e.g GAWSER).
6. A sensitivity analysis should be completed on the model to determine what areas of the model are sensitive to parameter variations, resulting in further data collection or model refinement.

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1 Introduction

1.1 Overview

The Six Conservation Authorities (Six CA's) watershed is comprised of the following conservation authorities:

- Maitland Valley
- Ausable Bayfield
- Upper Thames
- Lower Thames
- St. Clair Region; and
- Essex Region

A groundwater study was initiated by the Six CA's to follow the Conceptual Model Report (Appendix B) developed to improve understanding of local groundwater conditions within the context of a larger regional groundwater flow system. The study area included in the Six CA's Groundwater Study is presented on **Figure 1-1**.

The study acknowledges that the basic groundwater functions of recharging, transmitting, storing and discharging water play an essential role in maintaining a healthy ecosystem. Understanding these regional groundwater functions is necessary to provide a secure supply of clean water to municipal and communal water systems, as well as individual groundwater users who do not have access to a municipal supply.

The groundwater model can be used as a tool to:

- Examine the impacts of various changes to the natural system on regional groundwater flow;
- Assess the role of large-scale regional features on regional groundwater flow;
- Determine groundwater flow rates to evaluate groundwater budgeting; and,
- Identify pathways and linkages between both local and regional recharge and discharge areas.

Waterloo Hydrogeologic, Inc., A Schlumberger Company (WHI) was retained by the Upper Thames Region Conservation Authority (UTRCA) to develop a three-dimensional conceptual geological model and a three-dimensional hydrogeological (groundwater flow) model that encompasses the entire Six CA's watershed.

1.2 Objectives

Understanding of the groundwater flow system is gained through the review of available information, the development of a conceptual geological model, and the construction of a three-dimensional groundwater flow model that represents the elements of the conceptual geological model. The groundwater flow model is utilized as a tool to further understand and simulate the groundwater flow system. To meet these objectives the following goals were defined for this project:

1. Develop a spatially referenced database of hydrogeologic information for visualization of regional hydrogeologic information, and construct a numerical model.
2. Develop a watershed-scale, three-dimensional, conceptual geological model that builds upon the existing conceptualization and numerical models that have been developed within the watershed.
3. Develop a calibrated steady-state regional groundwater flow model that incorporates details from existing groundwater flow models.

1.3 Scope and Major Tasks

The scope of this project was to construct a calibrated groundwater flow model at the regional scale encompassing the Six CA's watershed. At this scale the model may not capture the complexities of either the glacial deposits or the underlying Paleozoic geology within each of the watersheds identified through local scale studies. The following tasks were completed for both the development of the conceptual model and the hydrogeological model:

1. Identified, acquired and reviewed all available data including previous studies, available digital information and previous groundwater models.
2. Developed a spatially referenced database of hydrogeological information for the study area and completed mapping using GIS to characterize the aquifers and aquitards across the watersheds.
3. Identified regional and local boundaries of groundwater flow (e.g. groundwater/surface water divides) for the conceptual model development, which is consistent with other studies and includes regional and local elements (e.g. surface water features).
4. Constructed and calibrated a three-dimensional hydrogeological model based on the conceptual geological model utilizing the database information and GIS mapping. The focus of the model calibration was at the regional scale. Calibrated model to average conditions based on static

water levels (from water well records) and spot baseflow measurements in area streams between 1915 and 2003.

1.4 Mapping, Database Development, and Data Limitations

A number of existing data sets and maps were utilized in this project to develop the conceptual geological model. These included watershed-wide thematic maps, parameter distributions and model layers for the geologic and numerical models. The data sources were compiled and analyzed in a relational database and GIS mapping system.

1.4.1 GIS Mapping

The Six CA's provided data the following features in a GIS format:

- Topography (Digital Elevation Model – DEM)
- Quaternary Geology
- Bedrock Geology
- Surface Water features (e.g. streams, wetlands, sub-basin boundaries)
- Recharge classification
- Municipal features (e.g. roads and land use)

The majority of the mapping is considered regionally accurate. The DEM was available at a resolution of 100 metres. In developing the conceptual geological model, WHI completed a detailed evaluation using information from previous reports. A number of maps were created as part of this project including an updated bedrock surface, overburden thickness, shallow water levels, deep water levels, recharge and discharge, and regional cross-sections. All maps were created to a 5 km buffer of the outermost Six CA watershed boundary and subsequently trimmed to the watershed boundary for display purposes.

1.4.2 Relational Database of Water Well Records

The primary source of geologic and hydrogeologic information for this project was the water well database, which was generated from the MOE Water Well Information System (WWIS). The WWIS is a compilation of more than 50 years of water records completed by various water well contractors. This background information was organized into a relational MS ACCESS database format for use in the ArcGIS environment. It is recognized that the WWIS database, which WHI received from the Six CA's, contains limitations, including different reliabilities for well locations, inconsistent geologic descriptions and variable well completion techniques. Recognizing the limitations of the WWIS, WHI screened the WWIS database and identified the most reliable well records based on the following criteria:

- Location and elevation of all available water wells
- Consistency and accuracy of description of lithology
- Static water levels for groundwater head (pressure) and flow mapping
- Well details including depth of water bearing zones
- Well construction details such as depth of casing and recommended pumping rates.

Furthermore, the reliability of the well location and elevation was assessed by: 1) verifying the coordinates against the Lot-Concession layer from the Ontario Base Map (OBM), which was completed by the MOE; and 2) checking the elevations against the Digital Elevation Model (DEM). Only the WWIS wells that had good location reliability (< 300 m) and where the DEM elevation was within 10 metres of the reported elevation, were used in the development of the GIS map layers and the conceptual geological model. All elevation data within the database was updated to be consistent with the DEM. This included for example tables that deal with construction details, geologic unit elevations, and static water levels.

Figure 1-2 shows the spatial distribution of the high quality water well records. The original MOE WWIS database consisted of approximately 27,000 well records. The number of reliable wells was reduced to approximately 25,000 after the screening process was completed. The poor reliability wells were not removed from the database but rather flagged and excluded from any subsequent analysis.

The WWIS Formation table includes a description of the well geology for each interval that was recorded by the water well contactor. Under the Provincial legislation Ontario Water Resources Act Regulation 128/03 (previously Regulation 903), all water well contractors are required to log the geologic material encountered when drilling or boring a water well. These materials are used to determine the hydrostratigraphic units of the well and to determine the uppermost bedrock unit. The geology material descriptions were adjusted to match the Geological Survey of Canada (GSC) descriptions as per the MOE Technical Terms of Reference for the Provincial Groundwater Studies (MOE 2001).

Additional tables have been added to the database to include point information from regional geologic and hydrogeologic mapping (hydrostratigraphic layer elevations), hydraulic conductivity, water level elevations, and pumping well locations. This was done through a WHI in-house Visual Basic program that identified each geologic record within the well and then identified systematically what hydrostratigraphic unit it belonged to.

1.4.3 Relational Database of Oil and Gas Well Records

Oil and gas well records were obtained from wells drilled in the Six CA's watershed and adjacent areas. The Oil and Gas well records were combined and appended to the WWIS database for inclusion in the GIS mapping layers. These well logs list the elevations of bedrock formations in the area, which were used to define the lower bedrock layers in the conceptual geological model. The geologic material description, listed in the well logs, was updated to reflect the standardized GSC nomenclature that was used in the MOE WWIS.

Figure 1-3 shows the spatial distribution of the high quality Oil and Gas well records. The original Ministry of Natural Resources (MNR) database consisted of 7,906 well records. However, it was found that several wells were either duplicates or did not have complete records. These incomplete records were flagged within the database and were not used during the generation of the conceptual geological model.

1.4.4 Permit to Take Water Database

The MOE issues Permits to Take Water (PTTW) that allow the withdrawal of a large volume of surface and/or groundwater (greater than 50 000 litres per day). These permits are contained within a database that identifies the location, source of water; maximum permitted volume and pumping rate, number of days of extraction, and expiry date of the permit. Permits that are temporary, cancelled or expired prior to 1993 were not included in the groundwater flow model. The permit information indicates the amount of water that can be withdrawn from areas within the watersheds. However, the information contained in the PTTW files does not contain details related to the actual pumping rate at which these wells are currently operating. This information must come from permit owners, who would have the documentation available. For the development of the Six CA's watershed model, additional information on actual pumping rates was available for selected wells. For municipal wells the average daily pumping rates were complied and supplied to WHI for inclusion in this report.

A steady-state saturated groundwater flow model required the specification of the long-term average pumping rate for each pumping well. Thus, for municipal wells where actual operational information was available, the average municipal pumping rate was used. All surface water takings were excluded from the groundwater flow model, as they cannot be explicitly simulated.

1.4.5 Regional Cross-Sections

To obtain a thorough understanding of the hydrostratigraphic conditions and to construct the conceptual geological model of the study area, WHI developed twelve regional cross-sections along areas of greatest interest within the study area, as depicted on **Figure 1-4**. The interpreted cross-sections illustrating the general geologic and hydrostratigraphic structure are shown on **Figures 1-5** through to **Figure 1-16**. The cross-sections utilize water well records form the MOE WWIS and the MNR Oil and Gas well records. Detailed geologic information for high quality well records, including the municipal wells in the watershed and deep wells drilled for oil and gas exploration, were included in the cross-sections.

The regional cross-sections provided a basis for construction of the conceptual hydrostratigraphic units, which was used to define the layers and parameter distributions (e.g. hydraulic conductivity) for the numerical groundwater flow model.

CS Mapper was utilized, a custom GIS application developed by WHI, to query the project database and create the cross-sections. CS Mapper is a Windows based application that resides within the MapInfo GIS environment as an add-on application. CS Mapper utilizes the many standard GIS tools available for selecting and querying the data. In addition, all GIS data are available to CS Mapper, allowing spatial data such as topography (DEM), or borehole metadata to be directly displayed on the cross-sections. A GIS is used to manage and visualize large information databases, create and confirm interpretations on-screen, and store layer definitions for use in the model development.

Application of CS Mapper is a three-step process:

1. Select the boreholes to be displayed on the cross-section, and the straight-line segment onto which the boreholes will be projected within the standard GIS windows.
2. Build the cross-section from the pull-down menu and select the appropriate options using the CS Mapper window.
3. Interpret the appropriate geologic structure in the cross-section window, and save the interpretations back to the GIS database.

Once the “Interpretation Database” was populated, these data were used within the GIS for interpolation of model layers. This provided a useful functionality for developing the groundwater flow model, where a GIS database of geologic and hydrogeologic information was developed.

2 Conceptual Geological Model

The following section provides a description of the hydrogeologic features of the Six CA's watershed and surrounding areas. The conceptual model report (WHI 2004) was used to guide the development of the numerical model in a manner consistent with the geology and hydrogeology of the area.

Figure 2-1 shows the conceptual hydrostratigraphic structure across the Six CA's watershed. Not all layers were present everywhere throughout the watershed. Where aquifer/aquitards and bedrock units do not exist, the conceptual geologic layers were pinched out to represent a zero thickness. Provided below is a brief summary of the regional geological setting that makes up the three dimensional numerical model development.

