Six Conservation Authorities FEFLOW Groundwater Model

Conceptual Model Report

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1 Introduction

1.1 Overview

The Upper Thames River Conservation Authority (UTRCA), with five other Conservation Authorities (CAs), is taking an active role in the management of groundwater resources within the study area. To enhance the understanding of the groundwater flow system, which was developed through the completion of comprehensive groundwater studies throughout southwestern Ontario, a groundwater model of southwestern Ontario (covering six Conservation Authorities jurisdictions) is being developed.

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. (WHI) was retained by the UTRCA to develop a three-dimensional conceptual geological model and a three-dimensional hydrogeological (groundwater flow) model that encompasses the lands within the following Conservation Authorities: Ausable Bayfield, Maitland Valley, Essex Region, St. Clair Region, Lower Thames Valley and Upper Thames River (**Figure 1**). The following report describes the conceptual geological model that will be used as the basis for the FEFLOW groundwater model.

1.2 Objectives

An understanding of the groundwater flow system is achieved through the review and compilation 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 model can be utilized as a tool to further understand and simulate the groundwater flow system.

To meets these major objectives, the following goals have been identified for this project:

1. Develop a spatially referenced database of hydrogeologic information for visualization of regional hydrogeologic information, and construction of a numerical model.

2. Develop a regional-scale, three-dimensional, conceptual geological model that builds upon the existing conceptualization and numerical models that have been developed within the study area.

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

1.3 Scope and Major Tasks

To achieve the goals listed above, the following major tasks will be completed:

1. Identify, acquire and review all available data including previous studies, and previous groundwater models.

2. Develop a spatially referenced database of information on the hydrogeology of the study area and complete mapping using GIS to characterize the aquifers and aquitards across the study area.

3. Identify regional and local boundaries for groundwater flow (e.g. groundwater / surface water divides) and develop a conceptual geological model that is consistent with other studies and includes regional (e.g. buried valleys) and local elements (e.g. surface water features).

4. Construct and calibrate a three-dimensional hydrogeological model based on the conceptual geological model utilizing the database information and GIS mapping. The focus of the model calibration will be at the regional scale while attempting to calibrate to existing local scale models.

5. Apply the groundwater model to evaluate groundwater flow conditions and flow rates for different hypothetical future scenarios.

Tasks 1 to 3 have been completed for the development of the geological model and are the focus of this report.

1.4 Previous / Concurrent Studies and Other Data Sources

Many localized studies related to the geology and hydrogeology of the study area have been completed in the last 30 years. Regional groundwater study reports were compiled and reviewed, as well as relevant papers in the academic literature. This information was used to develop a comprehensive understanding of the geologic and hydrogeologic setting of the study area. The documents were reviewed with the purpose of developing the conceptual geologic and groundwater flow model.

The geologic structure, hydraulic conductivity and layer information were used to develop the conceptual geological model and will be used to develop the groundwater flow model. Local scale models, developed during the MOE funded groundwater studies, were also reviewed and will be used as reference when defining the regional model input parameters. Calibration data, including measured groundwater levels, groundwater discharge rates to rivers and streams, and isotropic tracer data from previous groundwater studies, will be incorporated into the calibration data set for the regional groundwater model.

Section 4 presents a list of referenced reports that pertain to the development of a conceptual geological model for the study area.

1.5 Mapping and Database Development

A number of existing data sets and maps were utilized in this project to develop the conceptual geological model. These included study area 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.

1.5.1 GIS Mapping

The GIS mapping provided by the UTRCA, Ministry of Environment, and Ministry of Northern Development and Mines through their corporate GIS system included:

- Topography (Digital Elevation Model – DEM);
- Quaternary Geology;
- Bedrock Geology;
- Surface water features (e.g. streams, wetlands, subbasin boundaries);
- Recharge classification; and,
- 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 25 metres. In developing the conceptual geological model, WHI evaluated information from previous reports. A number of maps were created during this analysis, including an updated bedrock surface, overburden thickness, bedrock water levels, recharge and discharge areas, and cross-sections. All maps generated were clipped to a 5 km buffer of the study area boundary. This is discussed further on the following pages.

1.5.2 Relational Database of Water Well Records

The primary source of geologic and hydrogeologic information for this project was the water well database constructed 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. WWIS limitations include different reliabilities for well location, inconsistent geologic descriptions, and variable well completion techniques.

WHI received the WWIS from the MOE. Recognizing the limitations of the WWIS, WHI screened the WWIS and identified the most reliable well records based on the following criteria:

- Location and elevation reliability of water wells;
- Static water levels for groundwater head (pressure) and flow mapping;
- Well details including depth of water bearing zones; and,
- Well construction details such as depth of casing and recommended pumping rate.

The reliability of the well location and elevation was assessed by verifying the coordinates against the Lot-Concession layer from the Ontario Base Map (previously completed by the MOE) and checking the elevations relative to the Digital Elevation Model (DEM).

To improve the data quality within the WWIS, WHI updated the ground elevation reported in the database to coincide with the DEM elevation at all well locations. Using the DEM as the ground surface promotes consistency between all records within the WWIS.

MOE 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 describe construction details, geologic unit elevations, and static water levels.

Figure 2 shows the spatial distribution of water well records that met the screening criteria. The original MOE WWIS database consisted of approximately 27,000 well records. The number of reliable wells was reduced to approximately 23,000 after the screening process was completed. The remaining records were not removed from the database but made inactive and excluded in any subsequent analysis.

The WWIS Formation table includes a description of the well geology for each interval that was recorded by the driller. These materials are used to determine the hydrostratigraphic units of the well and to determine the uppermost bedrock unit.

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.

1.5.3 Permit to Take Water Database

The MOE issues Permits to Take Water (PTTW) that allow the withdrawal of a large volume of surface and 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.

Groundwater studies completed throughout the study area (ie. Perth County, Middlesex – Elgin County, etc) examined the large permitted groundwater users (>200,000 L/day) within each of the study areas. These large permitted users were surveyed during the groundwater studies to determine actual water taking. Where available, actual water taking information will be utilized in the groundwater model.

For municipal wells in the study area, average daily pumping rates were also obtained from the groundwater studies for inclusion in this project. For all other wells identified in the PTTW database that do not have average pumping rates available, the maximum permitted rate will be used.

1.5.4 Oil and Gas Well Records

Oil and gas well records are maintained by the Ministry of Natural Resources at the Petroleum Resources Centre in London. Their records include well information regarding the date of construction, status, geologic interval depths, ground elevation, and information regarding water producing zones and water quality. This information will be used to define the elevation and thickness of the different bedrock units throughout the study area.

The following bedrock units will be incorporated into the FEFLOW model:

- Salina Formation
- Bass Island Formation
- Bois Blanc Formation
- Detroit River Group (Amherstberg and Lucas Formations)

- Dundee Formation
- Marcellus Formation
- Hamilton Group
- Port Lambton Group

The oil and gas well records were received in late-November, and therefore the mapping associated with the geologic units listed above are not included in this report, however they will be included in the final study report.

1.5.5 Cross-Sections

To obtain an understanding of the hydrostratigraphic conditions and to construct the conceptual geological model within the study area, WHI developed 12 regional geological cross-sections to understand the units that would be encountered in the smaller scale cross-sections. **Figure 3** to **Figure 8** shows the locations of the regional cross-sections that have been interpreted. Due to the high density of cross-sections, they are shown in six figures, with each figure corresponding to the boundaries of a CA.

The interpreted cross-sections, illustrating the general geologic and hydrostratigraphic structure, are included in the CD-ROM provided at the end of this report. Two example cross-sections are shown in **Figure 9** and **Figure 10**.

Following interpretation of the regional cross-sections, 109 local scale cross-sections (oriented north-south and east-west) were drawn and interpreted across the study area. The intersecting cross-sections were spaced using a 10 km grid, and all cross-sections were less than 40 km in length. These smaller scale cross-sections provided the basis for construction of the conceptual hydrostratigraphic units (Section 2.2.2), which will be used to define the layers and parameter distributions (e.g. hydraulic conductivity) for the numerical model. These cross-sections are also included in the CD-ROM discussed above.

An additional 84 local scale cross-sections were also drawn (also included on the CD-ROM) to examine the spatial extent of intermediate sand and gravel units within kame moraines, and intermediate aquifers, and also to examine areas where buried bedrock valleys have previously been reported to exist. Additional cross-sections may be developed during groundwater model calibration to further characterize portions of the study area if warranted. All cross-sections will be presented on CD-ROM with the final report.

Oil and Gas well logs were obtained from the Ministry of Northern Development and Mines for all of the wells drilled in the study area. The Oil and Gas well records were combined and appended to the WWIS database for inclusion in GIS mapping layers. These well logs list the elevations of bedrock formations in the area, and will be used to define the lower bedrock layers in the conceptual geological model.

Figure 11 (Bedrock Geology) shows the spatial distribution of the Oil and Gas well records. The original MNR Oil and Gas database consisted of approximately 7,900 well records.

WHI utilized CSMapper, a custom GIS application developed by WHI, to create the cross-sections, and interpret the individual layers for the FEFLOW model.

