Middlesex-Elgin Groundwater Study

Final Report

July, 2004

Middlesex and Elgin Counties

Project No. 02-0394

Submitted by

Dillon Consulting Limited

in association with

Golder Associates Ltd.

Our File: 02-0394

July 14, 2004

County of Middlesex
399 Ridout Street North
London, Ontario
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Attention: Mr. Stephen Evans
Director of Planning and Economic Development

Middlesex Elgin Groundwater Study
Final Report

Dear Mr. Evans:

We are pleased to present the Final Report of the Middlesex Elgin Groundwater Study. This study was completed by Dillon Consulting Limited in association with Golder Associates Ltd. The study was completed mainly in 2002 and 2003. The Study was directed by a Steering Committee consisting of municipal and agency representatives and project management was provided by the Upper Thames River Conservation Authority.

Yours sincerely,

DILLON CONSULTING LIMITED

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Project Manager

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cc: Ms. L. Nicks, UTRCA

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Middlesex-Elgin Groundwater Study
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1. INTRODUCTION

1.1 Background

Groundwater is a major source of potable water for domestic, industrial and agricultural uses in southwestern Ontario. Groundwater is also an integral component of the water cycle and water resource ecosystems.

The Ontario Ministry of the Environment has provided funding to complete groundwater studies throughout Ontario. The primary goals of these studies are to examine groundwater resources at a local and regional level, and to identify potential risks to these resources. The studies include delineation of wellhead protection areas for municipal wells, mapping of groundwater recharge and discharge areas, and identification of sensitive groundwater areas.

On a regional level, aquifer recharge and discharge areas are identified. As well, potential contaminant sources are assessed on a regional basis. Groundwater use is researched to provide information on how much water is used, and what it is used for (e.g., agricultural, commercial, industrial or residential purposes).

With this in mind, the County of Middlesex, member municipalities of Elgin County (excluding Bayham Township), City of St. Thomas and the City of London, have undertaken a groundwater management study to assess existing groundwater conditions and to recommend future management and protection practices to maintain the quantity and quality of the groundwater resource. The Study Area is shown with major roads and municipal boundaries as described above, in **Map 1.1**.

This groundwater management study is organized into four parts. These are:

Part 1: ***Water Resource Assessment*** (Section 2, 3 and 4)
Part 2: ***Existing Use Assessment*** (Section 5 and 7)
Part 3: ***Contaminant Assessment*** (Section 6)
Part 4: ***Groundwater Management and Protection*** (Section 8)

Integrated into all four parts are public consultation, uniform data management, and geographical information systems (GIS).

1.2 Study Objectives

The principal objective was to develop a detailed understanding of the groundwater resources in the Study Area, and to develop strategies and action plans to protect groundwater resources as a safe supply of potable water for current and future generations.

Specific objectives of the **Part 1:** ***Water Resource Assessment*** task were:

i) compilation of data relating to the physical description of the Study Area including water well records, geological mapping, topographical mapping, watershed mapping, and municipal mapping;

ii) characterization of regional groundwater flow systems including areas of significant groundwater recharge and discharge;

iii) assessment of the water resource capabilities of the regional aquifers;

iv) mapping of areas vulnerable to groundwater contamination; and

v) development of Geographical Information System (GIS) mapping to present data and to allow for updates in the future.

Specific objectives of the **Part 2: *Existing Use Assessment*** task were to:

i) compile data relating to the existing use of the groundwater resource (including the results of public consultation input);

ii) define Wellhead Protection Areas (WHPAs) for 6 municipal well systems. These systems occurred in the City of London (Fanshawe system), Middlesex Centre (Birr, Melrose, Komoka-Kilworth systems) and Thames Centre (Dorchester, Thorndale systems). WHPA studies were not performed on the municipal systems in Belmont, Strathroy or Mount Brydges, as these communities have undertaken their own WHPA studies.

Specific objectives of the **Part 3: *Contaminant Assessment*** task were to:

i) identify major existing and potential sources of groundwater contamination and their present/potential impact on both groundwater and surface water;

ii) develop a GIS inventory of contaminant sites that can be updated in the future, as more information becomes available.

Specific objectives of the **Part 4: *Groundwater Management and Protection*** task were to:

i) inventory the existing regulatory and voluntary framework that supports groundwater management and protection; and

ii) develop recommendations on groundwater management and protection strategies that can be implemented at the municipal level.

1.3 Report Organization

This report is organized in eleven sections. **Section 1** presents an overview of the study objectives and summary of the study methodology. **Section 2** reviews the physiography, climate and surface drainage of the Study Area. The geology of the bedrock and overburden deposits is summarized in **Section 3**. **Section 4** details the hydrogeology and water resources. **Section 5** presents the existing groundwater use assessment of this study. **Section 6** provides a regional assessment of the historical and potential sources of contamination. A Municipal Wellhead Protection Assessment is presented in **Section 7.** **Section 8** presents the results of the groundwater management and protection assessment. **Sections 9** is a summary of the main components of the study. **Section 10** summarizes the recommendations of the study. References are listed in **Section 11**. A Glossary of Technical Terms used in the report is presented in **Section 12.**

There are two types of illustrations used in the report. Figures are included in the text, following the page that they are first referenced. The figures are letter size (i.e., 8 ½ by 11 paper) and are generally used to illustrate concepts or ideas discussed in the report. Maps are located at the back of the report. The maps are a major part of the report, and present ideas, themes and analysis that are central to the evaluation of groundwater resources. The maps are ledger size (i.e., 11 by 17 paper). Both figures and maps are numbered similarly, first by the Section number of the report that discusses the map or figure, and then consecutively for that section. For example, there is both a Figure 2.1 (found in the text) and a Map 2.1 (found at the back of the report).