2.1 Regional Geological Setting

The Six CA's watershed includes portions of many counties including Essex, Chatham-Kent, Elgin, Perth, Oxford, Middlesex, Huron, Bruce, Brant, Wellington and Lambton Counties and the Regional Municipality of Waterloo. This watershed is approximately 143 km wide (east to west through London, Ontario) by 300 km long (from Windsor to north Perth) with a ground surface elevation ranging from 472 m amsl in the northern portion of the study area to 170 m amsl at the southern portion where the Thames River enters Lake St. Clair at Windsor, as shown in **Figure 2-2**.

2.1.1 Physiography and Surficial Geology

The physiographic regions within the watershed are primarily a result of the last glaciation, approximately 25,000 years ago. The present day geologic setting consists of eroded Paleozoic sedimentary bedrock units, overlain by glacial deposits and more recent alluvial deposits, which is shown on **Figure 2-3** and can be grouped into the following five general features:

1. Low permeability, moderate relief plains:

- Stratford Till
- Rannoch Till
- Elma Till
- Mornington Till

- St. Joseph's Till
- Port Stanley Till
- Tavistock Till

2. Higher permeability, moderate relief, coarse-grained (potential kame) moraines:

- Dorchester Moraine
- Easthope Moraine
- Ingersoll Moraine
- Staffa Moraine

3. Low permeability, low relief lacustrine clay plains:

- Ekfrid Clay Plain
- St. Clair Clay Plain

4. Higher permeability, low relief outwash sand and gravel deposits:

- Caradoc Sand Plain
- Bothwell Sand Plain
- Leamington Sand Plain
- Komoka Delta (London)

5. Higher permeability, low relief recent alluvial deposits

2.1.2 Bedrock Geology

The bedrock units in the Six CA's watershed consist of Paleozoic sedimentary rocks, composed of limestone, dolostone, and shale that overlie the Precambrian basement. The bedrock units, in the northern to central portion of the watershed, exhibit a regional dip of 0.2 percent to the southwest as is observed across the eastern Michigan Basin and bedrock units in the lower southern portion of the watershed exhibit a regional dip of 0.5 percent to the south, as is observed across the Appalachian Basin (Johnson et al., 1992).

Figure 2-4 presents the bedrock geology for the study area which shows the uppermost bedrock unit across the watershed. **Table 2.1** is a summary of the bedrock geology of the Six CA watershed and outlines the approximate thickness of the bedrock units that were used in the conceptual geological model.

Table 2.1: Model Representation of Hydrostratigraphic Units

Formation	Sub-Members	Geology	Sub-crop Location	Thickness
Port Lambton		Grey/black shale and sandstone	Near Sarnia along St. Clair River	60 m
Kettle Point		Black, organic-rich, shale with minor beds of silty shale	Lambton and Kent Counties	~30 m at Chatham
Hamilton Group	Ipperwash	Coarse-grained, grey brown bioclastic limestone	South of Chatham to the Lake Eire shoreline	Max. 90 m
	Widder	Interbedded shale and fossil rich limestone		
	Hungry Hollow	Interbedded grey shale and fossiliferous limestone		
	Arkona	Blue-grey shale with minor discontinuous limestone beds		
	Rockport Quarry	Fine-grained limestone with occasional thin shaley beds		
	Bell	Blue/grey shale beds with minor limestone lenses		
Marcellus Formation		Black, organic-rich shale	North shore of L. Erie	Up to 15 m
Dundee Formation		Fossiliferous Limestone	Central Portion of study area from L. Huron to L. Erie	35 to 45 m
Detroit River Group	Sylvanian	Orthoquartzitic sandstone	Small area near Windsor	60 to 90 m
	Lucas	Microcrystalline limestone	Central portion of the study area from L. Huron to L. Erie	
	Amherstburg	Crinoidal limestone and dolostone		
Bois Blanc		Cherty brownish grey, fossiliferous limestone	Beneath Woodstock, Listowel, to Port Elgin (L. Huron)	45 m
Bass Islands		Oolitic dolostone with minor thin beds of shaley dolostone	Eastern portion of the study area	30 m: thickens to southwest
Salina		Interbedded shale, mudstone, dolostone, and evaporates (including gypsum and salt)	East of Listowel and Woodstock	120 to 200 m

2.1.3 Bedrock Topography and Overburden Thickness

The interpolated bedrock topography of the study area is illustrated on **Figure 2-5**. The bedrock surface topography was interpreted using both high quality MOE water well records and the MNR oil and gas well records. The process of interpolating the bedrock surface was completed in several steps:

1. The first step was to interpolate the bedrock surface using only wells (both water wells and oil/gas wells) that penetrated to bedrock (bedrock was listed in the geology table according to the classified GSC description).
2. This bedrock surface was then inspected to identify areas where wells that did not penetrate to bedrock (according to the well records), penetrate the interpolated bedrock surface.
3. The bedrock surface was then re-interpolated using both the top of bedrock and the bottom of the borehole (for overburden wells that penetrated the original bedrock surface).
4. Using the bottom of the borehole for overburden wells prevented the bedrock surface from being interpolated across a natural bedrock valley system. This process was repeated until all high quality overburden wells were above the interpolated bedrock surface.

The bedrock slopes from a high of 442 m amsl at the most north eastern extent of the watershed to 87 m amsl where the Thames River enters the channel between Lake St. Clair and Lake Erie.

The overburden thickness map, in **Figure 2-6**, was derived by subtracting the interpolated top of bedrock surface, shown on **Figure 2-5**, from the DEM in **Figure 2-2**. The overburden thickness is greatest around the many moraines with the thickest accumulation of overburden (up to 125 m) occurring near Strathroy, London, St. Thomas and along the Lake Erie shoreline west of St. Thomas. The overburden is very thin to non-existent around bedrock outcrops and in several of the river valley systems.

2.1.4 Geological Model Development

The conceptual hydrogeologic model for the Six CA's watershed includes seven aquifers, which represents an upper unconfined aquifer, a middle confined aquifer, a lower confined aquifer and four bedrock aquifers. Each aquifer is separated from the underlying aquifer(s) by an upper aquitard (at the base of the upper unconfined aquifer), the middle aquitard and the lower bedrock aquitard. **Table 2.2** compares the Six CA's watershed regional groundwater model to the Norfolk County regional groundwater study layering system.

2.2 Regional Hydrogeologic Setting

Groundwater occurrence and flow within the Six CA's watershed is primarily controlled by:

- Topography
- Precipitation and evapotranspiration
- Piezometric levels of the geologic units, which define porosity and hydraulic conductivity; and
- The spatial distribution and connectivity of geologic units.

Precipitation is the primary source of groundwater recharge, which is the portion that infiltrates into the ground, and is not retained as soil moisture or discharged to rivers and streams as interflow or overland flow. In some areas rivers and streams may act to recharge the aquifer.

2.2.1 Hydrostratigraphy and Groundwater Flow

Topography exerts a controlling influence on the configuration of the water table and thus on the direction of groundwater flow. The layering of aquifer and aquitard units results in predominately horizontal flow directions. In areas where lateral discontinuities exist in the geology (e.g. river valleys and pinch outs), or where low hydraulic conductivity units exist, vertical flow may be more dominant.

Figure 2-7 and **Figure 2-8** present generalized groundwater level maps of the overburden and bedrock units in the Six CA's watershed. These maps were created by interpolating the static water level found in the MOE water well records (high location reliability only), which were divided into overburden and bedrock wells.

2.2.2 Hydrostratigraphic Units

Complex geologic units with similar hydrogeologic properties, textural characteristics and a similar stratigraphic position can be grouped together to form a 'hydrostratigraphic unit'. A hydrostratigraphic unit can be a formation, a part of a formation, or a group of formations that possess similar hydrologic characteristics that allow the subsurface to be divided into aquifers and aquitards. Grouping geologic units in this manner allows the subsurface to be simplified into a series of 'packages' that can be examined for the analysis of groundwater flow.

Table 2.2: Comparison between Hydrogeologic Conceptual Models

Norfolk Municipal Groundwater Study (WHI 2003)				Six CA Watershed Groundwater Study (WHI 2005)			
Hydrogeologic Unit	**Approx. Thickness (m)**	**Formation**	**Detailed Unit**	**Hydrogeologic Unit**	**Approx. Thickness (m)**	**Formation**	**Detailed Unit**
Major Aquifer	< 5	Glacial-Lacustrine	Medium to coarse sand and gravel	Aquitard/Aquifer (AQ1)	< 10		Quaternary Geology
Aquitard	10 to 30	Port Stanley Till – Glacial Till	Clayey silt to silty till	Aquitard (AT1)			Fine-grained tills and lacustrine sediments
Aquifer	15 to 35	Glacial-Lacustrine	Sand or fine sand	Aquifer (AQ_{int})			Interstadial sands and gravels
Aquitard	20 to 70	Catfish Creek Till-Glacial Till	Moderately stoney to very stoney very compact sandy silt to silty sand	Aquitard (AT1)			Fine-grained tills and lacustrine sediments
Aquifer	7 to 10	Glacial-Lacustrine	Sand and gravel	Aquifer (AQ2)			Basal sands and gravels
				Aquitard (AT2)			Overconsolidated Tills
Aquifer	~4	Dundee Formation	Fractured-Fossiliferous with bituminous and chert nodules	Aquifer	~3	Port Lambton formation	Fractured Grey shale and Limestone
Aquifer	100 to 150	Dundee Formation	Fossiliferous with bituminous partings and chert nodules	Aquitard	~60	Port Lambton Group	Grey Shale and Limestone
Aquitard	~120	Salina Formation	Interbedded dolostone and shale	Aquitard	90	Hamilton Group	Grey Shale and limestone
Aquifer	~100	Guelph–Amabel Formation	Dolostone beds overlie bituminous argillaceous fossiliferous dolostones	Aquifer	35 to 45	Dundee Formation	Fossiliferous with bituminous partings and chert nodules
				Aquifer	60 to 90	Detroit River Group	Limestone and Dolomite
				Aquitard	45	Bois Blanc Formation	Cherty brownish grey, fossiliferous limestone
				Aquifer	30	Bass Island Formation	Oolitic dolostone with minor thin beds of shaley dolostone
				Aquitard	120 to 200	Salina Formation	Interbedded dolostone shale and mudstone

Within the study area, three distinct aquifer units were identified during cross-section interpretations:

1. Surficial Unconfined Aquifers: This aquifer is associated with the coarse-grained surficial deposits such as the extensive sand plains, or outwash sand deposits that blanket the flanks of the end moraines within the study area (i.e. Wyoming Moraine). These shallow aquifers are commonly used in private and domestic water use, but as they are highly susceptible to groundwater contamination, they are not often used as municipal groundwater resources.