2 Conceptual Geological Model

The following section provides a description of the important geologic features within the Six Conservation Authorities study area and how these features relate to the development of the conceptual geological model. The conceptual geological model will be used to guide development of the numerical model such that it is consistent with the geology and hydrogeology of the area.

2.1 Regional Geological Setting

The Six CAs study area includes many political boundaries including portions of Bruce, Elgin, Wellington, Middlesex, Huron, Perth, Oxford, Brant, Essex, Kent and Lambton Counties, and the Regional Municipality of Waterloo. The study area is approximately 20,000 km^2; 143 km wide (east to west through London) by 300 km long (from Windsor to north Perth) with a ground surface elevation ranging from 472 m asl in the northern portion to 168 m asl at Lake Erie (**Figure 11**).

County scale geologic and hydrogeologic features are well documented in the recent MOE funded groundwater studies. Within the model area, these studies include the Perth Groundwater Study (WHI 2002), Oxford Groundwater Study (Golder, 2001), Middlesex-Elgin Groundwater Study (Dillon 2004), Essex Chatham-Kent Groundwater Study, Huron Groundwater Study (International Water Consultants 2003), and the Lambton Groundwater Study.

Figure 12 shows the generalized geologic structure across the study area. Not all layers extend throughout the study area. Where aquifer / aquitards and bedrock units do not exist, the conceptual geologic layers will not be present (zero thickness). A summary of the Quaternary and bedrock geology within the study area that makes up the conceptual geological model is included in the following pages.

2.1.1 Proterozoic Bedrock of Southern Ontario

Canadian Shield gneisses, granites and various types of volcanic rocks commonly outcrop along the highways and lake shorelines of eastern and northern Ontario. These rocks also exist beneath southern Ontario, however they are deeply buried beneath Paleozoic rocks, and Quaternary sediments. Beneath the study area, the rocks of the Canadian Shield were formed during the Proterozoic period (2.5 billion to 545 million years old) as landmasses (terranes) separated by small oceans, pushed together during continental collision to form the Grenville Province portion of the Canadian Shield (Easton 1992). A portion of this geological province, termed the Central Gneiss Belt underlies the study area, where the bedrock is comprised of igneous and metamorphic rocks (predominately gneisses, amphibolites and younger granitic plutons) (Easton 1992; Turek and Robinson 1982). Due to their depth below ground surface, these rocks are not expected to have an influence on groundwater flow through the study area.

2.1.2 Paleozoic Bedrock of Southern Ontario

The highly metamorphosed and deformed Proterozoic basement rocks discussed above underwent varying amounts of crustal displacement from the time of their deposition (1.3 to 1.1 billion years ago) to the deposition of the overlying Paleozoic rocks (approximately 545- 300 million years ago; Johnston et al.,1992). This intense crustal displacement led to differential regional uplift and depression of the Precambrian basement, which in southern Ontario led to the formation of 3 main structural elements: the Michigan Basin, the Appalachian Basin, and the Findlay-Algonquin Arch (Johnson et al. 1992). These three structural elements greatly impacted the nature and form of the sedimentary rocks deposited beneath the study area.

The Michigan Basin is generally circular, deep (approximately 4200 m), carbonate- dominated sedimentary basin centred in the state of Michigan (Johnston et al. 1992). The vast majority of Paleozoic rocks underlying the study area were deposited within this basin, and most rocks dip southwestwards towards the centre of this basin.

The Appalachian Basin is a large, elongate, siliciclastic-dominated foreland basin located between the Appalachian Mountains and southern Ontario. This basin reaches depths of approximately 7000 m in the eastern US states.

A southwest trending Precambrian basement high termed the Findlay- Algonquin arch separates the two basins and stretches from Cincinnati, Ohio in the southwest to Collingwood in the northeast (Johnson et al. 1992). The Findlay-Algonquin Arch is comprised of the Algonquin Arch (stretching from Chatham to

Collingwood), and the Findlay Arch (extending from Ohio to Essex County) but for simplicity, the term Findlay-Algonquin Arch is commonly used to describe the structural high created by these 2 features. The Findlay-Algonquin Arch was active until the late Devonian, and it greatly influenced the sedimentation patterns that took place throughout the Paleozoic. This bedrock ridge acted as an open shallow water barrier, or transition zone that separated the two basins, and as a result, several of the geologic formations within southern Ontario thin towards the Findlay-Algonquin Arch (Johnson et al. 1992).

Rise and fall of the Canadian Shield during the Paleozoic (including the Michigan and Appalachian Basins) led to the deposition of shallow (carbonates, sandstones) and deep water (shales, siltstones) facies within the interior of North America (Johnson et al., 1992). Up to 1500 m (Boyce and Morris 2002; Johnston et al. 1992) of interbedded carbonates, shales, and sandstones deposited predominately during the Devonian, Ordovician, and Silurian Periods subcrop beneath the study area (505-430 million years ago; Johnson et al, 1992). Carbonate rocks include the Salina, Dundee, Lucas, Bass Island, Bois Blanc, Amherstburg, Guelph and Ipperwash Formations, and shale formations include the Kettle Point Formation, Marcellus Formation and some members of the Hamilton Group. The following sections discuss the depositional history (oldest to youngest) of the Paleozoic bedrock underlying southwestern Ontario as well as the geological and hydrogeological characteristics of each formation. Refer to **Figure 13** for spatial distribution of the uppermost bedrock formation (mapping conducted by the Ministry of Northern Development and Mines, scale of 1:1,000,000).

Salina Formation

The oldest Paleozoic bedrock subcropping beneath the study area is the Salina Formation. This formation consists of approximately 120 to 200 m of interbedded shale, mudstone, dolostone, and evaporates (including gypsum and salt), and reaches a total thickness of over 500 m near the southern extents of Lake Huron (Jackson et al. 1992). The Formation is subdivided into eight members designated by the letters A1, A2, B, C, D, E, F, and G (Hewitt 1972). Units A1, A2, B and D are mainly evaporite deposits of salt and anhydrite, and are well developed in the subsurface in many areas of southwestern Ontario (Hewitt 1972). Within the study area, the Salina subcrops in the far eastern reaches of the study area east of Listowel and Woodstock (Jackson et al., 1992). Several companies extract salt from this Formation with deep brine wells at Windsor, Sarnia and Goderich (Hewitt 1972).

Groundwater associated with the Salina Formation is generally of poor quality as the evaporite deposits (anhydrite, gypsum and salt) often encounter undesirable sulphurous qualities including sulphate and/or hydrogen sulphide gas. This formation is used primarily for irrigation, and due to the sulphurous qualities is seldom used for domestic water supply.

Bass Islands Formation

Subcropping west of the Salina Formation is the younger Upper Silurian aged Bass Islands Formation. It forms a narrow (1-3km wide) band of oolitic brown dolostone (with minor thin beds of shaley dolostone) along the eastern edges of study area. The unit is approximately 30 m thick and it thickens to the northwest (Hewitt 1972; Karrow 1993).

Bois Blanc Formation

Stratigraphically above the Bass Island Formation is the Devonian aged Bois Blanc Formation. This formation consists of cherty brownish grey, fossiliferous limestone and is estimated to be 45 m thick, and 10-13 km wide extending from Woodstock, Milverton, and Listowel, to Port Elgin on the shores of Lake Huron (Hewitt 1972; Karrow 1993).

The Devonian aged Bois Blanc Formation and the underlying Silurian aged Bass Islands are separated by a disconformity (Hewitt 1972; Jackson et al. 1992). This feature may be significant from a hydrogeologic perspective as the upper surface of the Bois Blanc is interpreted to be weathered, highly fractured and therefore, able to transmit greater volumes of water than the more competent rock at depth.

Detroit River Group

A large portion of the study area is directly underlain by the Detroit River Group, a 60 to 90 m thick unit that stratigraphically overlies the Bois Blanc Formation and extends through Stratford, and Wingham, to Kincardine on Lake Huron (Hewitt 1972). This Middle Devonian aged unit consists of the Sylvanian Formation, an orthoquartzitic sandstone restricted to the subsurface in the Windsor area, the Lucas Formation, a microcrystalline limestone, and the Amherstburg Formation, a crinoidal limestone and dolostone (Karrow 1993).

The Lucas Formation is known to be a good water bearing aquifer (Bobba 1993) and the several communities in the study area, including those in Perth County, extract water from the Lucas and the Amherstburg bedrock aquifers for their municipal and domestic groundwater needs (WHI 2001). A concurrent study being conducted by the Ausable Bayfield Conservation Authority is investigation the distribution of sinkholes and kastic conditions in the Lucas Formation (Abbey et. Al. 2004).

Dundee Formation

The next youngest bedrock to subcrop beneath the study area is the Dundee Formation, a grey to brown fossiliferous limestone that lies stratigraphically above the Detroit River Group. This formation is the subcrop strata across much of the area between Lake Erie and Lake Huron, and on average is 35 to 45 m thick (Johnson et al. 1992). The Dundee outcrops along the Lake Huron shoreline between Grand Bend and Goderich (Hewitt 1972), in areas along the Thames River, Ausable River (Karrow 1977), and near the town of Wheatley in Essex County (Kelly 1995).