Appendices contain data tables and other detailed material and information which are referred to in the text of the report.

<u>Appendix A</u> contains the detailed tables that are the basis for the groundwater use assessment.

Appendix B contains the detailed documentation on wellhead protection area delineation.

Appendix C is a detailed summary of the public and agency consultation completed for the study.

Appendix D contains a summary of the existing federal, provincial and municipal framework in the context of water resources protection.

Appendix E is a detailed summary of the groundwater management strategy.

2. OVERVIEW OF STUDY AREA

The Study Area lies in the centre of Southwestern Ontario and consists of the City of London, the City of St. Thomas, the entire area of Middlesex County, and all of Elgin County, with the exception of the Municipality of Bayham. The Study Area is bounded to the north by Huron and Perth Counties, to the east by Oxford County, and to the west by Chatham-Kent (southwest) and Lambton County (northwest). The southern extent of the Study Area is delineated by approximately 75 km of Lake Erie shoreline.

The Study Area has an area of 4,880 km^2, including approximately 500 km^2 of urban land. The remaining land is predominantly rural. The City of London occupies the majority of the urban area (421 km^2). Other large prominent urban regions include the City of St. Thomas and communities of Glencoe, Parkhill, Aylmer, Strathroy, Mount Brydges, Port Stanley, and Belmont.

The population of the Study Area is 485,169 (2001Canadian Census data). The majority (70%) of the population lives within the City of London. St. Thomas and the towns of Glencoe, Parkhill, Aylmer, Strathroy, Mount Brydges, Port Stanley, and Belmont account for approximately 15 % of the total population. Urban population, including the cities and towns of London, St. Thomas, Strathroy, and Aylmer, accounts for approximately 75 % of the population. The population of people living in cities or towns with populations over 1,000 accounts for approximately 85 % of the total population.

Table 2.1 - Population Distribution in Study Area

Population Type	Included Population Centres	% of Population
Urban (Cities & Large Towns)	London, St. Thomas, Strathroy, Aylmer	75
Transitional (Small Towns)	Mount Brydges, Belmont, Port Stanley, Glencoe, Parkhill	10
Rural	Not Applicable	15

The urban areas consist of residential, commercial, and industrial land uses. Manufacturing and food processing are key industries in the cities of London and St. Thomas. Land use in rural areas is predominantly agricultural, with other miscellaneous land uses being present such as aggregate pits, quarries, golf courses, and conservation areas.

The Study Area has moderate topography which is generally controlled by the glacial landscape features such as moraines, and modern geomorphological processes such as stream morphology and erosion. The topography ranges from 170 metres to 360 metres above sea level throughout the Study Area. **Map 2.1** shows the presence of topographically high moraines and incised river valleys. This map also shows that the Study Area is relatively flat except for the northeastern portion which is notably higher than the rest of the Study Area.

The soil type throughout the majority of the Study Area is silty clay till, with three principal areas of sandy surficial soils. Sandy surficial soils are found in three sand plain regions referred to as the Bothwell Sand Plain, the Caradoc Sand Plain (and London Annex), and the Norfolk Sand Plain. There are also smaller isolated areas of coarse grained sand and gravel deposits in localized areas of glacial river beds and spillways. There is very little exposed bedrock, and a thick overburden layer (10-100 m) exists throughout most of the Study Area.

Major water bodies include Fanshawe Lake, the Thames River, the Ausable River, Parkhill Creek, the Sydenham River, Catfish Creek, and Kettle Creek. These water bodies are part of six tertiary watersheds found in the Study Area including the Ausable, the Big (including Catfish Creek/Kettle Creek), the Upper Thames, the Lower Thames, the Northwestern Erie Shore, and the St. Clair-Sydenham River watersheds. **Map 2.2** shows the locations of the tertiary watersheds. These watersheds are managed by seven Conservation Authorities (C.A.), including:

- Ausable/Bayfield Conservation Authority
- St. Clair Region Conservation Authority
- Upper Thames Conservation Authority
- Lower Thames Conservation Authority
- Kettle Creek Conservation Authority
- Catfish Creek Conservation Authority
- Long Point Conservation Authority.

2.1 Methodology / Data Sources

This groundwater management study involved the perusal and compilation of a variety of data sources for one or more tasks. These sources of information included:

- Digital mapping provided by Ministry of Natural Resources and the Ministry of the Environment;
- MOE Water Well Records;
- MOE Groundwater Files;
- Oil and gas well information from the Ministry of Natural Resources
- Agricultural Water Use by the Ministry of Agriculture and Food
- Reports on Municipal Water Supply Systems;
- Ecolog ERIS Database.