2. Confined Overburden Aquifers: The second aquifer unit includes two confined overburden aquifers; one deep and one intermediate. Confined aquifers that lie at this stratigraphic position

include the intermediate aquifer of the Middlesex-Elgin Counties, as well as the deep basal aquifer that overlies the Catfish Creek Till in many portions of the study area. The basal aquifer is interpreted to be outwash, or interstadial sands and gravels deposited following the retreat of the Nissouri Stade ice. These deep overburden aquifers are spatially discontinuous, but can act as highly productive aquifers in some areas.

3. Paleozoic Bedrock Aquifers: The third aquifer unit within the study area includes the numerous limestone, dolostone and lesser sandstone rock formations. These aquifers are regionally extensive and are productive aquifers for both municipal and domestic water supply.

Table 2.3 presents a summary of the hydrostratigraphic units in the study area including a description of the type of hydrostratigraphic unit (aquifer/Aquitard), a brief description, and the geologic sub-units identified within the hydrostratigraphic unit.

Mapping of the distribution of each of these hydrostratigraphic units in the study area was undertaken by interpreting stratigraphic picks using over two hundred cross-sections. The cross-sections were completed on a 10 km grid spacing throughout the study area and were included in the Conceptual Model Report (WHI 2004).

Surface elevations and isopach maps were interpolated for each of the hydrostratigraphic units using ArcGIS. The three-dimensional view of the conceptual geological model for the study area is shown in **Figure 2-1**. The isopach maps for the Quaternary hydrostratigraphic units I through VI and the details of each hydrostratigraphic unit are available in the Conceptual Model Report (WHI 2004).

2.2.3 Hydraulic Conductivity

Hydraulic conductivity is a property that can vary considerably from one geologic unit to the next. Estimates of hydraulic conductivities are typically derived from aquifer test data, literature values, or from previous groundwater flow studies and models. **Table 2.4** presents the estimated lateral hydraulic conductivity values for each hydrostratigraphic unit along with values used in local wellhead protection area models completed as part of the MOE funded groundwater studies.

Table 2.3: Hydrostratigraphic units in the study area

Hydrostrat. Unit	Hydrostratigraphic Description	Specific Geologic Subunits
HU I – Aquifer (AQ1)	Coarse-grained glaciofluvial/ glaciolacustrine/ ice-contact sands and gravels	Includes: Bothwell, Caradoc, Norfolk and Leamington Sand Plains as well as Easthope, and Staffa Kame Moraines.
HU II – Aquitard (AT1)	Fine-grained subglacial till sheets, glaciolacustrine diamicts and lacustrine clay plains	Tills include: Rannoch, Stratford, Wartburg, St. Joseph's, Elma. Clay plains include: Ekfrid and St. Clair Clay Plains.
HU III – Aquifer (AQ_{int})	Intermediate depth interstadial outwash sands and gravels.	Includes intermediate aquifers located in Elgin and Middlesex Counties.
HU IV – Aquitard (AT2)	Lower fine-grained subglacial till sheets, and lacustrine clays	Tills include: Tavistock and Port Stanley.
HU V – Aquifer (AQ2)	Basal outwash sand and gravel (interstadial complex) overlying Catfish Creek and older tills.	Discontinuous sands and gravels.
HU VI – Aquitard (AT2)	Subglacial lodgement (overconsolidated) tills	Tills include: Catfish Creek, Canning, Early and Mid-Wisconsinan tills.
HU VII - Aquifer	Weathered and highly fractured upper portion (3-5 m) of the bedrock surface	Variable bedrock depending on location.
HU VIII – Bedrock Aquifer	Fractured Paleozoic bedrock	Carbonates and shales of the bedrock formations underlying the study area.

Typically, the vertical hydraulic conductivity is assumed to be one order of magnitude less than the horizontal hydraulic conductivity. The variation in hydraulic conductivity between different studies reflects the degree of heterogeneity of the hydrostratigraphic unit and the largest discrepancy lies in the bedrock aquifers where the bedrock formation and intensity of fracturing varies widely across the study area.

Within the groundwater flow model, hydraulic conductivities will vary across each hydrostratigraphic unit. For example, the Stratford and Mornington Tills are grouped with other similar subglacial tills to form HU II. Although these two units will be represented in the model as one layer, the extent of the Stratford Till Plain (sandy silt till) will be assigned a higher hydraulic conductivity than that of the Mornington Till (clay till) to account for the differences in matrix grain size. During the development and calibration of the FEFLOW groundwater model, initial and calibrated hydraulic conductivity values used in the model will aim to be consistent with the range of values utilized within previous models, and also with hydraulic conductivities cited in literature for studies completed within the Six CA's study area.

2.2.4 Groundwater & Surface Water Interaction

The network of rivers and lakes in the study area can be delineated into a series of watersheds and subwatersheds. The study area comprises the Six CA's, each with a series of watersheds and major river systems. The CA's, their watersheds and major river systems are shown in **Figure 2-9**. There are thirteen major river systems and many more subwatersheds within the study area. The rivers and their tributaries are ecologically important.

Figure 2-10 shows estimated zones of potential recharge and discharge within the study area. These areas were mapped by comparing the static water levels in the bedrock aquifer and the ground surface topography. Where the static water level is greater than the ground surface elevation, discharge is expected to occur. This map shows that discharge occurs primarily along the major river systems and their tributaries.

Flow rates measured during baseflow periods can be used to identify areas of significant groundwater discharge. The baseflow values presented at each measurement station are assumed to be equal to the quantity of groundwater that discharges to the upstream reach of the river and its tributaries. These flow rates will be used as a component of the three-dimensional groundwater flow model calibration process.

2.2.5 Recharge

Recharge occurs throughout the study area in all areas except where water is applied directly to surface water features (Singer et al., 1994). The rate of recharge is dependent on the ground surface topography, land use cover and surficial geology.

Areas with steep topography experience greater overland flow and therefore less groundwater recharge than areas where the terrain is more subdued. In the study area, there are few areas with steep terrain changes; however, there are a few areas of hummocky topography where enhanced recharge is expected, as water that would otherwise be lost to runoff becomes trapped in closed storage depressions.

Recharge is interpreted to be reduced on clay and till plains as a larger proportion of precipitation will likely be lost as overland flow to rivers and streams rather than infiltrating. Recharge will be greatest on the sand plains and kame moraines where water infiltrates rapidly into the deeper groundwater system. In most studies, the ice-contact stratified drift is estimated to have a higher net recharge than the sandy silt to sandy till. Sinkhole capture zones may also provide a significant amount of recharge to the subsurface through the artificial drainage systems in the study area. The sizes and locations of the sinkholes receiving drainage water are randomly distributed throughout the study area, which may provide a strong conduit to the groundwater system (WHI 2004).

Table 2.4: Range of Hydraulic Conductivity Values (m/s) of Hydrostratigraphic Units

Hydrostratigraphic Unit (HU)		Lit. Values	Huron	Perth	Lambton	Middlesex-Elgin	Essex-Chatham Kent	Oxford
HU I (AQ 1) –Surficial Sands		6×10^{-3} to 1×10^{-7}	n/a	n/a	n/a	1×10^{-4} to 5×10^{-4}	n/a	1×10^{-4} to 6×10^{-4}
HU II (AT1) – Fine-grained tills and lacustrine sediments		1×10^{-6} to 1×10^{-11}	n/a	2×10^{-6} to 2×10^{-8}	1×10^{-7}	1×10^{-6} to 5×10^{-8}	n/a	3.5×10^{-6} to 1×10^{-7}
HU III (AQ_{int}) – Interstadial sands and gravels		3×10^{-2} to 1×10^{-6}	n/a	n/a	n/a	1×10^{-4} to 2×10^{-4}	n/a	5×10^{-5} to 5×10^{-4}
HU IV (AT 1) – Fine-grained tills and lacustrine sediments		1×10^{-6} to 1×10^{-11}	n/a	2×10^{-6} to 2×10^{-8}	n/a	1×10^{-6} to 5×10^{-8}	n/a	3.5×10^{-6} to 1×10^{-8}
HU V (AQ 2) – Basal sands and gravels		3×10^{-2} to 1×10^{-6}	n/a	n/a	n/a	1×10^{-4} to 2×10^{-4}	n/a	1×10^{-4}
HU VI (AT 2) – overconsolidated tills		2×10^{-7} to 1×10^{-12}	n/a	n/a	n/a	n/a	n/a	n/a
HU VII – Bedrock Formations	Salina Formation	1×10^{-4} to 1×10^{-7}	n/a	n/a	n/a	n/a	n/a	n/a
	Bass Islands Fmn	1×10^{-4} to 1×10^{-7}	n/a	1×10^{-5}	n/a	n/a	n/a	n/a
	Bois Blanc Fmn	1×10^{-4} to 1×10^{-7}	n/a	8×10^{-5}, 8×10^{-6}	n/a	n/a	n/a	1×10^{-4} to 5×10^{-5}
	Lucas/ Sylvanian Fmn	1×10^{-4} to 1×10^{-7}	n/a	7×10^{-5}	n/a	n/a	n/a	5×10^{-5} to 7.5×10^{-5}
	Amherstburg Fmn	1×10^{-4} to 1×10^{-7}	n/a	7×10^{-5}	n/a	n/a	n/a	1.3×10^{-4} to 3×10^{-5}

Hydrostratigraphic Unit (HU)		Lit. Values	Huron	Perth	Lambton	Middlesex-Elgin	Essex-Chatham Kent	Oxford
	Dundee Fmn	$1x10^{-4}$ to $1x10^{-7}$	n/a	$2x10^{-4}$ to $1x10^{-5}$ (IWS)	$1.6x10^{-4}$	$5x10^{-6}$	n/a	$1.2x10^{-4}$
	Marcellus Fmn		n/a	n/a	n/a	n/a	n/a	n/a
	Hamilton Group		n/a	n/a	n/a	n/a	n/a	n/a
	Kettle Point Fmn		n/a	n/a	n/a	n/a	n/a	n/a
	Port Lambton Fmn		n/a	n/a	n/a	n/a	n/a	n/a

Land use also plays a role on the amount of recharge entering the groundwater system. Built-up urban areas have reduced recharge as water flows over concrete, buildings and streets into managed storm drains and other similar infrastructure rather than recharging the groundwater system.

2.2.6 Groundwater Discharge & Baseflow

The primary source of groundwater in the study area is from recharge. Water also enters the groundwater system along portions of numerous rivers, tributaries, and wetlands. Wetlands are commonly found in hummocky terrain associated with moraines.

One large source of groundwater discharge within the study area is the regional flow through bedrock units to the Great Lakes (Lakes Erie, Huron and Ontario). To date, the location and quantity of groundwater discharge to the Great Lakes is not fully understood but this aspect is briefly investigated in the model discussion of this report.

Large groundwater takings by municipal wells along with large industrial water takings (i.e. quarrying) also represent a large contributor of outflow within the study area. Information on well location and operations, for these pumping wells, is contained in the MOE Permit to Take Water (PTTW) database. Information on the municipal wells operation is contained in the Well Operations Reports.