The Lucas and Dundee Formations are believed to be karstic in areas of western Perth County (near Staffa), eastern Huron County (near Hensall). Karstic conditions in the Dundee Formation have also been noted in Norfolk County near Port Dover. In Huron-Perth, bedrock water levels decrease dramatically from east to west at the subcrop boundary between the Dundee Formation (west) and the underlying Lucas Formation (east).

As noted above, an investigation into the karstic properties of the Dundee and Lucas Formations, including the examination of sinkholes in parts of West Perth, and East Huron Counties, is currently underway, by members of the Ausable Bayfield Conservation Authority (Abbey et al. 2004).

Marcellus Formation

Shales of the Marcellus Formation make up the next youngest formation within the study area. This formation is localized in the southern portions of the study area on the north shores of Lake Erie where it overlies the Dundee Formation. The Marcellus Formation has been described as black, organic-rich shale, and this unit marks a sharp change in the bedrock from older carbonate-dominated bedrock below to shale-dominated strata above (Kelly 1995).

Hamilton Group

Overlying the Dundee Formation are the interbedded mudstones, shales and thin carbonate horizons of the Hamilton Group. The Hamilton Group outcrops in Middlesex, Elgin, Lambton, Kent and Essex Counties (Hewitt 1972). It is made up of the following Formations from oldest to youngest: Bell, Rockport Quarry, Arkona, Hungry Hollow, Widder and Ipperwash (Kelly 1995).

The Bell Formation consists of blue and grey shale beds with minor limestone lenses. This formation is overlain by the Rockport Quarry Formation, which is described as a grey and brown fine-grained limestone with occasional thin shaley beds, and an estimated total thickness of approximately 6 m (Kelly 1995). The Arkona Formation is a blue-grey shale unit with minor thin discontinuous limestone beds, and thicknesses of up to 37 m have been recorded (Kelly 1995). Overlying the Arkona is the thin (2 m) Hungry Hollow Formation, which consists of interbedded grey shale and fossiliferous limestone.

The Widder Formation lies stratigraphically above the Arkona and Hungry Hollow Formations, and it is described as interbedded shale and fossil rich limestone with thicknesses of up to 14 m. The Ipperwash Formation is the uppermost formation in the Hamilton Group, and it consists of coarse-grained, grey-brown bioclastic limestone (Kelly 1995). The shales of the Hamilton Group subcrop between Lake Erie and Lake St. Clair in Essex and Lambton Counties, with a total thickness of 90 m (Bobba 1993).

The Hamilton Group forms the Ipperwash Escarpment that extends from Port Franks (south of the Pinery on Lake Huron) southeast towards Strathroy. This bedrock escarpment is named after the Ipperwash Formation, which forms the caprock of the feature (Cooper 1979). The western side of the Escarpment rises approximately 30 to 60 m above the bedrock to the east, which has been interpreted to be part of a buried bedrock valley drainage network (see Section 2.1.3 for more details) extending from Lake Huron to Lake Erie.

Kettle Point Formation

A major unconformity separates the underlying Hamilton Group from the Kettle Point Formation above. The Kettle Point Formation is a black, organic-rich (up to 15% by weight organic carbon), siliciclastic, non-calcareous shale with minor beds of silty shale (Coniglio and Cameron 1990). This formation is part of a widespread black shale sequence that extended through much of the eastern United States and parts of central Canada during the Upper Devonian and Early Mississippian. The Kettle Point Formation is unique as it contains large (up to 1.2 m) spherical or subspherical calcite concretions locally referred to as 'kettles' (Kelly, 1995; Coniglio and Cameron, 1990). This formation outcrops mainly in Lambton and Kent Counties in southern Ontario (Hewitt 1972), and ranges from 30 m thick southwest of Chatham, to over 300 m beneath Lake Erie (OGS 1991).

Port Lambton Group

The Port Lambton Group, a group of clastic rocks consisting mainly of grey and black shales and sandstones, unconformably overlie the Kettle Point Formation. It has a thickness of up to 60 m and within southern Ontario, the Port Lambton Group strata are restricted to the subsurface in a small area south of Sarnia along the St. Clair River (Hewitt 1972).

2.1.2.1 Summary of Bedrock Geology

The bedrock units in the study area consist of Paleozoic sedimentary rocks, composed of limestone, dolostone, sandstone and shale that overlie the Precambrian basement. The bedrock units, in the western and central portion of the study area, exhibit a regional dip of 0.2% to the southwest, as is observed across the eastern Michigan Basin and bedrock units in the eastern portion of the study area near Lake Erie exhibit a regional dip of 0.5% to the south, as is observed across the Appalachian Basin (Johnson et al. 1992).

Table 1: Bedrock Geology Underlying the Study Area

Formation		Geology	Subcrop Location	Thickness
Port Lambton		Grey/black shales and sandstone	Near Sarnia along St. Clair River	Up to 60 m
Kettle Point		Black, organic-rich, shale with minor beds of silty shale	Lambton and Kent Counties	30 m at Chatham (>300 under L. Erie)
Hamilton Group	Ipperwash	Coarse-grained, grey brown bioclastic limestone	South of Chatham to the Lake Erie shoreline	Maximum of 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 Gp.	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 (Lake Huron)	45 m
Bass Islands		Oolitic dolostone with minor thin beds of shaley dolostone	Eastern portion of study area	30 m; thickens to southwest
Salina		Interbedded shale, mudstone, dolostone, and evaporates (including gypsum and salt),	East of Listowel and Woodstock	Avg- 120- 200 m >500 m at Lake Huron

Figure 13 presents the bedrock geology for the study area, which shows the uppermost bedrock unit across the study area. **Table 1** summarizes the uppermost bedrock geology of the study area and outlines the approximate thickness of the bedrock units that will be used in the conceptual geological model.

2.1.3 Bedrock Topography

Bedrock topography of southern Ontario loosely follows surface topography. The highest elevations in the study area (440 m asl) are found near the towns of Palmerston and Harriston, in Perth and Wellington Counties. This area lies on the crest of the broad Algonquin Arch, the Precambrian structural feature discussed above (Karrow 1973). The lowest bedrock surface elevations in the study area (110-130 m asl) correlate with the shorelines of Lake Huron, Lake St. Clair and Lake Erie. Slightly depressed bedrock topography also exists in the Chatham area. This broad low-lying area (140 m asl) between Lake St. Clair and Lake Erie lies between the crests of the Findlay Arch and the Algonquin Arch and is commonly referred to as the 'Chatham Sag' (Johnson et al. 1992). Bedrock topography is presented in **Figure 14**.

Erosional Bedrock Features and Valleys

Fluvial erosion played a major role in sculpting the bedrock topography of southern Ontario. The Grand, Thames and Ausable Rivers are sizeable river courses within the study area that transport large volumes of water to the Great Lakes. Analogous rivers existed millions of years ago when the bedrock was exposed, and similar to our modern day river valleys, these paleochannels formed persistent topographic lows into which surficial drainage was focussed over long periods of time (Karrow 1973; Eyles et al. 1997).

Three major valleys are understood to have been carved into the bedrock surface of southern Ontario; a channel that linked Georgian Bay to Lake Ontario near Toronto, a second channel that formed the Dundas Valley re-entrant at the western end of Lake Ontario, and a third channel, near St. Catherines, that connected Lake Ontario and Lake Erie (Eyles 1997). None of these major bedrock valleys underlie the study area; however a few smaller scale bedrock valleys are believed to exist beneath the study area.

The first example is the broad low-lying bedrock depression observed between Grand Bend (Lake Huron) and Port Stanley (Lake Erie) (**Figure 14**). This depression was interpreted to represent ancestral drainage between the two great lakes (Spencer 1881; Karrow 1973). Glaciation likely broadened a fluvial drainage feature, leading to a broad (approximately 10 km wide) bedrock depression. This feature was mapped on a local scale in the London region to extend beneath the towns of Strathroy, Parkhill and Mount Bridges (Dillon 2004). The western extent of this valley is marked by the Ipperwash Escarpment, which rises 30 to 60 m above the bedrock valley (Cooper 1979). This feature is labelled "A" on **Figure 14**.

West of Chatham, a local scale bedrock valley has been interpreted to exist. The valley is carved approximately 15 m into bedrock and is interpreted to represent ancestral drainage between Lake St. Clair and Lake Erie (Karrow 1973; Kelly 1995). This valley is difficult to identify on **Figure 14** due to the contour interval utilized in the regional mapping.

A regionally extensive buried bedrock valley is also interpreted to lie along the north-central reaches of Perth County. Some researchers have suggested that the valley, which extends in the study area beneath Milverton in Perth County to Wingham in Bruce County, is a continuation of the Dundas valley re-entrant at the western end of Lake Ontario (Karrow 1973). Previous studies examining the regional hydrogeology of Perth County found that the valley was infilled with fine-grained tills and sediments, and is unlikely to cause a noticeable impact the regional groundwater flow across the valley. This feature is labelled "B" on **Figure 14**.