MOE Water Well Records

The Ministry of Environment (MOE) Water Well Records provided information on the subsurface geology, aquifer properties and groundwater use. These records were provided by EarthFx Limited of Toronto, Ontario on behalf of the MOE, and covered the period between 1945 and 1999. The records were provided in a digital form compatible with Microsoft database program Access97™. The files were converted to Access2000™ prior to manipulation.

MOE Groundwater Files

A review of the groundwater files at the MOE Southwestern Region office in London, Ontario, was conducted to identify investigated sites within the Study Area. A site may have been investigated for a number of reasons including groundwater interference complaints, groundwater quality complaints, reported spills or fires, terrain analysis reports, presence of landfills and proposed developments on private services. Each file was georeferenced using 1:50,000 mapping.

MOE Permits to Take Water

Information on the types of commercial and industrial uses of the groundwater resource was assessed through the available MOE Permit to Take Water (PTTW) database. Under the *Ontario Water*

Resource Act (R.S.O. 1990), a permit is required for any water taking that exceeds 50,000 litres/day. The PTTW system classifies the permits as being from either a groundwater source, a groundwater and surface water source or an unidentified source. Permitted volumes are usually greater than the actual taking. In addition, once a permit is issued, there is no commitment on the part of the permit holder to withdraw any water. As a result, the PTTW records may overestimate the actual quantity of water that is taken. PTTW records do not identify smaller takings of groundwater <50,000 litres/day; therefore, other commercial/industrial uses cannot be identified using this method. Nevertheless, this method does provide an adequate means to identify the larger and more significant commercial/industrial usages in the study area.

Reports on Municipal Water Supply Systems

Various reports were reviewed on the municipal water supply systems for Dorchester, Thorndale, Birr, Melrose and Komoka/Kilworth. Information was provided from a number of sources including municipal clerks, and the review of the MOE files.

Ecolog ERIS Database

The Ecolog Environmental Risk Information Services (ERIS) is an environmental database and information services company. The Ecolog ERIS system provides environmental and historical information compiled from government and private sources. The following information sources were obtained from the Ecolog ERIS:

- Anderson's Wate Disposal Sites (1930-2000)
- National PCB Inventory (1988-1998)
- Inventory of Coal Gasification Plants (to 1988)
- Pesticide Register (1988-1998)
- Private Fuel Storage Tanks (1989-1996) by the Fuel Safety Branch who previously maintained a database of all registered fuel storage tanks in the province. (As of 1991, all fuel storage tanks had to be registered; but all historical tanks may not have been registered).
- Retail Fuel Storage Tanks (1989-1999) previously obtained by the Fuel Safety Branch and now obtained from private sources of all of the licenced retail fuel outlets in the province.

2.2 Physiography and Topography

The physiography and topography of the Study Area is varied and consists of ten physiographic regions (Chapman and Putnam, 1984). **Map 2.3** shows the physiographic regions, including 11 prominent moraines. The physiographic characteristics of a region are related to the overburden geology. Groundwater characteristics such as recharge and discharge areas are often controlled by physiographic features such as moraines and river valleys.

The characteristics of each physiographic region are described below. The physiography of the Study Area (and much of the hydrogeology) is dominated by the effects of continental glaciation. The regression of the last glaciation period in the Study Area is illustrated in **Figure 2.1**. The moraines, sand plains, till plains and clay plains were all formed during this period. Glacial Lake Warren is not shown on **Figure 2.1**, as it was present in three distinct stages of recession between Glacial Lake Whittlesey and Glacial Lake Lundy. However, Glacial Lake Warren is referred to in the discussion below as the stages of recession of its shoreline are significant in the development of the physiography of the Study Area.

2.2.1 Physiographic Regions

The sections below describe the physiographic regions identified within the Study Area, as presented in *The Physiography of Southern Ontario, Third Edition*, (Chapman and Putnam, 1984). The various types of physiographic regions are generally described, and the specific physiographic regions within the Study Area are identified.

<u>Sand Plains</u>

Sand plains are important physiographic regions, as they form shallow, unconfined aquifers that typically exhibit water of good quality. They are used extensively as a domestic water supply for private and municipal uses, and are important areas of groundwater recharge. They are also often used for the growing of specialty agricultural crops such as tobacco.

Caradoc Sand Plain (and London Annex)

The Caradoc Sand Plain is located in the Strathroy/Mount Brydges area and is a large (78,500 ha) deposit of water-laid alluvial/beach deposits. The plain was formed when the early Thames River discharged sediment into Glacial Lake Warren, forming a sand gravel deltaic deposit. The Caradoc Sand Plain is composed predominantly of sand but contains some gravel as well. This deposit thins towards the west where the water became deeper, and blends into the Ekfrid Clay Plain. There are prominent dunes and sand ridges (terrace escarpments) that were formed by the wave action and wind over the majority of this physiographic region as Glacial Lake Warren receded. This region is known for specialized agriculture such as tobacco farming due to its sandy soil. There are also prominent gravel pits and aggregate mining operations in the Komoka area.