The pumping rate for each of the permitted wells is specified using average rates where available for calibration of the groundwater flow model. Where average rates are not available, estimated pumping volumes are applied to generate best estimate conditions. An example of where rates may be estimated is for agricultural irrigation wells, where pumping is for a short time period and a portion of the pumped volume re-infiltrates.

3 Numerical Model

Numerical models are structured tools for integrating a multitude of data (e.g. lithologies, water levels, groundwater/surface water features, or pumping well information) and conceptual ideas to understand groundwater flow paths. This helps the modeller to predict variations caused by changing conditions in light of new data about the system. Models are used throughout the world to evaluate groundwater systems and have been growing in their application since the 1970's. Applications have migrated from simplified models, where geologic complexities were grossly generalized, to more detailed models, which utilize all available data in an effort to represent the hydrogeologic system as accurately as possible. In our experience, incorporation of geologic/hydrogeologic detail produces a more realistic model and a more useful tool. Despite these efforts, natural uncertainty will be inherent in the model predictions since nature's complexities, hidden beneath the ground surface, are at a finer scale than the model can represent.

In constructing this detailed model, all available data (such as water level, rivers, hydro-stratigraphic, topographic, and lithologic properties) described in the previous sections was incorporated into the numerical model. The detailed conceptual understanding is critical to the development of a realistic numerical groundwater flow model. After completing the three-dimensional conceptual model, a watershed scale, finite element groundwater flow model was developed using FEFLOW.

Once constructed, the model must be "calibrated" to observed field conditions to provide confidence that it is realistic. During the model calibration process, physical parameters are adjusted within accepted field and literature derived ranges to produce a model that closely simulates the field conditions.

Recognizing the inherent geologic and hydrogeologic uncertainty of the complex natural system, multiple conceptualizations were evaluated to provide an upper and lower bound to the flow system. This involved modeling scenarios that included the exclusion/inclusion of non-municipal pumping wells to provide a better understanding of their influence on the groundwater flow system. As part of the model development process, the Steering Committee members were encouraged to work closely with WHI to understand all aspects of the modeling process. The numerical model implementation of system parameters and boundaries described in previous sections are presented below along with the numerical model approach.

3.1 Numerical Model Code Selection

Numerous modeling tools exist, each with inherent strengths and weaknesses. Therefore it is important to select a modeling tool that meets the objectives of the given study. The important considerations in selecting a modeling code for the Six CA's model included:

- Desire to represent both regional and local-scale features in one integrated model and incorporate important features at both scales
- Incorporate steep changes in topography
- Incorporate dip bedding and discontinuous geologic layers
- Represent irregular distribution of rivers with variable properties
- Represent irregular distribution of pumping and other anthropogenic influences.

FEFLOW (WASY 2003) was used for this modeling project because of its advanced capabilities to simulate groundwater flow in complex aquifer conditions. FEFLOW is a commercially available application that is used to accurately characterize three-dimensional groundwater flow on a regional scale in complex environments.

The finite element method, which is employed in FEFLOW and other codes, addresses many of the shortcomings of the finite difference method and is often applied in more complex settings. The finite-element method uses more sophisticated numerical solution algorithms resulting in more stable, faster solutions, which help modeling in complex geologic areas (Martin and Frind 1998; WASY 2005; Wang and Anderson 1995). FEFLOW has been used to model complex groundwater systems worldwide by more than two hundred leading research, consulting, and government organizations. Prominent users in California include researchers at Lawrence Livermore National Laboratory (LLNL) who use FEFLOW as a modeling tool to manage a complex site remediation project for the US Department of Energy, as well as the Sacramento Water Resources Control Board.

The specific advantages of the FEFLOW application include:

- Ability for the mesh discretization to focus calculation points in the areas of interest to more precisely simulate observed physical features (pumping wells, rivers, etc.) and follow naturally complex boundary conditions
- Efficiency of localized mesh discretization, far fewer required calculation points to achieve the same level of precision than with finite difference grids 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
- Stable water table simulation that facilitates more accurate simulation of the shallow subsurface and allows the modeler to focus on conceptual rather than numerical issues. FEFLOW avoids the wetting-drying cycling typical of MODFLOW that can cause solution convergence and stability problems.

Since river discharge and pumping are thought to have a dominant influence on groundwater flow within the Six CA's watershed, FEFLOW's enhanced capabilities to incorporate these features were considered necessary to develop a realistic modeling tool.

4 Groundwater Model Development

A major focus of the modeling is to explore the interactions of groundwater and surface water at the regional and local scales to meet the anticipated needs of the Conservation Authorities for implementing source water protection initiatives.

4.1 Model Domain

The location, extent and finite element mesh of the model domain is presented in **Figure 4-1**. The project area encompasses all of the Six CA watersheds (**Figure 2-9**). The model domain is approximately 143 kilometers in width (East-West) and approximately 168 kilometers in length (North-South).

The mesh is refined in areas where it is important to have an enhanced definition of the potentiometric surface. This includes rivers, (Thames, Maitland, Ausable, Avon, Sydenham Rivers and their tributaries), and large pumping wells (identified in the PTTW dataset). The model domain was subdivided into the six defined watershed basins, which allows us to calculate detailed water budgets and model any future refinements. The detailed mesh consists of 2,656,430 elements and 1,430,595 nodes.

4.2 Model Layer Structure

Table 4.1 presents a summary of the hydrostratigraphic units represented in the numerical groundwater flow model. The model layers were developed through a GIS analysis of the MOE water well records and MNR Oil & Gas well records within a five kilometer buffer around the perimeter of the Six CA watersheds. All high quality water well records were assigned overburden interpretations based on the geology of each well (Layers 1 to 6). Layer 7 represents a 3 m thick weathered portion of the bedrock. Layer 8 represents the Port Lambton Group. Layer 9 is composed of all the Hamilton Group sub-members. Layer 10 represents the Dundee Formation. Layer 11 is composed of all the Detroit River Group sub-members. Layer 12 represents the Bois Blanc formation. Layer 13 represents Bass Island formation. Layer 14 (the bottom layer of the model) is composed of all the Salina sub-members.

The data points for each layer were interpolated using a natural neighbour routine to a 50 m grid. For areas where layers are not present, for both overburden and bedrock, a minimum layer thickness of 0.2 m was assigned to maintain model layer continuity. Where the minimum layer thickness was assigned, the hydraulic properties and boundary conditions from the layer above were assigned to preserve the hydrostratigraphic aspects of the conceptual model.

4.3 Hydraulic Conductivity

Hydraulic conductivity information used to calibrate the model was derived from several sources. These include:

- MOE Water Well record geology
- Quaternary geology maps
- Bedrock geology maps
- Previous groundwater studies

Horizontal hydraulic conductivity values were estimated to be ten times greater than the vertical hydraulic conductivity. The calibrated vertical and horizontal values for hydraulic conductivity are summarized in **Table 4.2** and **Table 4.3**.

The calibrated hydraulic conductivity distribution for the overburden layers are shown on **Figures 4-2** to **4-15**. The legends for these figures show hydraulic conductivity values in units of 1e-4 m/s, which means that a hydraulic conductivity value of 1 in the legend represents a hydraulic conductivity value of 0.0001 m/s (or 1e-4 m/s). **Figures 4-2** to **4-15** present the hydraulic conductivity values used in the FEFLOW model.

The hydraulic conductivity values for model layer 1 were developed by assigning hydraulic conductivity values to polygons from the Ontario Geological Survey (OGS) surficial geology for the study area **(Figure 2-3)**. This is considered the most appropriate distribution to use as the Quaternary geology mapping provides field-mapped distribution of the sediments in the near surface soil layer as shown on **Figure 4-2**. The hydraulic conductivity values for clay were determined through the model calibration to allow recharge to enter the upper layers of the model, particularly in areas where water may pond and infiltrate over a longer period of time.

The hydraulic conductivity values for model layer 2 were developed by assigning values to represent the fine-grained tills and lacustrine sediments that comprise Aquitard HU II – AT1 as shown on **Figure 4-3**. In areas where model layers are discontinuous, hydraulic conductivity values from underlying layers are represented. This is consistent throughout the entire model.

The hydraulic conductivity values for model layer 3 were developed by assigning values to represent the interstadial sands and gravels that comprise Aquifer HU III – AQ_{int}. The interstadial sands and gravels as shown on **Figure 4-4** represent the intermediate aquifer.

The hydraulic conductivity values for model layer 4 were developed by assigning a value of 6e-5 m/s to represent the fine-grained tills and lacustrine sediments that comprise Aquitard HU IV – AT1 as shown on **Figure 4-5**. The Port Stanley and Tavistock tills are identified in the southwestern most extent of the model layer at Windsor.

To represent the basal sands and gravels that comprise Aquifer (HU V – AQ2) a hydraulic conductivity value of 5e-4 m/s was assigned. The basal aquifer distribution for model layer 5 is identified in the southwestern most extent of the model layer within Essex CA extending easterly along the Lower Thames Valley CA boundary as shown on **Figure 4-6**. Basal sands are also identified between Ausable Bayfield and St. Clair Region CAs. Another localized area of basal sands is also identified along the eastern model boundary near Woodstock.

To represent the overconsolidated tills that comprise Aquitard (HU VI – AT2) a hydraulic conductivity value of 8e-7 m/s was assigned to model layer 6. The Catfish Creek till (**Figure 2-1**) is identified throughout the entire northern portion of the model area extending into Ausable Bayfield CA as well as portions of Essex and the Lower Thames Valley CAs as shown on **Figure 4-7**.

For overburden model layers that are not at surface, the quaternary geology map is less applicable, given the variation in depositional environment as observed in the regional cross-sections. Therefore spatial distributions of hydraulic conductivity were developed based on the high quality water well records and their hydrostratigraphic interpretations as described by Martin and Frind (1998). Each lithology listed in the water well record was assigned a hydraulic conductivity value for the media, based on values reported in **Table 2.4**. This provided point estimates of hydraulic conductivity at each high quality well record. The natural logarithm of the point estimates were then used to create laterally continuous 100 m gridded hydraulic conductivity layers throughout the model domain for each hydrostratigraphic layer.

The hydraulic conductivity values for model layer 7 were developed by assigning a value of 5e-4 m/s to represent the 3 meters thick weathered bedrock zone that comprise Aquifer (HU VII). The weathered bedrock is identified throughout the entire model layer as shown on **Figure 4-8**.

To represent the grey shale and limestone that comprise Aquitard (HU VIII) a hydraulic conductivity value of 7.5e-5 m/s was assigned to model layer 8. The Port Lambton Formation is identified throughout the Lower Thames and St. Clair Region CAs extending into the northern portion of Essex CA just east of Windsor as shown on **Figure 4-9**.

The hydraulic conductivity value of 7e-8 m/s was assigned to model layer 9 to represent the grey shale limestone that comprise Aquitard (HU VIII). The Marcellus Formation within the Hamilton Group is identified south of St. Thomas within the Lower Thames Valley watershed as shown on **Figure 4-10**.