Bedrock Depth (Overburden Thickness)

The depth to bedrock throughout the study area was determined by subtracting the bedrock topography grid from the surface topography grid. As shown in **Figure 15**, bedrock depth (or overburden thickness) varies widely throughout the study area. Bedrock depths are greatest along the axis of moraines and within bedrock valleys described above.

2.1.4 Quaternary Geology of Southwestern Ontario

A major unconformity separates Paleozoic rocks from overlying Quaternary deposits across southern Ontario. This unconformity represents a 300 million year period of non-deposition (Paleozoic to Quaternary period) where the Paleozoic bedrock surface was exposed and eroded (Johnson et al. 1992). Exposure to the elements (wind, rain, etc), repeated glacial advances, and other forms of weathering (freeze-thaw action, biological, etc) likely caused intense fracturing of the upper portions of the bedrock surface prior to deposition of glacial sediments. This weathering and fracturing is expected to have greatly increased the transmissivity of the uppermost bedrock formations.

The physiography of southern Ontario was altered considerably by the glacial and interglacial episodes that took place throughout the Quaternary (2 million years to present). Southern Ontario's glacial history is very complex and has been interpreted and discussed by many (Barnett 1992; Karrow 1967; Chapman and Putnam 1984; Dreimanis and Goldthwait 1973; etc). The sedimentary record of southern Ontario provides evidence for three distinct climatic stages during the Quaternary: the Illinoian glacial stage (130-180,000 years before present (y.b.p), Sangamonian interglacial stage (110-130,000 y.b.p.) and the Wisconsinan glacial stage (110-10,000 y.b.p; Johnson et al, 1997). The record of the Illinoian and the Sangamonian are limited to very few exposures near Toronto, and as such they will not be discussed further within this report. Wisconsinan glacial deposits are the dominant surficial material in the study area, and will be discussed in detail below.

During the Wisconsinan glacial period (115,000 to 7,000 y.b.p.; **Table 2**), a continental scale glacier, termed the Laurentide Ice Sheet, advanced and retreated over Ontario, and extended southward into Ohio and Indiana in the United States (Dreimanis and Goldthwait, 1973). The ice front advanced in cold periods (glacial stades), and retreated when the climate temporarily warmed (glacial interstades) leaving behind a complex subsurface sedimentological record. As the ice sheet advanced over southern Ontario, it scoured the bedrock surface and reworked the vast majority of pre-existing glacial and interglacial sediments. This essentially erased over 250,000 years of climatic history (period of time between the deposition of the Paleozoic rocks (350,000 y.b.p.) and the deposition of pre-Wisconsinan overburden (115,000 y.b.p.).

Sediments that were preserved prior to the last advance, during the Late Wisconsinan, are rare and found only in topographic lows on the bedrock surface, such as buried bedrock valleys and lake basins (Eyles et al., 1985). In Ontario, the glacial events of the Late Wisconsinan and their resulting deposits are by far the most common and extensive, and therefore the best understood. Till sheets are the most continuous and extensive sediments deposited within the study area and they offer the most detailed information when reconstructing the glacial history of an area. In general, subglacial till sheets (commonly aquitards) are laterally extensive across regional areas, whereas fluvial sands, or kame deposits (aquifers) for example, are often much smaller scale deposits. For these reasons, the Late Wisconsinan sediments (notably the widespread till sheets) found within the study area will be discussed in detail below. (Note: the Wisconsinan is commonly subdivided into the Early, Middle and Late substages, see **Table 2**).

Table 2 Quaternary Deposits Located Within the Study Area

Age (y.b.p)*	Glacial Stage	Substage	Glacial Stade/ Interstade	Associated Deposits
5000-11,500	Wisconsinan	Late Wisconsinan	Holocene/ Recent	Modern alluvium, organic deposits, Glacial Lake Algonquin shoreline deposits, Lake Nippissing deposits
11,500-12,000			Twocreekean Interstade	Shoreline Formation, Glaciolacustrine Deposits
12,000-13,200			Port Huron Stade	St. Joseph's Till, Lake Warren and Lake Whittlesey shoreline deposits

Age (y.b.p)*	Glacial Stage	Substage	Glacial Stade/ Interstade	Associated Deposits
13,200-14,000			Mackinaw Interstade	Lake Arkona Shoreline deposits, Paris/ Galt Moraines
14,000-15,500			Port Bruce Stade	Elma, Mornington, Tavistock, Stratford, Port Stanley, Wartburg, and Rannoch Tills, Glaciolacustrine Deposits
15,500-18,000			Erie Interstade	Wildwood Silts, Glaciolacustrine Deposits
18,000-25,000			Nissouri Stade	Catfish Creek Till
25,000-53,000		**Middle Wisconsinan**		Unnamed/ undifferentiated silty tills, (Huron-Georgian Bay lobe)
53,000-80,000		**Early Wisconsinan**		Canning Till (Erie-Ontario lobe)

* y.b.p. represents number of years before present

The flow of the ice through southern Ontario was largely controlled by the broad topographic depressions of the Great Lakes basins (Barnett 1992). Ice lobes extending out of the main body of the ice sheet developed in these basins and at times acted independently to one another in response to local conditions at the base of the glacier, rather than, or in addition to, climatic change. The individual lobes bear the name of the lake basin(s) in which they are located.

Surficial geology for the study area was obtained from the Ontario Geological Survey and is presented in **Figure 16**. The following sections describe the different Quaternary deposits located within the study area.

2.1.5 Early to Middle Wisconsinan

As mentioned above, there is little sediment preserved within the study area that is older than the Catfish Creek Till (see below). These unnamed and undifferentiated tills are found locally in small outcrops along creek and river channels and at the base of borehole logs scattered throughout the study area. Modern day river channels and paleochannels made good repositories for pre-Wisconsinan sediments as those channels oriented perpendicular to the ice flow direction were shielded from the scouring action of the overpassing glacier.

The Canning Till is the only till deposited during the Early or Middle Wisconsinan found in the study area that has been assigned a formal name and description. The Canning Till was deposited subglacially beneath the Erie-Ontario ice lobe during the Early Wisconsinan glacial stage (estimated as 80,000 to 53,000 years ago; Cowan 1975). The till has been described as a fine-grained till lying stratigraphically below the

Catfish Creek Till (see below) in the Woodstock area and areas to the east. The till is generally dark grayish brown, stiff, with clay to silt rich matrix, and contains approximately 5% clasts (Cowan 1975).

Samples from borehole logs suggest that this till is a remnant ground moraine that ranges in thickness from 0.5 to 6 m. There are no estimates of total thickness due to its limited exposure. The Canning Till has very similar characteristics to the Catfish Creek Till (discussed below), making it difficult to distinguish between the two in borehole logs.

2.1.6 Late Wisconsinan Glacial Stage

The Late Wisconsinan lasted from 23,000 years ago to 10,000 years ago (Dreimanis and Goldthwait 1973). This period is divided into several different stades and interstades, and it was during this period that the Laurentide Ice Sheet reached its most southerly extent, advancing through Ontario extending into the United States. It was also during the Wisconsinan that the Laurentide thinned and formed a series of sublobes, each moving independently of one another at different rates, and in different directions. Each of these sublobes deposited a series of distinct subglacial tills and associated landforms within the study area (see discussion below). The discussion of Quaternary deposits found within the study area progresses chronologically from oldest to youngest, with a summary timeline including the glacial substages, stades/ interstades and deposits illustrated in **Table 2**.

The Nissouri Stade

The Nissouri Stade (25,000 to 18,000 years ago) represents the initial stage of ice advance of the Laurentide Ice Sheet during the Late Wisconsinan (Barnett 1992). It was during this time period that the Laurentide Ice Sheet last moved as one thick cohesive ice sheet, depositing the most extensive subglacial till sheet in southern Ontario; the Catfish Creek Till (deVries and Dreimanis 1960; Karrow 1977; Barnett 1992).

The Catfish Creek Till has been mapped in areas across southern Ontario including Port Talbot (Dreimanis, 1958), St. Thomas (Dreimanis 1964), Guelph (Karrow 1968), Brantford (Cowan 1972), London (Fenton and Dreimanis 1976), St. Marys (Karrow 1977), Tillsonburg (Barnett 1982), and Waterloo (Karrow 1988). The till is composed of stacked layers of subglacial lodgement till as well as stratified glaciofluvial and glaciolacustrine sediments and supraglacial till layers and lenses (Dreimanis 1982; Barnett 1992). The till overlies bedrock throughout the study area and outcrops in small areas near the town of Woodstock. It has been described as very compact, poorly sorted, highly calcareous with a sandy silt to silt matrix, and it is often described as hardpan in water well drillers' records because of its stoniness and stiffness (Barnett

1992). The thickness of the Catfish Creek Till is generally less than 6 m; however it reaches up to 12 m thick in some areas (Cowan 1975). This till would likely have a high acoustic impedance signal compared to many of the other tills discussed below.