Bothwell Sand Plain

This sand plain is very similar to the Caradoc Sand Plain, as it was also created by the early Thames River emptying sediment into Glacial Lake Warren, which post-dates the deposition within Glacial Lake Whittlesey. It was deposited to the west of the Caradoc Sand Plain in the Bothwell area, as Glacial Lake Warren receded farther to the west. The Bothwell Sand Plain also shows dunes and terrace escarpments, though they are not as abundant as they are on the Caradoc Sand Plain.

Norfolk Sand Plain

There is only a small portion of the extensive Norfolk Sand Plain (315,000 ha) within the Study Area, as the majority of this physiographic region lies to the east. The portion of this sand plain within the Study Area is relatively flat lying, and is located to the south of St. Thomas and Aylmer. This sand plain is also an alluvial/deltaic feature formed by the early Grand River as it emptied into the glacial lakes.

Clay Plains

Clay plains occur in association with sand plains as they represent the sediment that was deposited in deeper water farther off-shore than the alluvial/beach deposits (sand plains). The fine grained clay and silt were deposited in a relatively flat, quiet water basin, resulting in the development of a somewhat featureless topography. These clay plains often represent regional aquitards, which may overlie important aquifers.

Ekfrid Clay Plain

The Ekfrid Clay Plain exists between and surrounds the Caradoc and Bothwell Sand Plains. This physiographic region dominates the southwestern portion of the Study Area. As described above, the deposition of the clays and silt make for a featureless, flat lying area that is often good for agriculture.

<u>Till Plains</u>

Till plains are regions where glacial till is the surficial soil type. Till is a heterogeneous mixture of clay, silt, sand, and pebbles. They often display surface features such as prominent moraines, terrace escarpments, and beach/bar/spit deposits. Till soils are very dense, stiff materials often covered by a thin veneer of topsoil.

There are different types of till plains including bevelled till plains, till moraines, and drumlinized/un-drumlinized till plains. Bevelled till plains are relatively flat, reworked till plains that were previously deposited by another glacial event, and then over-ridden by a subsequent glacial advance. Till moraines occur as mounds of till deposited at the end of a glacier and are expressed as prominent topographic features (moraines within this till plain type can also be sub-classified). Drumlinized or un-drumlinized till plains simply refers to the presence or absence of drumlins on the surface of a till plain.

Stratford Till Plain

The Stratford Till Plain is a large till plain of ground moraine features interrupted by terminal moraines such as the Lucan, Mitchell, and Arva moraines. The till making up this plain consists of calcareous silty clay and contains very little coarse grained material, but some gravel terraces exist along the Thames River. Summer droughts often desicate this soil type making agricultural practices difficult.

Oxford Till Plain

This is a large physiographic region (160,000 ha) that only covers a small area in the northeast portion of the Study Area adjacent to the Stratford Till Plain. The soil type and characteristics of this physiographic region are similar to that of the Stratford Till Plain described above.

Moraine Dominated Regions

Moraine dominated areas have regional topographic highs and are characterized by hummocky terrain and till soils. Moraines commonly occur in sub-parallel groups as they are deposited by the receding glacier. These areas are important for groundwater recharge as surface water is trapped on or between topographically high moraines and can infiltrate into the groundwater environment.

Mount Elgin Ridges

This physiographic region lies between the Thames River Valley, and the Norfolk Sand Plain, and covers a large area (147,000 ha). This region is made up of several prominent moraines accounting for its name. The Ingersoll, Westminster, St. Thomas, Sparta, and Tillsonburg moraines are all located within this physiographic region. These moraines give the region a rolling topography which controls the surface water drainage patterns. The soil type is similar to that of the Stratford Till Plain, but contains more sand, making it better for agricultural use.

Horseshoe Moraines

The Horseshoe Moraines are part of the Port Huron Moraine system that forms a horseshoe shaped region. The region contains the Seaforth and Wyoming moraines which are large continuous features that mimic the shape of the shore of Lake Huron. The soil is a pale brown, calcareous, fine-textured till, with some small beach deposits composed of sand and gravel being present near Ailsa Craig.

Huron Slope

This physiographic region occupies an area in the northwest of the Study Area, while the majority of the region follows the shore of Lake Huron northwards. The region is north of the Wyoming Moraine and contains beach deposits from Glacial Lake Warren and lacustrine clay deposits. The majority of the region is poorly drained and is not ideal for agriculture except for livestock operations.

2.2.2 Prominent Moraines

Map 2.1 shows the topographical expression of the moraines. **Map 2.3** shows the locations of the moraines in the Study Area.