To represent the limestone that comprise Aquifer (HU VIII) a hydraulic conductivity value of 1.2e-4 m/s was assigned to model layer 10. The Dundee formation is identified throughout the central portion of the study area including the Lower Thames Valley, St. Clair Region, Ausable Bayfield and portions of the Upper Thames River and Essex watersheds as shown on **Figure 4-11**.

The hydraulic conductivity value of 8e-5 m/s was assigned to model layer 11 to represent the limestone and dolomite that comprise Aquifer (HU VIII). The Detroit River Group is identified throughout the entire study area excluding the eastern most boundary of the Maitland and Upper Thames River watersheds as shown on **Figure 4-12**.

The hydraulic conductivity of 4e-5 m/s was assigned to model layer 12 to represent the cherty limestone that comprises Aquitard (HU VIII). The Bois Blanc Formation is identified throughout the entire study area excluding the eastern most boundary of the Maitland and Upper Thames River watersheds as shown on **Figure 4-13**.

To represent the dolostone that comprise Aquifer (HU VIII) a hydraulic conductivity value of 5e-5 m/s was assigned to model layer 13. The Bass Island Formation is identified throughout the entire study area excluding the eastern most boundary of the Maitland and Upper Thames Valley watersheds as shown on **Figure 4-14**.

The hydraulic conductivity of 5-e6 m/s was assigned to model layer 14 to represent the dolostone and shale that comprise Aquitard (HU VIII). The Salina Formation which makes up the bottom layer in the FEFLOW model, is identified throughout the entire study area as shown on **Figure 4-15**.

Table 4.1: Model Representation of Hydrostratigraphic Units

Model Layer	Hydrostratigraphic Unit	General Lithology
1	Aquitard / Aquifer (HU I – AQ1)	Quaternary Geology (Aquifer / Aquitard)
2	Aquitard (HU II – AT1)	Fine-grained tills and lacustrine sediments
3	Aquifer (HU III – AQ_{int})	Interstadial sands and gravels
4	Aquitard (HU IV – AT1)	Fine-grained tills and lacustrine sediments
5	Aquifer (HU V – AQ2)	Basal sands and gravels
6	Aquitard (HU VI – AT2)	Overconsolidated tills
7	Aquifer (HU VII)	Contact Zone (3 m thick weathered bedrock zone)
8	Aquitard (HU VIII)	Port Lambton Formation - Grey Shale and Limestone
9	Aquitard (HU VIII)	Hamilton Group - Grey Shale and Limestone
10	Aquifer (HU VIII)	Dundee Formation - Limestone
11	Aquifer (HU VIII)	Detroit River Group – Limestone and Dolomite
12	Aquitard (HU VIII)	Bois Blanc Formation – Cherty Limestone
13	Aquifer (HU VIII)	Bass Island Formation– Dolostone
14	Aquitard (HU VIII)	Salina Formation – Dolostone, and Shale

Bedrock hydrostratigraphic layers (model layers 7 to 14) were assigned hydraulic conductivities across each of the layers as shown in **Table 4.4**. A high conductivity zone of 1 E-03 m/s was assigned in the vicinity of the sinkholes in the ABCA boundary region (**Figure 4-12**). The region corresponds to the Detroit River Group (Layer 11) in an area with a high concentration of sinkholes as reported in previous studies

(WHI, 2004). Where bedrock units pinch out (layer thickness was less than 0.2 m) the hydraulic conductivity from the hydrostratigraphic layer immediately below was used.

Table 4.2: Calibrated Hydraulic Conductivity Values of OGS Surficial Geology

Material	Model Calibrated K_x (m/s)	Model Calibrated K_z (m/s)
Clay – well laminated	5 E -06	5 E -07
Silt	7 E -05	7 E -06
Sand Till	7 E -05	7 E -06
Sand & Gravel	3 E -03	3 E -04

Table 4.3: Hydraulic Conductivity Values of Hydrostratigraphic Units

Hydrostratigraphic Units (HU)	Model Calibrated K_x (m/s)	Model Calibrated K_z (m/s)
HU I (AQ1) –Surficial Sands	3 E -03	3 E -04
HU II (AT1) –Fine-grained tills and lacustrine sediments	8 E -07	8 E -08
HU III (AQ_{int}) – Interstadial sands and gravels	7 E -05	7 E -06
HU IV (AT1) –Fine-grained tills and lacustrine sediments	8 E -07	8 E -08
HU V (AQ2) –Basal sands and gravels	7 E -05	7 E -06
HU VI (AT2) – overconsolidated tills	8 E -07	8 E -08

Table 4.4: Hydraulic Conductivity Values of Standardized MatGSC Codes

Bedrock Unit (Model Layer)	Model Calibrated K_x (m/s)	Model Calibrated K_z (m/s)
Contact Zone (7)	1E-4 – 7E-5	1E-5 – 7E-6
Port Lambton Group (8)	7.5 E -05	7.5 E -06
Hamilton Group (9)	1 E-06	1 E-07
Dundee Formation (10)	1 E -04	1 E -05
Detroit River Group (11)	8 E-05/1 E-03*	8 E-06/1 E-04*
Bois Blanc Formation (12)	4 E -05	4 E -06
Bass Island Formation (13)	5 E -05	5 E -06
Salina Formation (14)	5 E -06	5 E -07

* High conductivity zone that represents sinkhole cluster in ABCA watershed.

4.4 Boundary Conditions

Boundary conditions represent the interaction between the model domain and the surrounding environment. Four types of boundary conditions were used in the model. These include:

- Specified Head to represent flow into or out of the model domain either through lakes or reservoirs or regional flow boundaries along the perimeter of the model
- Specified Flux to represent vertical recharge through the upper layer of the model
- Head Dependent flux to represent rivers and lakes that are connected to the groundwater system through a conductance layer
- Pumping/Injection wells to represent wells that are screened over a specific model/hydrostratigraphic layer

4.4.1 Regional Flow Boundaries

Figure 4-16 shows the location of constant head (specified head) boundary conditions that were assigned to the overburden aquifer layers of the model to represent areas where water is entering or leaving the perimeter of the model domain. The specified head values were assigned based on the interpreted water levels from the MOE water well records.

Lake Erie was modeled as a specified head boundary at a constant elevation of 174.6 m amsl to the overburden layer. Lake Huron and Lake St. Clair was also modeled as a specified head boundary at a constant elevation of 176 m amsl and 175.4 m amsl, respectively.

4.4.2 Recharge

Recharge occurs throughout the Six CA's Watershed in all areas except where water is directly discharging to surface water features (Singer et al. 1994). The rate of recharge is dependent on the slope of the ground surface, soil moisture, grain size and stratification.

In areas of hummocky terrain, depression storage is an important feature that increases the amount of groundwater recharge that would otherwise be lost to runoff. On till plains recharge is reduced because a larger proportion of precipitation is lost as direct runoff to rivers and streams. When soil moisture is at saturation (during snowmelt and spring rainfall) recharge will be greatest. The recharge will decrease, as soil becomes increasingly unsaturated. Stratification may also decrease the rate of recharge by limiting the rate of downward migration of water. For example, the moraines composed of ice-contact stratified drift may contribute less recharge per unit area than unstratified till moraines.

Table 4.5 presents the estimates of recharge derived from a number of previous studies carried out in the watershed. In most studies the ice-contact stratified drift is estimated to have a higher net recharge than the sand silt to sand till. However, it may be that the stratification of the drift reduces this net recharge to less than that observed in the sandy silt to sand till. The modeled recharge capability is physically based on the surficial geology, which has the greatest control on net recharge.

High recharge rates also occur through transmissive sinkholes. In this modeling study, the sinkhole investigation conducted by WHI and the ABCA (WHI, 2004[b]), was used to incorporate high recharge rates in regions with sinkhole clusters. In particular, the Tuckersmith and Chiselhurst sinkhole clusters were specifically assigned a volume of water, which was injected into the subsurface based on the size of their sinkhole capture areas and a high recharge rate (475 mm/yr). **Table 4.6** provides an approximate recharge rate applied to the sinkhole locations, which are represented as injection wells, shown in **Figure 4-17**.

4.4.3 Rivers & Lake Boundaries

The finite element mesh was specifically designed to conform to the major surface water features in the watershed. Head dependent (transfer) boundaries were assigned to model layers 1 and 2 to represent interaction with creeks and rivers (**Figure 4-16**).

This type of boundary condition allows the model to simulate potential resistance to flow between the river and the underlying aquifer by specifying an "In" and "Out" transfer rate through the conductance layer. The conductance layer represents the bulk properties of the sediments that separate the river from the aquifer. The resistance to flow was based on the riverbed material properties (globally set to 1E-5 m/s) while the hydraulic conductivity of the quaternary geology will also affect the amount of water recharging/discharging from the streams.

Table 4.5: Recharge Estimates for Surficial Geologic Material

Material	WHI (2001) (mm/yr)	Dames & Moore (1996)	Hunter / Raven Beck (1996) (mm/yr)	Singer et al. (1994)
Glacial Outwash	250	250	250	Very high
Ice Contact Stratified Drift	250	200	250	High
Sandy Silt to Sand Till	150	-	150	Medium-high
Glaciolacustrine Deposits	25	-	10	Low-medium
Silt to Clayey Silt Till	150	100	150	Low
Fractured Bedrock Outcrop	-	-	300	-
Bedrock Outcrop	-	-	180	Low

Table 4.6: Sinkhole Estimated Recharge

Sinkhole Drainage Area	Drainage Area (ha)	Recharge (mm/yr)	Recharge Rate Applied to Injection well (m/d)
Tuckersmith	258	475	3358
Chiselhurst	389	475	5062

Major lakes in the watershed were represented in the model as specified head boundaries (**Figure 4-16**) and the elevations were taken as the average annual level within the lakes. These included Lake Huron (176 m amsl), Lake St. Clair (175.4 m amsl), and Lake Erie (174.6 m amsl). Other small lakes and ponds were not included, as these are understood to be an expression of the water table and not significant for this regional-scale analysis.

4.4.4 Pumping Wells

Municipal pumping wells were represented using the well boundary condition in FEFLOW. Similar to the river boundaries, the finite element mesh was developed to have mesh refinement around each of the 102 municipal wells. A total of 158 municipal wells were identified from the Six CA's WWIS database; however, pertinent information was missing to include them into the model. A total of 26 non-municipal permitted pumping wells were identified as having enough information to use in the model.

The model was evaluated based on an average pumping rate for the municipal and PTTW wells. Each of the 102 municipal wells and 26 non-municipal permitted groundwater extraction wells were assigned a pumping rate equal to their average permitted rate. Assigning the average permitted rate for all wells is more accurate compared with using the maximum permitted rate from the perspective of assessing the current groundwater impacts of groundwater extraction.

The total amount of water extracted from the pumping wells is approximately 183,746 m^3/day. Additional pumping well information may be added to any future model updates.

4.5 Model Calibration

An important aspect of groundwater modeling is comparing and verifying the conceptual geological model with real world conditions.