At the end of the Nissouri Stade, the Laurentide Ice Sheet began to thin, break up and form three distinct sublobes; the Huron, Ontario-Erie and the Simcoe. It was during this time that the Easthope, Waterloo, Orangeville and Dorchester interlobate moraines were formed. The Waterloo and Orangeville Moraines lie outside the study area to the east, and north respectively, however the Easthope (Perth County near Shakespeare) and Dorchester (near London) Moraines lie within the study area.

Erie Interstade

The Erie Interstade was estimated to take place between 16,500 and 15,500 years ago. It was during this period that the ice margin of the Erie-Ontario lobe of the Laurentide Ice Sheet retreated eastward to the Niagara Escarpment, while the Huron lobe margin retreated northward to the Goderich and Port Elgin areas (Dreimanis and Goldthwait 1973; OGS 1983b). A series of large ice contact lakes are believed to have formed in front of these receding ice margins at the southern ends of Lakes Michigan, Erie and Huron depositing fine-grained silts and clays (Barnett 1992; Kelly 1995). Although subsequent ice advances may have removed a substantial portion of the Erie Interstadial sediment record, the fine-grained nature of the overlying tills suggests the ice lobes were overpassing and reworking previously deposited glaciolacustrine muds.

South of Stratford near the town of St. Mary's lies thick (several metres) deposits of stratified silt termed the "Wildwood Silts" (Sigleo and Karrow 1977). These silts were overlain by sand and minor gravel, and are inferred to overlie the Catfish Creek Till, and underlie the Tavistock Till (see below). The silts were interpreted to have formed in a deep but localized lake, and overlying sands are interpreted to represent lacustrine or deltaic sands (Karrow 1977). Analysis completed on pollen and spores found within the silts support the hypothesis that these sediments were laid down during an interstadial (warm, ice-free) period (Karrow 1977; Barnett 1992).

In the Woodstock area of the study area, there is considerable evidence to suggest there were several localized water bodies that led to the deposition of fine-grained glaciolacustrine sediments during the Erie Interstade. Near Plum Point, silts and clays are found sandwiched between the Catfish Creek Till and the overlying Port Stanley Till (discussed below). The elevation of these sediments suggests that glacial lakes inundated much of the Woodstock area during the Erie Interstade (Cowan 1975).

Port Bruce Stade

The Port Bruce Stade (approximately 14,800 years ago) records the second advance of the Laurentide Ice Sheet into the United States during the Late Wisconsin. The Great Lakes basins controlled the direction of flow of the individual sublobes, with glacial flow occurring radially outward from the centre of each lake basin (Barnett 1992).

Various silt and clay rich subglacial tills were deposited during this Stade each bearing the name of their type location and/or distribution such as the Port Stanley Till, the Stratford Till and the Tavistock Till. The grain size of the matrix of the subglacial tills, as well as their clast composition, is largely dependent on the substrate over which the ice passed, whether they be pre-existing glacial sediments, bedrock, or glacial lakes. The majority of the tills deposited during the Port Bruce Stade are fine-grained suggesting the ice overrode and incorporated extensive fine-grained glaciolacustrine sediments deposited throughout the area during the Erie Interstade.

In the early stages of the Port Bruce Stade, the southward advancing ice sheet blocked the drainage of the Lake Huron and Lake Erie basins, leading to the formation of a glacial lake (Lake Leverett) over much of the southern portion of the study area. The Essex Chatham-Kent area was inundated with water leading to the deposition of clay-rich massive (structureless) to faintly laminated glaciolacustrine sediments. As the climate continued to cool, the Huron-Georgian Bay ice lobe overrode the study area southward into Ohio depositing the Tavistock Till (see below) through much of the study area. Some time later during the same stade event, ice flow in the Ontario-Erie ice lobe increased and ice flow in the Huron lobe began to diminish. This led to the advance of the Erie-Ontario ice lobe westward depositing the clayey-silt rich Port Stanley Till (see below). The Erie-Ontario ice sheet was interpreted to override the Huron lobe till south of Blenheim and Wheatley in the southern portion of the study area.

Port Stanley Till

Advance of the Ontario-Erie ice lobe deposited the Port Stanley Till. The extent of the till is poorly understood, however it is believed to extend from Brantford in the east, Lake Erie in the south to areas west of Woodstock, likely terminating at the Ingersoll Moraine near Embro (Cowan 1975; OGS 1982a). Along the north shore of Lake Erie, the till complex consists of up to 5 layers of subglacial till separated by glaciolacustrine sediments. Further inland, it consists of only one layer of Port Stanley Till with associated glaciofluvial sediments. The properties of the till vary spatially across the study area. The northern reaches of the till are strongly calcareous, with a silty to sandy silt till with a clast content ranging from 10 to 30%. The southern reaches of the till complex are described as having a clayey silt to silty clay till with a clast content less than 2% (Barnett 1992). The Port Stanley Till forms rolling till plains and hummocky moraines, and has a maximum observed thickness of 30 m, but is usually 1 to 6 m thick (Cowan 1975).

In the London area, the Ingersoll and Dorchester Moraines may act as shallow overburden aquifers for domestic water supply. Stratigraphy through the Ingersoll moraine was recorded to consist of Catfish Creek Till overlain by ice contact sand and gravel, and up to 30 m of Port Stanley and Tavistock Tills (OGS 1982a). Similarly, the buried Dorchester Moraine consists of interbeds of tills and coarse grained sands and gravels (OGS 1982a).

The Huron- Georgian Bay ice lobe deposited the vast majority of the surficial till sheets found within the study area. Each of these tills was deposited subglacially during the Port Bruce Stade and each represents a readvance of the ice through the area. The following tills are associated with the advance of the Huron- Georgian Bay ice lobe.

Tavistock Till

The Tavistock Till is a highly varied till sheet that lies on surface along much of the eastern portion of the study area. In the London and Woodstock areas, the Tavistock Till sheet is highly calcareous, silt to sandy silt to sand till with a clast content ranging between 5 and 10%. Further north (north of the Waterloo Moraine) the matrix of the till is finer grained (silty clay to silt till) as the ice overrode localized glaciolacustrine (Erie Interstade) sediments. In the London area however, the till is much coarser grained as the ice overrode and incorporated the stony Catfish Creek Till, and coarse-grained glaciofluvial sediments (Barnett 1992). The till in this area is also noted to be interbedded with glaciolacustrine sediments laid down during successive melting of the ice lobe (OGS 1983a).

The Zorra Till of Cowan (1975) is interpreted to be analogous to the Tavistock Till described in adjacent map areas by Karrow (1993), and Barnett (1982 and 1992). Landforms associated with the Tavistock Till include the Cherry Grove and Arva Moraines (OGS 1983a).

Mornington Till

The Mornington Till is similar to the Tavistock Till described above except the Tavistock Till has more clasts. The Mornington Till is a thin (<5 m), clast poor, silty clay till incorporated into the till from pre-existing glaciolacustrine silts, clays and tills (Barnett 1992). The Mornington Till is the surface till north of Stratford between the Milverton Moraine and the Conestogo River and this till is believed to form the core of the hummocky Macton Moraine (Karrow 1993; Barnett 1992). This till is interpreted to have been deposited subglacially as the ice sheet flowed from northwest to southeast through the study area. The Mornington Till is overlain by the Stratford Till in the southwest, and by the Elma Till in the northeast (Karrow 1993).

Stratford Till

The Stratford Till is named after the city of Stratford, where this till lies on the surface overlying the Tavistock Till. The Stratford Till is described as a stony, strongly calcareous, sandy silt to silt till with 5 to 10% clast content. The Stratford Till occurs as a thin sheet ranging in thickness from 1-3 m, and is commonly overlain by glaciolacustrine silts and clays (Barnett 1992). The Stratford Till is similar in texture to the Catfish Creek Till, however the matrix of the Stratford Till is finer-grained, and there are fewer clasts than the Catfish Creek Till. The till extends to the Thames River in the west, and east to the Easthope Moraine (near the town of Shakespeare). The Stratford Till is overlain by the Wartburg Till (Milverton Moraine) northwest of Stratford, and by the Rannoch Till (Mitchell Moraine) southwest of Stratford (Karrow 1993).

Wartburg Till

The Wartburg Till is a silty clay till with few clasts (<1%) (Karrow 1993). It ranges in thickness from 2 to 10 m and is largely enigmatic as its exposure is isolated to only a few areas in Perth County (west of Stratford). It forms the bulk of the Milverton Moraine between Fullarton to Brunner, but is inferred to lie largely buried beneath the younger Elma Till. Similar to the Mornington and Stratford Tills, the Mornington Till is interpreted to have formed when the Huron- Georgian Bay ice margin re-advanced briefly over the local area.

Elma Till (Georgian Bay lobe)

The Elma Till is a deposit of the Georgian Bay ice lobe and it has been mapped northeast through Stratford, Conestogo, and Palmerston (Cowan 1973). This till is silt to sandy silt to clayey silt till with a clast content that ranges from 5 to 25%. The till was deposited in the latter stages of the Port Bruce Stade (and possibly into the Mackinaw Interstade), and it ranges in thickness between 2 and 15 m. The Elma Till lies on surface in the northern portions of Perth County.