Huron Lobe Moraines

The moraines within the Study Area were created by glacial processes of the Huron Lobe, and includes the Wyoming, Seaforth, Lucan, Mitchell, and Arva moraines. The orientation of these recessional moraines and end moraines mimic the shape of the shore of Lake Huron forming a concentric pattern of topographically high ridges. The Wyoming moraine is the largest moraine in the Study Area at over 20 km wide and very long (though most of its length is outside the Study Area). It is located in the northwest corner of the Study Area, just south of the town of Parkhill. The Seaforth moraine is very similar in shape to the Wyoming moraine, but it is much more narrow (between 5 - 10 km wide), with more of its length being within the Study Area. This moraine is located north of the village of Poplar Hill. The Lucan moraine is concentric with both the Wyoming and Seaforth moraines, but does not run continuously through the Study Area. The Lucan moraine begins west of London and bends northwards to the east of Lucan and out the northern limit of the Study Area. The Mitchell moraine runs in a northeasterly direction and converges with the Lucan moraine just south of Lucan. The Arva moraine is discontinuous, and trends north-northeast for approximately 30 km north of London.

Erie Lobe Moraines

The recessional and end moraines formed by the Erie Lobe are oriented in an east-west direction in the London area and trend more southwest/northeast as they approach the shore of Lake Erie. The

Erie Lobe created the Ingersoll, Westminster, St. Thomas, Sparta, and Tillsonburg moraines. The Ingersoll moraine varies in width from 1- 10 km and trends east from the area southwest of London. Running parallel 5 km south of this moraine, is the Westminster moraine. The St. Thomas moraine is a discontinuous moraine located south of the Westminster moraine that begins near the West Lorne/Rodney area, and runs northeast through the city of St. Thomas. The Sparta and Tillsonburg moraines are similar to the St. Thomas moraine in that they are discontinuous but begin east of St. Thomas.

The Dorchester moraine is an irregular shaped end moraine located in the Dorchester area. This moraine, formed at the most northward advance of the Erie Lobe, represents the oldest moraine in the Study Area (Cowan, 1975). It is composed of a sandy drift till that is part of the Catfish Creek Till. Glacial processes around Dorchester deposited till in a mound-like moraine, rather than the linear shape that is common to recessional or end moraines.

2.2.3 Other Topographic Features

Map 2.1 shows the topographic highs created by the moraines described above, as well as some notable topographic lows. These lows are created by a variety of processes both modern and glacial. Two features creating topographic lows are described below.

Incised River Valleys

There are several incised river valleys creating topographic lows in the Study Area. River valleys were created by glaciofluvial processes and continue to evolve as a result of current stream morphology. The Thames River and the Ausable River are prominent topographic lows created by old glacial rivers that continue to evolve. There are also a series of smaller, modern incised river valleys that cut through the relatively flat lying areas in Elgin County and drain directly into Lake Erie.

Erie Shore Bluffs

The lowering of the water levels in the Great Lakes since glacial times has created sharply eroded shorelines along Lake Erie. Wave action, the loss of vegetation, and continued development along the shores of Lake Erie has created high bluffs that can be seen on **Map 2.1**.

2.3 Surface Water Drainage

Surface water drainage in the Study Area is complex as surface water drains to Lake Huron to the north, Lake Erie to the south, and to Lake St. Clair in the west. There are six major tertiary watersheds in the Study Area that are managed by seven Conservation Authorities. **Map 2.2**, Surface Water, shows the six tertiary watersheds including Ausable River, Catfish and Kettle Creeks, Upper Thames River, Lower Thames River, Lake Erie Drainage, and the Sydenham River watersheds. The Study Area boundaries are municipal, and do not follow the watershed boundaries. As a result, the watersheds are not located entirely within the Study Area boundaries. In general, the surface water drainage patterns are controlled by the topography created by moraines in the eastern portion of the Study Area. In the flat clay plains in the west, the drainage patterns are characterized by meandering river valleys.

Lake Huron Drainage

The Ausable basin, which empties into the lower portion of Lake Huron, drains an area of 1142 km^2. The Ausable River is approximately J-shaped, arising near the Village of Staffa in Perth County. Just west of the Town of Exeter, the river intersects the glacial spillway of the Wyoming Moraine and follows this valley southward towards Nairn, where it takes a curve to the west. Near Arkona, the Ausable River takes an abrupt turn to the north and enters a deep gorge. Prior to 1873, the original channel continued to flow northward towards Grand Bend, at which point it took a sharp turn to the southwest and flowed parallel to Lake Huron until it broke free of the sand dunes at Port Franks. A channelized section called the “Cut” has since been excavated from its current mouth in Port Franks to intercept the original channel to the southeast. The old Ausable channel (remaining channel north of the “Cut”) still receives water from Parkhill Creek. Parkhill Creek drains a watershed of 456 km^2, which flows parallel to the Ausable for most of its length. A diversion channel was created in 1892 that directed the flow from Parkhill Creek into Lake Huron at Grand Bend. This cut off the channel from Grand Bend to Port Franks. This remnant channel of the Ausable River has been locally named the “Old Ausable Channel”. The main tributaries of the Ausable River include: Black Creek, the Little Ausable River and Nairn Creek.

St. Clair Drainage

The majority of the Study Area drains west into Lake St. Clair. The Sydenham River and the Thames River drain a combined area of approximately 8,300 km^2 to Lake St. Clair. Much of this area is beyond the limits of the study, including much of Perth and Oxford Counties to the east, and much of Lambton County to the west. These two rivers make up three watersheds that divide the drainage to Lake Huron and to Lake Erie.