Calibrating a groundwater flow model allows it to be used to simulate groundwater flow that is statistically representative of field conditions. Models can be calibrated to steady-state or transient field measured heads and flows. In this study, a numerical model was calibrated to a set of groundwater heads that represent steady-state groundwater flow conditions. The steady-state assumption is considered valid for the regional groundwater flow model.

Prior to numerical model calibration, the range of uncertainty in the parameters contained within the conceptual hydrogeologic model was evaluated. Some parameters were known with a higher degree of certainty, such as hydraulic conductivities in certain geologic formations.

Model calibration was conducted using an iterative, trial and error approach. This involved a process where a flow simulation was conducted out, the resulting groundwater heads were compared to observed heads, and the model input parameters were re-adjusted to achieve better agreement with observed (field measured head) conditions. The process of model calibration involves the adjustment of model parameter values to match field measured values within a pre-established range of error.

4.5.1 Measures of Calibration

Model calibration results were evaluated using quantitative measures. The calibrated model was evaluated using statistical measures based on calibration residuals. The statistical parameters used to evaluate the model calibration included:

- Mean Error (ME) – represents the mean of all the residuals. This parameter can be misleading because the sum of a large negative residual plus a large positive residual may be equal to zero. The Mean Error provides an indication of whether the residuals are biased positively or negatively.
- Mean Absolute Error (MAE) – represents the mean of the absolute values of all the residuals. This parameter will be larger than the mean error and provides the average error associated with each calibration point in the model.

- Root Mean Squared Error (RMS) – represents the square root of the sum of the squares of all the residuals. Squaring the residuals increases the weighting that a poor residual will have on the overall calibration statistic. A low RMS is the best measure of a good model calibration.
- Normalized Root Mean Square (NRMS) – represents the RMS divided by the difference between the highest and lowest observed head within the model domain.

4.5.2 Hydraulic Head Calibration

Hydraulic heads in the model were calibrated to water levels recorded in the MOE Water Well Information System (WWIS). Water levels in the MOE's WWIS represent approximate static water levels at the time the well was drilled and as such, seasonal fluctuations are not taken into consideration. Therefore, a level of scatter equal to the year-to-year fluctuation in water levels was anticipated.

Measured values that may be used as calibration targets include hydraulic head, baseflow, discharge to gauged reaches of rivers/streams and flow directions in aquifer/aquitard units. The following sections describe and quantify the parameter values and boundary conditions used to attain model calibration.

4.5.3 Groundwater Baseflow & Water Balance Calibration

The water budget analysis is undertaken within a watershed to measure and characterize the contribution of each component to the health of the hydrologic system. System stresses (e.g. development activities in a watershed and/or climate change) can modify the relative contribution and characteristics of the components of the hydrologic system and threaten its health. Stresses that result in increased peak river flows or significant reduction in groundwater discharge, which sustains river baseflow, threaten the health of the hydrologic system. Water budget analysis can be carried out to predict the effect of stresses on peak flows and groundwater discharge. Baseflow is the quantity of water that discharges from the saturated zone across the water-table surface (groundwater discharge) to a tributary, together with the flow toward the tributary that discharges from the unsaturated zone (interflow). The modeled component of baseflow is groundwater discharge. Variations in discharge may be significant in different portions of the Six CA's watershed.

In a given watershed there are a variety of processes that comprise the hydrologic system. It is impossible to measure and characterize every single component. In water budget analysis the volume of water entering the system will equal the volume of water leaving the system (assuming the change in storage is negligible); otherwise the analysis has neglected the contribution of at least one element of the system. A numerical model is used to simplify the representation of these processes and enables quantification and evaluation of the hydrologic system at the watershed, subwatershed, or local site scale.

A water balance is a systematic analysis of the inputs, storage, and outputs from the groundwater system. The inflows to the model domain (groundwater sources) include net recharge, river leakage and constant head influx. The outflows (groundwater sinks) from the system include river leakage, drain leakage, well pumping and constant head outflow. The definition of each component of the water balance allows the model to be used as a tool for determining the impact of groundwater taking within each watershed. Water balance calculations are completed for the entire study area and for each of the six watersheds within the model.

The model can be used to understand how potential changes in pumping conditions may affect discharge conditions on the major rivers within the model. It may also be used to estimate the cumulative impacts of many smaller removals on the overall water budget of either the subwatershed or watershed scale.

The baseflow values presented at each Water Survey of Canada measurement station are assumed to be equal to the quantity of groundwater that discharges to the upstream reach of the river and its tributaries. To characterize and assess the dynamics of groundwater discharge in the Six CA's watershed it was essential that the model predict observed baseflow with a reasonable degree of accuracy.

In terms of baseflow discharge to the rivers and streams, the water balance component that is of interest is the groundwater flux through the river boundaries. FEFLOW interface allows for the quantification of volumes and fluxes to be summed over any area or river reach, into and out of the model, using the Budget Analzyer or Fluid Flux Analyzer Tool in FELFOW. These flux values are then compared to observed groundwater discharge conditions. In practice, the uncertainty in hydraulic conductivity values in heterogeneous environments and the actual groundwater discharge component of baseflow leads to a wide range of feasible discharge values. More refined water budget calculations can be performed with the FEFLOW model to evaluate groundwater flows at a localized subwatershed scale.

Baseflow measurements for a number of river reaches (41 stations) are available from the Water Survey of Canada's (WSC) Gauge Stations. The measurement location of each of these data sources is presented on **Figure 2-9**. High and low estimates of baseflow were derived from the Water Survey of Canada gauge site information. The average low daily flows for the months of July, August, and September (lowest flow months) for the years 1915 to 2003 were used as the dataset to compare modeled results to observed flow rates. This dataset was chosen for calibration purposes because it is considered the most representative of steady-state conditions and represents baseflow that is mostly derived from groundwater discharge. Anthropogenic sources of discharge, such as flow augmentation or sewage outfalls, were not evaluated in the baseflow analysis.

The calculated baseflows at the stream gauge locations indicate that the rivers are gaining towards Lake Erie, Lake St. Clair and Lake Huron. The calculated baseflow values are within the range of average minimum and maximum baseflow values. The rivers were not interpreted at all the stream gauge locations resulting in some baseflows having a value of “0.0” m^3/day. Variations in discharge can be different in different portions of each watershed. To characterize and assess the dynamics of groundwater discharge it is very important that the model predict the observed baseflow with a reasonable degree of accuracy. **Table 5.3** and **Figure 5-4** to **Figure 5-6** show that the baseflow calculations reasonably represent the minimum observed baseflow values at the stream gauge locations.

4.5.4 Current Conditions

The equipotentials from the calibrated model indicate that groundwater divides closely coincide with the subwatershed boundaries. Overall, groundwater discharges to the river systems and nearby Great Lakes. The regional model shows groundwater flow from higher elevation toward the Great Lakes.

The equipotentials in the bedrock layers are strongly dictated by the deep channeled river courses. There are indications that the regional groundwater system is interconnected to the shallow system as upward vertical gradients are evident along the river courses and in some areas of the Ekfrid Clay Plain as well as in the southern portions of the study area. Downward vertical gradients are evident in the northern regions of the study area. This suggests that there may be potential for further groundwater development to occur in the study area.

4.5.5 Sensitivity Analysis

Model predictions should be expressed as a range of possible outcomes that reflect uncertainty in the parameter values. Natural uncertainty in hydrogeologic model parameters makes it necessary to conduct a model sensitivity analysis. To quantify the uncertainty associated with the parameter estimation, a series of sensitivity simulations were performed for the regional model as follows:

1. Hydraulic conductivity of the aquifers (within layers 1, 3 and 5) was increased by a factor of 2;
2. Hydraulic conductivity of the aquifers (within layers 1,3 and 5) was decreased by a factor of 2;
3. Hydraulic conductivity of the aquitards (within layers 1, 2 and 4) was increased by a factor of 5;
4. Hydraulic conductivity of the aquitards (within layers 1, 2 and 4) was decreased by a factor of 5;
5. Recharge was reduced by 25 percent;
6. Recharge was increased by 25 percent;

Table 5.1 summarizes the relevant calibration statistics for the sensitivity scenarios. These scenarios do not represent observed field conditions. The predictions from these scenarios provide insight into the possible range of material characteristics within the watershed. This simplified approach to the sensitivity analysis was completed to show how a range in parameter values will lead to multiple calibrated models. Assessing the sensitivity of the groundwater system to future developments, water takings, and any other future scenarios can be assessed by the Conservation Authorities for future groundwater evaluations.

5 Discussion

The calibrated regional-scale groundwater model of the Six CA's watershed was developed based on the Conceptual Geological Model (WHI, 2004), which itself was based on previous reports, maps and new analyses completed as part of this study. The model encompasses the entire Six CA's watershed boundaries and accounts for the regional groundwater flow.

5.1 Calibration

The MOE WWIS contains the static water level for each well, at the time of installation. These points can be used to assess the ability of the model to simulate groundwater flow by comparing the observed static water level with the model-calculated water level. The static water levels recorded in the WWIS are subject to errors relating to well location, ground elevation and temporal fluctuation. In the FEFLOW model each calibration point is assigned to the appropriate model layer based on the hydrostratigraphic unit that the well intersects. These point observations of hydraulic head represent the primary data for use in model calibration.

The model was calibrated such that observed water levels obtained from 4,102 wells lying within the model area matched those simulated by the FEFLOW model as closely as possible. The observed water levels are primarily for shallow wells; however, some deeper water level data was also available.

Model calibration involved the adjustment of model parameter values to match field measured values within a pre-established range of error. This involved a process where the resulting groundwater heads were compared to observed heads, and the model input parameters were re-adjusted to achieve better agreement with observed (field measured head) conditions. **Table 5.1** summarizes the relevant calibration statistics for the base case condition and the sensitivity scenarios. **Figure 5-1** presents the plot of the calculated versus observed head values for the calibration wells. The overall mass balance is conserved and the error is less than 0.05 percent. A model is considered calibrated when the percent NRMS is less than ten percent (ASTM, 1995) while reproducing observed flow directions and gradients. In the previous two sections, the model was shown to reasonably calculate vertical recharge and river discharge. The remaining flows into and out of the model therefore occur through the constant head boundaries at the edge of the model domain. The ability of the groundwater model to simulate the steady-state groundwater flow system in the Six CA's watershed was evaluated by comparison of model calculated head values, equipotential contours and river baseflow. The model calculated hydraulic head and baseflow measurements matched reasonably well with the observed values.

The calibration was achieved using input parameter values that are within the expected range or measured range for the groundwater system in the Six CA's watershed. A calibration comparison for each Conservation Authority boundary was also completed and tabulated in **Table 5.2**. These statistics show that the model produces a reasonable calibration for four of the six Conservation Authorities. The ERCA and LTVCA calibration statistics do not compare well between the calculated and observed head conditions. It is recommended that these areas be re-visited to update existing calibration wells and/or the hydrogeological parameters in these regions.