Rannoch Till (Huron Lobe)

The Rannoch Till was deposited subglacially beneath the Huron ice lobe, and is described as a strongly calcareous, silt to silty clay till with a low clast content (<2%) near Mitchell (Karrow 1977), but it is much more gritty or stony in areas further west (Cooper 1979). The name is taken from a small village along the Mitchell Moraine, west of St. Marys within Perth County. The Rannoch Till occurs as a surface till sheet across much of the area west of the Mitchell Moraine to the Wyoming Moraine and also is associated with several end moraines including the Mitchell, Dublin, Lucan, and Seaforth Moraines. The till has not been identified beneath the St. Joseph's till at any point west of the Wyoming Moraine, leading one to infer that the glacier reworked the Rannoch Till in forming the St. Joseph's Till. Cumming and Al-Aasm (1999) identified the Rannoch Till as a buried till on Walpole Island at the mouth of the St. Clair River, however it is possible that authors (Cumming and Al-Aasm 1999) interpreted a lower till (Catfish Creek Till?) at this site to be the Rannoch Till. The thickness of the Rannoch Till was mapped up to 70 m; however it averages between 2 and 6 m.

During the ice-marginal recession of the Erie-Ontario lobe into the Lake Erie and Ontario basins, a series of end moraines were formed (or extended) including the Ingersoll, Westminster, St. Thomas, Courtland, Norwich, Tillsonburg, Orangeville, and Blenheim moraines (Karrow 1987; Barnett 1992). These moraines mark standstills or minor re-advances of the ice margin.

As the ice lobes began to retreat out of southern Ontario, meltwater began to pond at the western end of Lake Erie, and the southern end of Lake Huron forming a large lake termed Lake Maumee. It was during this time that the Komoka Delta at London was formed as a meltwater stream (present day Thames River) emptied into Lake Maumee depositing silts, sands and gravels (Barnett 1992). Shoreline deposits of glacial Lake Maumee have also been mapped between London and Delhi (Barnett 1992), and numerous other smaller scale short-lived glaciolacustrine ponds existed throughout much of the study area (OGS, 1983; Barnett 1992).

Mackinaw Interstade

The Mackinaw Interstade took place from approximately 13,500 to 14,000 years ago and the onset of this interstade was characterized by the rapid retreat of ice out of southern Ontario. The Ontario-Erie lobe retreated into the Ontario basin east of Toronto and the Huron lobe retreated into northern Michigan (Dreimanis and Goldthwait 1973). During this ice-free time, thin glaciofluvial outwash deposits were laid down across much of the study area as sediment-laden meltwater streams discharging from the front of the melting glacier led to the deposition of pebbly sands and gravels (OGS 1983, 1989, 1991). As ice continued to retreat from the study area, a large lake formed over the southern margins of both Lake Huron and Lake Erie (termed Lake Maumee then Lake Arkona; Barnett 1992). Deep water sediments consisting of silts and clays were deposited at the base of this deep lake in the Essex County area (OGS 1989). In the shallower portions of the lake and on the lake margins, fine grained sand was deposited, especially near Leamington (OGS 1989). Sands associated with the glaciofluvial outwash, and with the glaciolacustrine shoreline deposits may be thick and transmissive enough to act as productive domestic groundwater aquifers.

Throughout Oxford and Middlesex Counties, the surficial till was incised by sediment-laden meltwater channels which deposited thick sequences of well sorted sand and gravel outwash (OGS 1983a). The North Thames, Thames, and Medway Rivers are all former meltwater channels deposited in this manner (OGS 1983a, 1983c). An older meltwater channel the flanks the eastern side of the Seaforth Moraine, and it was covered with thick layers of lacustrine silts making this feature a potentially productive groundwater aquifer (OGS 1983a). The City of London also lies on a sandy delta formed as a meltwater channel emptied into a glacial lake (OGS 1983a).

As the Erie-Ontario ice lobe retreated northeastward, the drainage outlet for the Lake Ontario basin returned to the east (Rome, NY), and the outlet for Lake Huron became ice free; this created progressively lower lake levels in the Lake Erie, and Lake Huron basins (Barnett 1992; Dreimanis and Goldthwait 1973).

Port Huron Stade

The Port Huron Stade took place from approximately 13,500 to 13,000 years ago, when three distinct lobes of the Laurentide Ice Sheet advanced for the last time over southern Ontario. The Halton and Wentworth Tills were deposited beneath the Ontario-Erie lobe, the Kettleby Till beneath the Simcoe lobe, and in our study area, the St. Joseph's Till was deposited beneath the Huron-Georgian Bay ice lobe.

The St. Joseph's Till is strongly calcareous silt to silty clay till with low clast content (1-2%; Barnett 1992). This till incorporated pre-existing fine-grained glaciolacustrine silts and clays deposited during the Mackinaw Interstade, and the Port Bruce Stade to give this till its fine texture. The extent of the St. Joseph's till plain is marked by the Wyoming Moraine which parallels the modern day Lake Huron shoreline, and it is commonly overlain by outwash sands and gravels and various glaciolacustrine sediments (Barnett 1992).

Glacial Lake Whittlesey is another glacial lake (similar to Lake Maumee and Lake Arkona) that formed over the southern reaches of Lake Huron, and the western reaches of Lake Erie (Barnett 1992). Associated with this glacial lake are several sandy shorelines and associated beach deposits seen on the surface in the western portions of the study area. In addition, extensive braided river systems flowed down the Grand and Thames River valleys and emptied into glacial Lake Whittlesey at Brantford and areas west of London depositing extensive sand plains (Chapman and Putnam 1984). The Bothwell Sand Plain was once the delta formed where the Thames River emptied into Lake Whittlesey (OGS 1991), and similarly, the Norfolk Sand Plain was formed at the mouth of the Grand River. As ice retreated from the Port Huron maximum near the end of the Port Huron Stade, elevated lake levels in the Huron and Erie basins began to fall. In the wake of this ice retreat, Glacial Lake Warren developed in place of Lake Whittlesey and sandy shoreline features associated with this lake were deposited throughout the western portion of the study area (OGS 1989). Shoreline and dune sands, as well as the sand plains may serve as localized aquifers for domestic water supply within the study area, however their shallow nature make these aquifers susceptible to contamination from surface activities.

Thick sequences of fine-grained glaciolacustrine sediments were deposited into the proglacial lakes mentioned above. These sediments exhibit a general coarsening upward trend whereby fine-grained silts and clays are overlain by silts and sands. Some of the largest sand plains (Caradoc, and Bothwell) and clay plains (St. Clair, and Ekfrid), are underlain by glaciolacustrine sediments deposited when lake levels in the Huron and Erie basins fell (Barnett 1992).

Twocreekean Interstade and the Greatlakean Stade

The Twocreekean Interstade represents a period of continued ice retreat out of southern Ontario, which began approximately 12,500 years ago (Barnett 1992). Ice marginal lakes began to drain as the retreating ice uncovered drainage outlets. Separate lakes formed in the Lake Ontario (Lake Iroquois) and Lake Erie (Early Lake Erie) basins, and Lake Huron and Lake Michigan merged to form one large lake; Lake Algonquin. Minor oscillations of the ice front during the Greatlakean Stade led to the deposition of localized tills in northern Ontario, but by this time, the ice front had fully retreated from the study area.

2.1.7 Holocene Deglaciation

The Holocene began approximately 10,000 years ago and at this time, Ontario was still undergoing massive deglaciation throughout much of the north. Lake Superior was still covered with ice, as were the areas now home to the cities of North Bay and Timmins (Barnett 1992). Isostatic depression of the North Bay area allowed the upper Great Lakes to drain through the Ottawa River, resulting in lower water levels in the Great Lakes than those seen today. This isostatic depression in the north also caused subaerial exposure of the St. Clair Clay Plain (Cumming and Al-Aasm 1999). Lake Champlain formed in the St. Lawrence and Ottawa River valleys (Terasmae 1980) until approximately 5,000 years ago when isostatic uplift closed an outlet near North Bay and delta deposits began to form again near Lake St. Clair Island (Cumming and Al-Aasm, 1999). From this point in time to the present day, the lake basins have rebounded and the lake levels returned to those found in the Great Lakes today.

Postglacial and erosional processes during the Holocene continued to shape the landscape within the study area. Point Pelee for example, was formed by the interaction of longshore currents carrying sand from shorelines in the west and east throughout this time period (OGS 1989), and aeolian dunes formed on the surface of the Bothwell sand plain as northwesterly winds have reworked the fine sand (OGS 1991).

2.1.7.1 Summary of Quaternary Geology

The physiographic regions within the study area are primarily the result of the last glaciation (~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, shown on **Figure 16**, and can generally be grouped into the following five general features:

- Low permeability, moderate relief till plains:
    - Stratford Till
    - Rannoch Till
    - St. Joseph’s Till
    - Tavistock Till
    - Elma Till
    - Mornington Till
    - Port Stanley Till
- Higher permeability, moderate relief, coarse-grained (potential kame) moraines;
    - Dorchester Moraine
    - Ingersoll Moraine
    - Easthope Moraine
    - Staffa Moraine
- Low permeability, low relief lacustrine clay plains;
    - Ekfrid Clay Plain
    - St. Clair Clay Plain
- Higher permeability, low relief outwash sand and gravel deposits;

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

- Higher permeability, low relief recent alluvial deposits.