– Thames River

The Thames River is the largest and most important surface water feature in the Study Area. The Thames drains approximately 5,700 km^2, and is divided into two watersheds and corresponding Conservation Authorities, the Upper and Lower Thames.

The Upper Thames has two branches and drains the area north and east of the forks (located in downtown London). This portion of the Thames River drains approximately 2,700 km^2 of till plains and moraine dominated landscape (Chapman and Putnam, 1984). The north branch originates from the convergence of several small tributaries in Logan Township north of Mitchell outside of the Study Area . The river runs through a shallow, but well defined river valley south of Mitchell. The gradient of the river bed is considerably steeper in the Upper Thames relative to the Lower Thames. Important tributaries to the north branch of the Upper Thames include the Avon River, Flat Creek and Trout Creek. Fanshawe Lake is an important artificial dam and reservoir located on the north branch that controls flooding, as well as providing some flushing in the dry summer months. Smaller water control facilities (dams) exist near St. Marys and Mitchell.

The south branch originates outside of the Study Area in a swampy area west of Tavistock and flows west where it joins a spillway through Woodstock and Ingersoll. The valley is approximately 1.6 km wide and over 30 metres deep near the eastern edge of the Study Area, exposing limestone that is quarried in Beachville. The Cedar and Reynolds Creeks are the main tributaries to the south branch of the Upper Thames.

The Lower Thames is a more gently sloped, meandering portion of the river that originates at the forks of the Thames in downtown London. This watershed drains a thin strip of land between the Sydenham watershed and the Erie drainage area. There are no significant tributaries to the Lower

Thames in the Study Area. There is very little runoff that enters the Lower Thames in the summer as it is mostly lost to evaporation/evapotranspiration. As a result, the Lower Thames has slow flow conditions in the summer. Spring flow conditions often cause flooding related to low and poorly defined banks resulting in a large flood plain area.

– Sydenham River

The Sydenham drains 2,600 km^2, most of which is in Lambton County. The Sydenham River runs across gently sloped clay plains in both the Study Area and Lambton County resulting in a small flow gradient (Chapman and Putnam, 1984). The headwaters of the Sydenham River originate near Arkona, on the south slope of the Wyoming Moraine, where gradients are steep for a short portion of the stream's length. The river then crosses clay plains where the gradient is reduced to as little as 6 metres in 50 km. The river valley of the Sydenham does not exceed 10 metres in depth anywhere along its length.

Lake Erie Drainage

Within the Study Area, Lake Erie receives drainage from several creeks that are located south of the Thames River. The creeks have formed steep-sided, deep gullies that cut through the bluffs on the Erie shoreline, and in some cases incise valleys down to bedrock. These creeks are short in length and are generally perpendicular to the shoreline. The Study Area contains two different watersheds including the Catfish Creek/Kettle Creek watershed (combined), and the Lake Erie Drainage watershed. The major creeks within the Catfish/Kettle Creek watershed are Catfish Creek and Kettle Creek.

3. GEOLOGY

3.1 Bedrock Geology

The bedrock geology has been interpreted by the Ministry of Northern Development and Mines, and the Ministry of Natural Resources using information from water well records and borehole logs from oil and gas wells. The bedrock geology consists of two main rock types; shales and carbonates (limestones). In the Study Area, these sedimentary rock formations were deposited on the Algonquin Arch, a Precambrian basement ridge forming the spine of the southwestern Ontario peninsula that occurs between the Michigan Basin to the northwest and the Appalachian Basin to the southeast. In the Study Area, there is approximately 1,000 metres of Paleozoic sedimentary rock underlying the overburden (Johnson et al., 1992).

As shown on **Map 3.1**, there are five different formations and/or groups of bedrock in the Study Area. A formation is a single layer of rock with similar characteristics. A group is a set of formations that make up a distinct succession. A brief description of the groups and formations found in and around the Study Area is provided in **Table 3.1**, starting with the most recent (i.e., youngest) formation (Kettle Point Formation) proceeding to the oldest formation (the Lucas Formation).

Table 3.1
Bedrock Types and Descriptions

Group or Formation Name	Lithological Description
Kettle Point Formation Period: Devonian Epoch: Late Age: Fransian to Famennian	Black organic rich shale with some organic shale and siltstone interbeds. Ranges from 30 - 75 m thick. Contains large calcareous concretions and fossils. Unconformably overlies the Hamilton Group.
Hamilton Group Period: Devonian Epoch: Middle Age: Givetian	Consists of six distinct units. Predominantly blue-grey soft shale. Thin layers of light grey calcareous interbeds. Group is up to 80 m thick.