5.1.1 Hydraulic Head Comparison

In addition to the point values, modeled potentiometric surface maps illustrate the general trends throughout the aquifer system. **Figure 5-2** presents the modeled head equipotential contours for the overburden (Layer 1) and **Figure 5-3** represents the bedrock (Layer 8) aquifer systems. The maps show good correlation between flow directions in both aquifer systems. The overburden groundwater levels illustrate that the shallow groundwater system has a large influence on the river system which is particularly evident in the St. Clair Region watershed.

5.1.2 Groundwater Baseflow & Water Balance Calculations

A water balance considering all of the model inflows and outflows provides an overall measure of the ability of the calibrated model to predict groundwater flow and simulate actual flow conditions. Specifically the water budget can be used to check the mass balance for the model solution and quantify flow into and out of the model through boundary conditions.

The water entering and leaving the model through aerial recharge and adjacent watersheds was calculated using the Budget Analyzer Tool in FEFLOW. The water entering the model is approximately 14,500,000 m^3/d. The total water leaving the system, through discharge to the rivers, lakes, and pumping is in the range of about 16,000,000 m^3/d. Overall, there is more water leaving the model system than entering it. This is due to the large amount of groundwater discharge through the bedrock units to the Great Lakes (which are represented using constant head boundaries). Three percent of the total water discharges to

Lake Erie. Another 0.5 percent of the total water discharges to Lake St. Clair, and about three percent discharges to Lake Huron.

Streamflow measurements for a number of river reaches (approximately 41) are available from Water Survey of Canada (WSC) Gauge Stations. The measurement location of each of these data sources is presented in **Figure 2-9**. In Phase 1, model development and initial calibration, the high and low estimates of baseflow were derived from the Water Survey Canada gauges by computing the average flow (Section 4.5.3).

In simple terms a water budget for a given area can be looked at as water inputs, outputs and changes in storage. The inputs into the area under investigation (recharge, groundwater or surface water inflows) must be equal to the outputs (municipal pumping, surface or groundwater outflows) as well as any changes in storage within the area of interest. This can be expressed as:

$$\text{Inputs} = \text{Outputs} + \text{Change in storage}$$

The following components of the water budget (**Figure 5-7**) were calculated in the Six CAs Watershed model:

1. Net infiltration or groundwater recharge to a given aquifer unit or region;
2. Groundwater discharge to stream / river reaches;
3. Groundwater recharge to aquifers from rivers;
4. Horizontal groundwater flow into or out of the model domain (e.g. discharge to Lake Erie);
5. Pumping well extraction.

Although it is important to quantify these values as totals for the watershed, water budget analysis for a sub-region of the model can also be informative, highlighting the spatial variability in each water budget component. A plot of the modeled baseflows for each of the water gauging stations is displayed in **Figure 5-4** to **Figure 5-6**.

Table 5.1: Calibration Results for the Basecase and Sensitivity Scenarios

	Calibration Statistics				Comments
	NRMS (Percent)[1]	RMS[2]	MAE[3]	ME[4]	
Base Case	3.87	11.93	8.66	1.63	Calibrated Model -good calibration
Case 1	3.80	11.73	8.50	0.73	Good Trend – unrealistic K values for Sands and Gravels
Case 2	4.02	12.39	9.05	2.67	Reasonable Gradient Trend - large scatter in data, high overall gradient
Case 3	3.66	11.28	8.33	-1.20	Good Trend – High Scatter in localized regions
Case 4	5.66	17.44	12.63	7.79	Poor Gradient Trend – Overall High Scatter in data points
Case 5	3.79	11.68	8.45	0.01	Good Trend – Some scatter in data points in localized areas
Case 6	4.19	12.90	9.41	3.74	Reasonable Gradient Trend - Overall High Scatter in data points

Notes:
NRMS = Normalized Root Mean Square Residual Value
RMS = Root Mean Square Error
MAR = Mean Absolute Error
RE = Mean Error

Table 5.2: Calibration Results for each of the Six Conservation Authorities

	Calibration Statistics				Comments
	NRMS (Percent)[1]	RMS[2]	MAE[3]	ME[4]	
ABCA	6.18	10.27	5.88	0.65	Reasonable calibration
UTRCA	6.91	13.28	10.10	-0.89	Reasonable calibration
LTVCA	14.33	14.05	11.08	9.85	Unreasonable calibration results – high heads
ERCA	18.91	10.49	8.11	-6.30	Unreasonable calibration – low head values
SCRCA	6.11	7.78	5.42	2.27	Reasonable calibration
MVCA	4.78	13.05	11.25	2.18	Reasonable calibration

The calculated baseflow to streams in the model was compared to information derived from gauging stations monitored by the Water Survey of Canada (WSC). **Table 5.3** lists the different stream gauging stations that were used for comparison of calculated model baseflows. The calculated baseflow should fall within the minimum estimated baseflow and maximum estimated baseflow values.

In total 15 streamflow gauges within the study area are under-predicting stream gauge baseflow values.

Three stream gauge stations located on the Maitland River near Belgrave, Listowel and Summerhill (i.e., 02FE008, 02FE003 and 02FE009) within the Maitland Valley watershed are underpredicting the minimum estimated baseflow values of 1.6, 0.2, and 1.0 m^3/s respectively. One stream gauge station located near Varna on the Bayfield River (i.e., 02FF009) within the Ausable Bayfield watershed is under-predicting the minimum estimated baseflow value of 0.3 m^3/s. Five stream gauge stations located on various tributaries and main branches along the Thames River (i.e. 02GD018, 02GD005, 02GD008, 02GD011 and 02GD016) within the Upper Thames River watershed are under-predicting the minimum estimated baseflow values of 0.6, 3.4, 0.5, 0.3, and 2.5 m^3/s respectively. One stream gauge station located near Strathroy on the Sydenham River (i.e., 02GG005) within the St. Clair Region watershed is under-predicting the minimum estimated baseflow value of 0.6 m^3/s. Three stream gauge stations located on various tributaries along the Thames River (i.e., 02GE006, 02GE003 and 02GE005) within the Lower Thames Valley watershed are under-predicting the minimum estimated baseflow values of 16.1, 16.1 and 0.4 m^3/s respectively. Two stream gauge stations located at Ruscom station on the Ruscom River and Windsor on Turkey Creek (i.e., 02GH002 and 02GH004) within the Essex watershed are under-predicting the minimum estimated baseflow values of 0.2 and 0.3 m^3/s respectively.

In total eight streamflow gauges within the study area are over-predicting stream gauge baseflow values. Two stream gauge stations located near Harriston and above Wingham along the Maitland River (i.e., 02FE011 and 02FE005) within the Maitland Valley watershed are over-predicting the maximum estimated baseflow values of 0.7 and 2.3 m^3/s respectively. Two stream gauges located near Spring and Parkhill along the Ausable River (i.e., 02FF002 and 02FF010) within the Ausable Bayfield watershed are over-predicting the maximum estimated baseflow values of 3.5 and 1.7 m^3/s respectively. Three stream gauges located at the Fanshaw Dam, near Tavistock and Ealing along the Thames River (i.e., 02GD003, 02GD023 and 02GD001) within the Upper Thames River watershed are over-predicting the maximum estimated baseflow values of 5.8, 0.1, and 6.2 m^3/s respectively. One stream gauge located at Chatham on the Thames River (i.e., 02GE004) within the Lower Thames Valley watershed is over-predicting the maximum estimated baseflow of 1.74 m^3/s.

In general, calculated baseflows along the main branches of the rivers match closer to the average estimated baseflow values. To better characterize these areas the model should be re-visited when additional information is made available (such as current water takings and/or tile drain effects).

Table 5.3: Water Survey of Canada – Long Term Baseflow Calibration

Stream Gauge ID	Description	River	Recording Dates	Minimum Est. Baseflow (m^3/s)	Maximum Est. Baseflow (m^3/s)	Average Est. Baseflow (m^3/s)	Calculated Baseflow (m^3/s)	Minimum Est. Recharge (mm/yr)	Maximum Est. Recharge (mm/yr)
02FF007	Bayfield R. near Varna	Bayfield R.	1966-2003	0.9	2.6	1.6	1.4	61.2	173
02FF009	Ausable R. near Exeter	Ausable R.	1984-2003	0.3	1.1	0.6	0.1	83.3	299.2
02FF008	Parkhill Cr. above Parkhill Rsr.	Parkhill Cr.	1973-2000	0.2	0.9	0.5	0.3	57.1	251.8
02FF002	Ausable R. near Spring Bank	Ausable R.	1945-2003	1.7	3.5	2.5	5.3	60.8	127.9
02FF004	S. Parkhill Cr. near Parkhill	Dewar-Thompson Drn.	1955-2003	0.1	0.3	0.2	0.13	60.4	243.8
02FF010	Ausable R. near Parkhill	Ausable R.	1997-2003	1.6	1.7	1.6	6.5	44.3	47.2
02GH002	Ruscom R. near Ruscom Stn.	Ruscom R.	1971-2002	0.2	0.6	0.4	0.1	44.4	147.2
02GH011	Little R. at Windsor	Little R.	1983-2003	0.2	0.3	0.3	0.25	127.7	213.5
02GH004	Turkey Cr. at Windsor	Grand Marais Drain	1982-2003	0.3	0.3	0.3	0.2	269.9	355.5
02GH003	Carnard R. near Lukerville	Canard R.	1976-2003	0.3	1.1	0.8	0.3	68.8	224.6
02GE006	Thames R. near Dutton	Thames R.	1971-1998	16.1	25.6	19.7	2.7	135.3	214.7
02GE003	Thames R. at Thamesville		1938-2003	16.0	21.3	18.5	6.5	117.6	156.1
02GE007	McGregor Cr. near Chatham	McGregor Cr.	1977-1998	0.59	1.19	0.92	0.7	92.6	185
02GE004	Thames R. at Chatham	Thames R.	1938-2003	1.69	1.74	1.72	7.4	11.6	11.9
02FE011	Maitland R. near Harriston	Maitland R.	1981-1998	0.2	0.7	0.4	1.2	66.6	195.5
02FE005	Maitland R. above		1953-2001	1.8	2.3	2.0	3.7	105.3	139.2