The surficial geology of the study area has been mapped in phases throughout the last 30 years by various geologists (Cowan 1975, 1979; Cooper 1979; Karrow 1977, 1988, 1993; Barnett 1982; Kelly 1995) and more recently these maps have been seamlessly assembled into a cohesive map covering the entire study area (Bajc et al. 2001). This map and its associated GIS metadata will be used to delineate the spatial extent of the above geological features.

2.2 Regional Hydrogeologic Setting

Groundwater occurrence and flow within the study area is primarily controlled by:

- precipitation and evapotranspiration
- topography and enhanced (tile) drainage;
- piezometric levels and soil moisture conditions;
- surficial 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. Recharge is defined as the portion of precipitation that infiltrates into the ground, and is not lost to evapotranspiration, or retained as soil moisture, and is not discharged to rivers and streams as interflow or overland flow. In some areas, rivers and streams may recharge aquifers.

2.2.1 Hydrostratigraphy and Groundwater Flow

When precipitation falls on the ground, a portion of this water moves overland to rivers and creeks as overland flow (or interflow), another portion is returned to the atmosphere by evaporation (or evapotranspiration) and the remainder infiltrates into the ground to become groundwater. We are most concerned with recharge, which is controlled by a number of factors including land use, permeability and porosity of surficial units, as well as topography. Recharge can also be influenced by drainage practices. Areas having artificial drainage (tile drains) are expected to have lower groundwater recharge rates than similar areas without artificial drainage.

Within the study area, there are a number of aquifers and aquitards that vary greatly in spatial extent and thickness. Overburden aquifers in the study area include the coarse-grained sands and gravels of the various sand plains, kame moraines and coarse-grained interstadial sediments that lie between till sheets. These aquifers are classified as either confined aquifers (bounded by two low permeability units) or unconfined (the upper surface is defined by the water table). Within the study area, the majority of the overburden aquifers are unconfined, including the sand plains (Bothwell, Caradoc) and a few of the kame moraines (e.g. Staffa Kame). As bedrock is buried throughout the study area (outcropping in only a few locations) the bedrock aquifers including the limestone and dolostone formations typically form confined aquifers.

Figure 17 presents a generalized groundwater level map for the bedrock units in the study area. The detailed interpretation and characterization of hydrostratigraphic units is presented in Section 2.2.2.

Regionally, groundwater flows from the topographically high areas to the lower elevations where it discharges to rivers, streams and the Great Lakes basins. Smaller scale features of the terrain, such as hummocky topography and moraine ridges can influence local groundwater flow directions.

Coarse-grained overburden deposits (e.g. outwash deposits and kame moraines) and fractured carbonate bedrock formations, particularly karstic environments, are the most transmissive units in the study area. Groundwater flows rapidly through these units making them excellent regional and local aquifers. Fine-grained overburden units such as till plains or clay plains represent local and regional aquitards that impede groundwater flow and recharge to deep aquifers.

As discussed earlier, the majority of the Paleozoic bedrock units within the study area dip regionally to the southwest toward the centre of the Michigan Basin, while the bedrock units in the southeastern portion of the study area (north shore of Lake Erie) dip regionally south toward the centre of the Appalachian Basin.

A major unconformity separates Paleozoic bedrock from the overlying Quaternary sediments, whereby the upper 3 to 5 metres of the bedrock surface is more weathered and fractured, and therefore more transmissive than the underlying competent bedrock units. Regionally, the limestone and dolostone bedrock formations form excellent aquifers, while the shale units act as regional aquitards.

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.

Within the study area, 3 distinct aquifer units were identified during cross-section interpretations:

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.

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.

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.

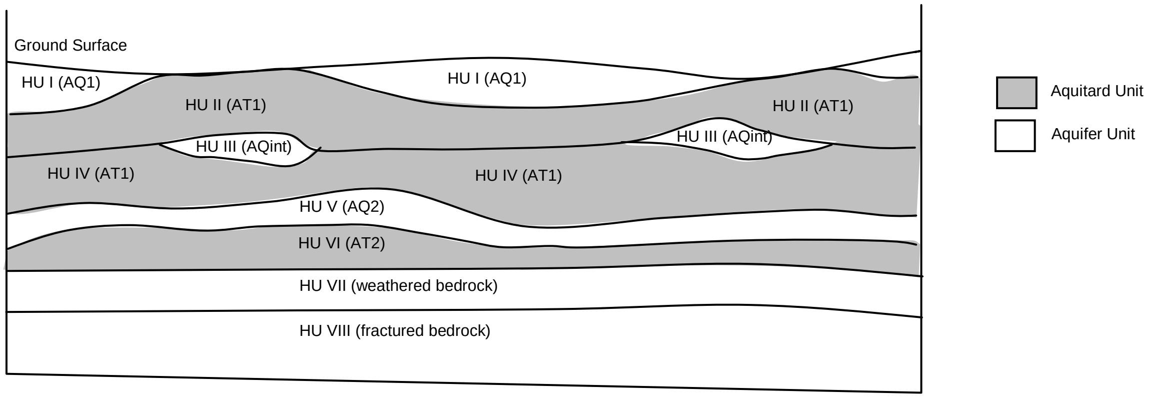
Table 2 below presents a summary of the hydrostratigraphic units in the study area including a description of the type of hydrostratigraphic unit (aquifer / aquitard), a brief description, and the geologic subunits identified within the hydrostratigraphic unit.

Table 2: Hydrostratigraphic units in the study area

Hydrostratigraphic Unit	Hydrostratigraphic Description	Specific Geologic Subunits
HU I - Aquifer	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	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	Intermediate depth interstadial outwash sands and gravels.	Includes intermediate aquifers located in Elgin and Middlesex Counties.

Hydrostratigraphic Unit	Hydrostratigraphic Description	Specific Geologic Subunits
HU IV - Aquitard	Lower fine-grained subglacial till sheets, and lacustrine clays	Tills include: Tavistock and Port Stanley.
HU V - Aquifer	Basal outwash sand and gravel (interstadial complex) overlying Catfish Creek and older tills.	Discontinuous sands and gravels.
HU VI - Aquitard	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.

Mapping of the distribution of each of these hydrostratigraphic units in the study area was undertaken by interpreting stratigraphic picks using over 200 cross-sections. The cross-sections were completed on a 10 km grid spacing throughout the study area and are included on the CD-ROM appended at the back of this report.



Conceptual Hydrostratigraphic Units (HUs)

Surface elevations and isopach maps were interpolated for each of the hydrostratigraphic units using ArcGIS. **Figure 12** shows a three-dimensional view of the conceptual geological model for the study area. **Figure 18** to **Figure 22** present isopach maps for the Quaternary hydrostratigraphic units I through VI. Due to the limited extent of HU III; the isopach map for HU II, HU III and HU IV are combined in **Figure 19**. The isopach map for HUIII is included in **Figure 20**.

Hydrostratigraphic Unit I (HU I), Aquifer 1 (AQ1)

As described above, HU I includes coarse-grained glaciofluvial/ glaciolacustrine/ ice-contact sands and gravels such as portions of the Bothwell, Caradoc, Norfolk and Leamington Sand Plains as well as Easthope, and Staffa Kame Moraines. **Figure 18** shows the distribution of HU I. The thickness of this hydrostatigraphic unit varies from 0 to 50 m throughout the study area. Thicker areas of HU I are identified near London, Grand Bend, Bayfield, Goderich, and near the Lake Erie shore in Essex County. All of the sand plains identified in the surficial geology were identified (HU I) on the isopach mapping.

Hydrostratigraphic Units II, III, and IV (HU II to IV), Aquitard 1 (AT1) and Intermediate Aquifer (AQint)

As noted above, HUs II, III, and IV were combined for the isopach map presented in **Figure 19**. Where the intermediate aquifer (HU III) is not present, it was very difficult to differentiate between the geologic sub-units in HU II (Rannoch, Stratford, Wartburg, St. Joseph's, and Elma Till; and the Ekfrid and St. Clair Clay Plains) and the geologic sub-units in HU IV (Tavistock and Port Stanley Tills). The geological descriptions provided on drilling logs generally do not provide enough detail to differentiate between these two fine-grained units. The thickness of the intermediate aquifer (HU III) is discussed below.

The package of HU II, III, and IV is extensive across the study area, ranging in thickness from 1 m to nearly 100 m. This package is interpreted to be thickest near Strathroy, London, St. Thomas, and along the Lake Erie shoreline west of St. Thomas. The bedrock valley interpreted to exist between Grand Bend, Strathroy, and St. Thomas is also interpreted to cause the increased thickness of this overburden package.