Group or Formation Name	Lithological Description
Marcellus Formation Period: Devonian Epoch: Middle Age: Eiefelian	Black organic rich shale with grey shale interbeds and sparse fossils. Up to 12 m in thickness. Lies conformably on top of the Dundee Formation. Present in the St. Thomas, Aylmer to Lake Erie area.
Dundee Formation Period: Devonian Epoch: Middle Age: Eiefelian	Brown limestone with fossils. Unit has an average thickness of 35-45 m. Contacts with the overlying Hamilton Group and the underlying Lucas Formation are sharp and erosional.
Detroit River Group: Lucas Formation Period: Devonian Epoch: Early to Middle Age: Emsian to Eiefelian	Light grey to brown, high purity limestones and bituminous and cherty dolostones with thin anhydrite-gypsum beds, partings and blebs. Approximately 40 m to 75 m in thickness. Lower contact is conformable with the Amherstburg Formation.

Reference: Johnson, et. al., (1992)

The Study Area is dominated by two of the lithologies described above, the Hamilton Group shales and the Dundee Formation limestone.

The Hamilton Group blue-grey soft shales with calcareous interbeds is the surficial bedrock in the western half of the Study Area, with three small windows of the Dundee Formation and one small window of the Marcellus Formation showing through the Hamilton Group in the southwestern portion of the Study Area. There are also several small fingers of the overlying Kettle Point Formation shales that are present along the western border of the Study Area.

The other dominant bedrock unit is the Dundee Formation limestone that occupies the majority of the eastern portion of the Study Area. There is a significant area in the southeastern part of the Study Area where the overlying Marcellus Formation is found with windows of the Dundee Formation showing through. There are also some fingers of the Detroit River Group, which underlies the Dundee Formation (specifically the Lucas Formation - see **Figure 3.1**), that protrude through the Dundee Formation. There are older, deeper sedimentary rock formations below the Lucas Formation. However, these formations are not used for groundwater extraction in the Study Area.

3.2 Quaternary Geology

The distribution of overburden deposit types is shown on **Map 3.2**. The geology of the overburden (Quaternary deposits) consists of geologically recent deposits of unconsolidated sediments left behind as the glaciers retreated north. Surficial geology within the Study Area is entirely Quaternary in age, as there is no exposed bedrock. The thickness of the overburden ranges from approximately 5 to 100 metres.

The evolution of the overburden geology was controlled by the last continental glaciation in North America. Large scale glaciation is capable of eroding bedrock as well as overlying unconsolidated sediments while the glacier advances. The eroded materials from the advancing glaciers are subsequently deposited during periods when the glacier retreats.

In Southwestern Ontario, the last continental scale glaciation was during the Wisconsin time. The glaciers extended south of Southwestern Ontario, into Michigan, Indiana, and Ohio. The glaciers then began to retreat during the Late Wisconsinan to the southern Ontario region, resulting in the deposition of the material contained in the glaciers (beginning approximately 23,000 years ago, and ending approximately 10,000 years ago). Lakes, rivers, and spillways created by the meltwater from the retreating glaciers deposited massive amounts of glacial debris and shaped the landscape of the Study Area.

The Late Wisconsinan can be broken into five distinct stages (stades and interstades), where the glacier split into two distinct lobes. Each lobe went through cycles of retreating and advancing, prior to the final retreat of the glacier due to a warming climate. **Table 3.2** summarizes the Quaternary deposits found in the Study Area including the name of the deposit and the lithology starting with the latest (i.e., youngest) deposits.

Table 3.2
Late Wisconsinan Quaternary Deposits
Middlesex and Elgin Counties

Stade/Interstade	Deposit Name	Lithological Description
Post Glacial	Modern Organic Deposits	peat, muck, and marl
	Modern Fluvial Deposits	gravel, silt, sand, and clay; deposited on modern floodplains
Port Bruce Stadial	Glaciolacustrine Deposits	sand, gravelly sand, and gravel; nearshore and beach deposits
	Glaciolacustrine Deposits	silt and clay, minor sand; basin and quiet water deposits
	Glaciofluvial Outwash Deposits	gravel and sand; includes proglacial river and deltaic deposits
	Ice Contact Deposits	gravel and sand; minor till; includes esker, kame, end moraine, ice-marginal delta, and sub-aqueous fan deposits
	St. Joseph Till	silt to silty clay matrix, clay content varies, clast poor
	Rannoch Till	silt to clayey silt matrix becoming finer grained southward, highly calcareous, clast poor
	Port Stanley Till (Erie Lobe)	silt to sandy matrix becoming silt to silty clay near Lake Erie, strongly calcareous, moderate to low clast content decreasing southward
	Tavistock Till (Huron Lobe)	sandy silt to silt matrix, moderate to high carbonate content, clast poor
Nissouri Stadial	Catfish Creek Till	sandy silt to silt matrix, strongly calcareous, moderately stony to stony

Reference: Barnett, (1992)

There were two distinct glacial lobes present in Southwestern Ontario during the Late Wisconsin. **Figure 2.1** shows the distinct glacial lobes, as well as the glacial lakes that covered Southwestern

Ontario during the Late Wisconsin time. The Huron Lobe advanced from Lake Huron southwards across the Study Area. The Erie Lobe advanced from the northeast, and receded to the east.