Stream Gauge ID	Description	River	Recording Dates	Minimum Est. Baseflow (m^3/s)	Maximum Est. Baseflow (m^3/s)	Average Est. Baseflow (m^3/s)	Calculated Baseflow (m^3/s)	Minimum Est. Recharge (mm/yr)	Maximum Est. Recharge (mm/yr)
	Wingham								
02FE002	Maitland R. below Wingham		1953-2003	4.4	6.8	5.4	5.4	85.4	131.2
02FE008	Maitland R. near Belgrave		1967-1998	1.6	3.7	2.5	1.3	78.4	177.8
02FE003	Mailtland R. near Listowel		1953-2003	0.2	0.4	0.3	0.1	81.2	145.5
02FE014	Blyth Brook Below Blyth	Blyth Brook	1984-2003	0.2	0.6	0.3	(0.2)	67.8	260.9
02FE009	S. Maitland R. at Summerhill	Maitland R.	1967-2003	1.0	2.0	1.3	0.5	81.9	165
02GG005	Sydenham R. at Strathroy	Sharpe's Cr.	1966-1992	0.6	0.8	0.7	0.2	104.0	139.9
02GG002	Sydenham R. near Alvinston	Sydenham R.	1947-2000	1.8	2.1	2.0	1.8	79.8	92.8
02GG006	Bear Cr. near Petrolia	Bear Cr.	1966-2003	0.3	0.9	0.6	0.6	36.6	112.2
02GG003	Sydenham R. at Florence	Sydenham R.	1984-2003	2.0	4.2	3.1	3.3	54.5	113.9
02GG009	Bear Cr. below Brigden	Bear Cr.	1981-2003	0.7	2.6	1.4	1.4	40.3	155.2
02GD014	N. Thames R. near Mitchell	N. Thames R.	1953-2003	0.7	1.6	1.0	0.7	71.2	159.8
02GD018	Avon R. below Stratford	Avon R.	1964-2003	0.6	1.0	0.8	0.3	139.7	216.3
02GD005	N. Thames R. at St. Mary's	Thames R.	1938-2003	3.4	5.5	4.2	3.0	98.8	161.3
02GD015	N. Thames R. near Thorndale		1953-2003	4.3	7.3	5.5	5.4	101.7	170.9
02GD003	N. Thames R. Fanshaw Dam		1915-1998	3.7	5.8	4.5	6.3	80.1	125.2
02GD008	Medway R. at London	Medway Cr.	1945-2003	0.5	1.0	0.7	0.2	73.0	154.5
02GD019	Trout Cr. near Fairview	Trout Cr.	1966-1998	0.1	0.2	0.2	0.1	89.1	204.5

Stream Gauge ID	Description	River	Recording Dates	Minimum Est. Baseflow (m^3/s)	Maximum Est. Baseflow (m^3/s)	Average Est. Baseflow (m^3/s)	Calculated Baseflow (m^3/s)	Minimum Est. Recharge (mm/yr)	Maximum Est. Recharge (mm/yr)
02GD023	Thames R. near Tavistock	Jackson Drn	1987-1999	0.1	0.1	0.1	0.16	67.3	119.6
02GD011	Cedar Cr. at Woodstock	Cedar Creek	1951-2003	0.3	0.4	0.3	0.01	112.6	127.2
02GD016	Thames R. at Ingersoll	Thames Chnl	1957-2003	2.5	2.9	2.8	2.1	154.9	177.3
02GD004	Thames R. at Thamesford	Woods Drain	1938-2003	1.0	1.3	1.2	0.00	106.8	130.4
02GD020	Waubuno Cr. near Dorchester	Waubuno Chnl	1965-2000	0.2	0.4	0.3	0.2	59.6	118.0
02GD001	Thames R. near Ealing	S. Thames R.	1915-2003	5.0	6.2	5.7	6.4	118.0	145.2
02GE002	Thames R. at Byron	Thames Chnl	1922-2000	12.1	16.5	14.1	14.1	122.2	166.9
02GE005	Dingman Cr. below Lambeth	Dingman Chnl	1965-2003	0.4	0.6	0.5	0.1	77.4	129.7

The calibrated model indicates that approximately 68 percent of all recharge is from the sand plains located within various watersheds within the study area. An additional 34 percent is from the till moraines and St Clair Clay plain. **Table 5.4** outlines calibrated recharge values for each watershed and the percent of recharge to the groundwater system.

Table 5.4: Model Recharge Calculations

Watershed	Areal Recharge (m^3/d)	Area (m^2)	Percent Area of Model Domain	Average Recharge in (mm/yr)	Percent Recharge
MVCA	1 323 394	3 265 000 000	18	148	19
ABCA	964 931	2 443 000 000	14	144	14
LTVCA	1 364 130	3 260 000 000	18	153	20
UTRCA	1 492 884	3 447 000 000	19	158	21
SCRA	1 341 968	3 989 000 000	22	123	19
ERCA	490 600	1 627 000 000	9	110	7
Total	6 977 907	18 031 000 000	100		100

Intercatchment flow has important implications for future groundwater use in the study area. The MVCA area contributes approximately 26 percent of groundwater flow to the ABCA and UTRCA catchment areas. ABCA receives groundwater from all of the surrounding catchment areas (i.e. MVCA, UTRCA, and SCRCA) and discharges into Lake Huron. The percentage groundwater contributions from the SCRCA watershed to the ABCA watershed are approximately 13 percent. SCRCA also provides about 19 and 10 percent, respectively, to the LTVCA and UTRCA watersheds. The UTRCA watershed contributes approximately 6 percent of its total groundwater outflow to the LTVCA. The remainder of the outflow flows out to the ABCA watershed. A significant percentage of total groundwater outflows from the LTVCA watershed directly to Lake Erie, while only 3 percent of the total groundwater outflow flows to the ERCA region. The ERCA watershed primarily discharges to Lake St. Clair.

To evaluate whether predicted groundwater flow through the calibrated model is representative of actual flow conditions, a water balance considering all of the model inflows and outflows was completed for each of the six Conservation Authorities. **Table 5.5** presents the flow budget balance for the calibrated model. The river boundaries estimate the overall flux of water into or out of the river boundary in each particular watershed. The constant heads represent areas where water is either entering or leaving the model domain. This boundary is used to represent the Great Lakes and how they interact with the groundwater model.

To improve upon the water budget for the Six CA's it is recommended that the groundwater model be updated with current information related to municipal water takings in each of the Six CA boundaries alongside any additional calibration points that could be incorporated to improve upon the hydrogeological characterization of local regions in the model.

Forward particle tracks were released from a variety of locations within aquifers throughout the Six CA's, in both the overburden and bedrock, to evaluate travel times through the groundwater system (**Figure 5-8**). The particles released in the UTRCA region extend in a west – southwest direction toward the ABCA, SCRCA, and LTVCA regions. A number of the particle tracks have longer travel times (i.e. greater than 500 years) in the subsurface, however in general the time of travel is in the range of 25 to 100 years. These travel times do not include the time of travel through aquitards, and therefore travel times from recharge areas to discharge areas will be longer than the 25 to 100 years.

These times of travel should be considered when assessing the security of the current and future water supplies in the region. This demonstrates how the model can be a useful tool to assist in predicting the pathways of groundwater flow throughout the study area. The applied particle tracks suggest that groundwater quality problems that occur today may take a long time to reach groundwater supplies. Installing sentinel wells in regions of high vulnerability would improve the security of the groundwater resources and help to mitigate any future impacts to public or domestic supply wells.

Table 5.5 Six CA Flow Budget Components.

UTRCA Flow Components	Inflow (m^3/day)	Outflow (m^3/day)
Constant heads	0.0	0.0
River (transfer) boundaries	425 944.3	1 761 140.0
Recharge	1 492 884.0	0.0
Pumping Wells	0.0	164 990.0
Total	1 918 828.3	1 926 130.0
LTVCA Flow Components	**Inflow (m^3/day)**	**Outflow (m^3/day)**
Constant heads	524.5	391 581.3
River (transfer) boundaries	96 826.9	1 098 929.0
Recharge	1 364 130.0	0.0
Pumping Wells	0.0	0.0
Total	1 461 481.4	1 490 510.3
SCRCA Flow Components	**Inflow (m^3/day)**	**Outflow (m^3/day)**
Constant heads	0.0	64 512.4
River (transfer) boundaries	86 091.9	1 105 717.0
Recharge	1 341 968.0	0.0
Pumping Wells	0.0	0.0
Total	1 428 059.9	1 170 229.4
ERCA Flow Components	**Inflow (m^3/day)**	**Outflow (m^3/day)**
Constant heads	214.1	198 396.2
River (transfer) boundaries	15 296.9	282 196.8
Recharge	490 599.7	0.0
Pumping Wells	0.0	0.0
Total	506 110.7	480 593.0
MVCA Flow Components	**Inflow (m^3/day)**	**Outflow (m^3/day)**
Constant heads	0.0	342 233.3
River (transfer) boundaries	589 892.0	1 648 420.0
Recharge	1 323 394.0	0.0
Pumping Wells	0.0	11974
Total	1 913 286.0	2 002 627.3
ABCA Flow Components	**Inflow (m^3/day)**	**Outflow (m^3/day)**
Constant heads	2 677.2	244 166.0
River (transfer) boundaries	538 692.4	1 475 430.0
Recharge	964 930.7	0.0
Pumping Wells	*8 419.9	3822.0
Total	1 514 720.2	1 723 418.0

* Injection wells used to represent high recharge rates in sinkhole cluster region – discussed in Section 4.4.2.

6 Summary and Recommendations

Groundwater modeling of the entire Six Conservation Authorities was undertaken to enhance the understanding of the groundwater flow system that supplies water to the area, and improve water balance analysis capabilities. The model developed will allow the Six CA's to evaluate the regional and cumulative impacts of water takings throughout the six watersheds. Such impacts may include impacts to the rivers and streams and other environmentally sensitive areas.

This report presented analyses that have been developed to date and the approach taken to construct the three-dimensional geological model, which was used to build and calibrate the three-dimensional groundwater flow model. The numerical model developed represents the full three-dimensional regional groundwater flow system and extends deep into the underlying bedrock to incorporate interaction with deeper groundwater systems. Through this approach, the model that was developed will allow the Six CA's to more accurately evaluate the interaction of groundwater and surface water and assess the potential influence of additional stresses (e.g land use, pumping, climate change etc.) on this balance. In addition, this model provides a robust and flexible tool that can be updated as new information becomes available and refined as necessary to focus calibration and prediction capabilities in local areas of concern.

The regional groundwater flow model is a flexible groundwater management tool for future evaluation of alternative groundwater uses and management strategies for various scenario situations, such as:

- Evaluating effects of climate change on the water balance
- Determining the effects of increased groundwater pumping and the associated drawdown
- Evaluating well interference, measuring influence of stresses on stream baseflow
- Evaluating the effects of changes in land use on the groundwater system
- Assessing potential contaminant pathways and proposed mitigation or remedial systems
- Identifying, and identifying and determining the sources of discharge in the study area.

Recommendations related to the further development and uses of the groundwater flow model as a groundwater management tool are:

1. Maintain a detailed analysis of PTTW Average Annual Extraction Rates to provide information for the model to understand the influence on the regional water balance.
2. The model should be updated to include any additional municipal pumping wells in the study area. It can also be used to test modeling scenarios that seek to understand how additional pumping wells will stress the groundwater system.
3. Update the model at regular intervals using detailed geological cross-sections and any other new information that becomes available.
4. Review the model at smaller scales (scale of future simulations; ie., sub-watershed scale) to verify the representation of the model layers and assess the need for localized refinement.
5. Examine interaction between the groundwater model and surface water models (e.g GAWSER).
6. A sensitivity analysis should be completed on the model to determine what areas of the model are sensitive to parameter variations, resulting in further data collection or model refinement.

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