In many portions of the study area, HU II and HU IV are in direct contact. Where this occurs, the isopach map presented in **Figure 19** represents the thickness of aquitard material between the upper aquifer HU I, and the lower aquifer HU V. Areas where HU II and HU IV are not in direct contact, or where the intermediate aquifer is interpreted to exist, are shown in **Figure 20** (further discussion below). These areas include large portions of Middlesex and Elgin Counties including the towns of Strathroy, London, Ingersoll, and Woodstock.

Hydrostatigraphic Unit III (HU III), Intermediate Aquifer (AQint)

The intermediate aquifer (HU III) is present erratically within the study area. This unit is interpreted to be interstadial outwash sands and gravels that lie at an intermediate depth below the ground surface(refer to **Figure 20**). The thickness of HU III varies between 0 and 30 m, and is thickest near Strathroy, London, Ingersoll, and Woodstock. The unit is also identified in Perth County at the Easthope Moraine, and in

Chatham-Kent east of Chatham, north and south of Highway 401. Determining the extent and distribution of HU III was difficult with the initial regional cross-sections. To improve the representation of this unit in the geological model, additional local scale cross-sections were interpreted.

Hydrostratigraphic Unit V (HU V), Aquifer 2

HU V represents discontinuous sands and gravels that are interpreted to be outwash sand and gravel (interstadial complex) overlying the Catfish Creek Till and other older well consolidated tills. The distribution of HU V is presented in **Figure 21**. The thickness of HU V varies from 0 to 40 m, with the thickest areas located near St. Thomas, Wingham, south of Ingersoll, and near the shore of Lake Erie in Essex County.

Hydrostratigraphic Unit VI (HU VI), Aquitard 2

HU VI is interpreted to be the Catfish Creek Till, and other older overconsolidated tills such as the Canning Till that lie immediately on top of the Paleozoic bedrock. . The isopach map of HU VI is presented in **Figure 22**. The thickness of HU VI varies from 0 to more than 50 m. HU VI is regionally extensive in the northern portion of the study area, throughout most of Perth and Huron Counties. It is interpreted to be thickest along the bedrock valley identified in Perth County, south and west of Listowel.

2.2.3 Hydraulic Conductivity

Hydraulic conductivity refers to the capability of subsurface materials such as sand, rock etc. to transmit water. It 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 3 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 (2002-2004).

Typically, the vertical hydraulic conductivity 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 study area.

Table 3: 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 –Surficial Sands		$6x10^{-3}$ to $1x10^{-7}$		n/a	n/a	$1x10^{-4}$ to $5x10^{-4}$		$1x10^{-4}$ to $6x10^{-4}$
HU II – Fine-grained tills and lacustrine sediments		$1x10^{-6}$ to $1x10^{-11}$		$2x10^{-6}$ to $2x10^{-8}$	$1x10^{-7}$	$1x10^{-6}$ to $5x10^{-8}$		$3.5x10^{-6}$ to $1x10^{-7}$
HU III – Interstadial sands and gravels		$3x10^{-2}$ to $1x10^{-6}$		n/a	n/a	$1x10^{-4}$ to $2x10^{-4}$		$5x10^{-5}$ to $5x10^{-4}$
HU IV – Fine-grained tills and lacustrine sediments		$1x10^{-6}$ to $1x10^{-11}$		$2x10^{-6}$ to $2x10^{-8}$	n/a	$1x10^{-6}$ to $5x10^{-8}$		$3.5x10^{-6}$ to $1x10^{-8}$
HU V – Basal sands and gravels		$3x10^{-2}$ to $1x10^{-6}$		n/a	n/a	$1x10^{-4}$ to $2x10^{-4}$		$1x10^{-4}$
HU VI– overconsolidated tills		$2x10^{-7}$ to $1x10^{-12}$		n/a	n/a	n/a		n/a
HU VIII – Bx10drock Formations	Salina Formation	$1x10^{-4}$ to $1x10^{-7}$		n/a	n/a	n/a		n/a
	Bass Islands Fmn	$1x10^{-4}$ to $1x10^{-7}$		$1x10^{-5}$	n/a	n/a		n/a
	Bois Blanc Fmn	$1x10^{-4}$ to $1x10^{-7}$		$8x10^{-5}$, $8x10^{-6}$	n/a	n/a		$1x10^{-4}$ to $5x10^{-5}$
	Lucas/ Sylvanian Fmn	$1x10^{-4}$ to $1x10^{-7}$		$7x10^{-5}$	n/a	n/a		$5x10^{-5}$ to $7.5x10^{-5}$
	Amherstburg Fmn	$1x10^{-4}$ to $1x10^{-7}$		$7x10^{-5}$	n/a	n/a		$1.3x10^{-4}$ to $3x10^{-5}$

Hydrostratigraphic Unit (HU)		Lit. Values	Huron	Perth	Lambton	Middlesex-Elgin	Essex-Chatham Kent	Oxford
	Dundee Fmn	1×10^{-4} to 1×10^{-7}		2×10^{-4} to 1×10^{-5} (IWS)	1.6×10^{-4}	5×10^{-6}		1.2×10^{-4}
	Marcellus Fmn			n/a	n/a	n/a		n/a
	Hamilton Group			n/a	n/a	n/a		n/a
	Kettle Point Fmn			n/a	n/a	n/a		n/a
	Port Lambton Fmn			n/a	n/a	n/a		n/a

2.2.4 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.

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.

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.

Table 4 presents the estimates of recharge determined from a number of previous studies carried out in the study area. In most studies, the ice-contact stratified drift is estimated to have a higher net recharge than the sandy silt to sandy till.

Table 4: Recharge Estimates (mm/year) for Surficial Geologic Material

Material	Huron	Perth	Lambton	Middlesex-Elgin	Essex-Chatham-Kent	Oxford
Sand and Gravel Kames or Outwash		150	n/a	300		250-350
Sand Plains		n/a	n/a	130-300		50-200
Clay Plains		n/a	80	n/a		50
Clay/ Silt Till		65-100	n/a	9 – 55		20-50
Sand/ Silt Till		85 - 130	n/a	9 – 55		100
Urban Areas		40	n/a	n/a		n/a

2.2.5 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 6 Conservation Authorities, each with a series of watersheds. These Conservation Authorities and their watersheds are listed in **Table 5** and located in **Figure 23**.

Table 5: Conservation Authorities and their Primary Watersheds

Conservation Authority	Watershed	
Ausable- Bayfield CA	• Ausable River • Bayfield River	• Parkhill Creek
Maitland Valley CA	• Maitland River • Nine Mile River	• Eighteen Mile River
St. Clair Region CA	• Sydenham River	• 15 smaller watersheds
Lower Thames Valley CA	• Lower Thames River • Two Creeks	• Talbot Creek
Upper Thames River CA	• Upper Thames River	
Essex Region CA	• Detroit River	• Canard River • Many smaller watersheds

There are 13 major river systems and many more subwatersheds within the study area. The rivers and their tributaries are ecologically important. **Figure 24** 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.

2.2.6 Groundwater Inflow / Outflow

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 to the Great Lakes is not fully understood but this aspect will be investigated throughout the model development and calibration.

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. For municipal wells, information on well operation may also be contained in Well Operations Reports.

The pumping rate for each of the permitted wells will be specified using average rates (where available) for calibration of the groundwater flow model. Where average rates are not available, estimated pumping volumes will be 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.

2.2.7 Water Balance Calculations

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 on the different watersheds within the study area. Water balance calculations will be completed for the study area as a whole, and for each of the six Conservation Authorities within the model. More refined water budget calculations can be performed with the FEFLOW model to evaluate groundwater flows at a localized subwatershed scale.

The model will also be applied to understand how potential changes in pumping conditions may affect discharge conditions on the major rivers within the model. As such, the model may also be used to estimate the cumulative impacts of many smaller takings on the overall water budget of either a subwatershed, watershed or study area as a whole.

3 Summary

Groundwater modeling of the majority of southwestern Ontario is being undertaken to enhance the understanding of the groundwater flow system within six Conservation Authorities; the Upper Thames River, Lower Thames Valley, Maitland Valley, St. Clair Region and Ausable-Bayfield. This model will examine the water budget across the area and between watersheds and it will allow the conservation authorities to evaluate the local and cumulative impacts of water takings throughout the study area. Such impacts may include disruption of cold-water discharge to fish spawning grounds, or potential loss of wetlands and other environmentally sensitive areas.

To develop this regional groundwater flow model, existing data sources such as available geology, recharge, pumping well, river information, and land use area being utilized. This project will build upon the geologic, hydrogeologic, and surface water modeling studies previously completed within the study area.

This report presents the analyses that have been compiled thus far and presents the approach taken to construct the three-dimensional geological model, which will be used to build and calibrate the groundwater flow model. The model being developed will represent the full three-dimensional regional groundwater flow and extend deep into the underlying bedrock to incorporate interaction with deeper groundwater systems. Through this approach, the model being developed will allow the six conservation authorities in the study to more accurately evaluate the interaction of groundwater and surface water (water balance) and assess the potential impacts of additional stresses (land-use, pumping, 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.

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