The Nissouri Stadial

The Nissouri Stadial represents the initial stage of ice advance in the Late Wisconsin. This stadial is represented in the Study Area by the Catfish Creek Till which was deposited by the Erie Lobe. It is the predominant sub-surface quaternary layer over a large portion of the Study Area. This till also outcrops in small windows east and west of London. The Catfish Creek Till is composed of several layers of subglacial till and stratified sediments of glaciofluvial or glaciolacustrine origin. The Catfish Creek Till is dense, usually grey in colour, calcareous, and quite pebbly. There are some discontinuous interbeds of sand within the till that may be good aquifers.

The Erie Interstadial

The Erie Interstadial is not represented by any stratigraphic units in the Study Area.

The Bruce Stadial

The Bruce Stadial is represented by several tills and un-named glacial deposits. The most dominant units in the Study Area representing the Bruce Stadial are the Port Stanley Till, the Tavistock Till, and the Rannoch Till. The St. Joseph Till is also found in the northwestern portion of the Study Area near Parkhill. All of these tills are found in large areas at surface in the Study Area.

The Port Stanley Till is the dominant surface overburden in most of Elgin county and the southern portion of Middlesex. The till is typically a brownish-grey, calcareous, clayey silt till. This till exists as a northeast-southwest trending band that begins at West Lorne and can be found as the surficial overburden northeast as far as Woodstock (beyond limit of Study Area). This band of Port Stanley Till is narrow at each end and is approximately 30 km wide between London and Port Bruce. The Port Stanley Till overlies the Catfish Creek Till and was deposited by the Erie Lobe of the Laurentide Ice Sheet. The Port Stanley Till often occurs as ground moraines and end moraines up to 25 metres thick.

Deposition of the basal portion of the till was formed during the initial advance of the Erie Lobe. This advance incorporated previously deposited glaciofluvial sand and gravel and dolostone bedrock. The younger overlying portion of this unit was deposited in oscillatory cycles of retreat by the Erie Lobe. This created a depositional environment of sub-aquatic flow in glaciolacustrine conditions. This produced some lacustrine silt and sand interbeds within the Port Stanley Till. This lithology makes the fine grained beds of the till have very low permeability, while the sandy interbeds are aquifers of varying quality. The upper portion of the till has developed deep vertical fractures, making the near surface more permeable and hydraulically active than deeper, unweathered till.

The Tavistock Till was deposited at the same time as the Port Stanley Till, but was deposited in the northeast portion of the Study Area by the Huron Lobe of the Laurentide Ice Sheet. This till is the predominant surficial overburden unit in the municipalities of Middlesex Centre and Thames Centre. The till was deposited during the advance of the Huron Lobe over previously deposited material making this till extremely fine grained. This till is highly calcareous, silty clay to clayey silt with few clasts of carbonate and shale. This unit occurs as ground moraines up to 12 metres thick, north of London. Drumlins are also composed of this till east of the Study Area near Woodstock.

The Rannoch Till was created by the Huron Lobe, and is a strongly calcareous, silt to silty clay till. This unit mimics the shoreline of Lake Huron, and occurs as end moraines deposited in a proglacial environment, including the Mitchell, Dublin, Lucan, Seaforth, and Centralia Moraines. The till moraines range from 2 to 6 metres in thickness and are usually covered in a veneer of glaciolacustrine silts and sands, or supraglacial tills.

The St. Joseph till is also a unit deposited by the Huron Lobe which follows the shoreline of Lake Huron. It occurs as end moraines and has similar lithology to the Rannoch Till, but with less carbonate content in the matrix of the till.

The Bruce Stadial also deposited many un-named Quaternary deposits. The un-named deposit types are generally not tills, and are more localized deposits. These deposits generally overlie the previously described tills, depending on their location. These deposit types and notable occurrences in the Study Area are described below.

Ice Contact Deposits

These deposits are localized successions of coarse grained sediments, predominantly gravel and sand, with some minor amounts of re-worked till. These deposits take on geomorphic expressions such as eskers, kames, localized end moraines, and ice marginal/sub-aqueous deltaic deposits. There are two notable occurrences of ice contact deposits in the Study Area, including a small (5 km long), narrow deposit south of St. Thomas, and a larger (15 km) irregular shaped deposit east of London. There are also several very small (approximately 1 km or less) ice contact deposits near the northwestern border of the Study Area.

Glaciofluvial Outwash Deposits

These coarse grained (gravel and sand) deposits were placed in proglacial rivers and proglacial deltaic environments. These deposits occur as sand plains (Caradoc, Bothwell) and in the paleo-river channel of the proglacial river that has now become the Thames River Valley. The Norfolk Sand Plain (a reworked alluvial/deltaic deposit from the early Grand River) is present in the southeastern portion of the Study Area. The high energy alluvial environment placed coarse grained overburden on the floodplain of the modern day Thames River. More recent veneers of finer grained sediment may cover these deposits from recent flooding.

Glaciolacustrine Deposits

During the waning stages of the glaciation in the Late Wisconsin, a number of large glacial lakes covered most of Southwestern Ontario. **Figure 2.1** shows four of these lakes, the Glacial Lakes Maumee III, Maumee IV, Glacial Lake Whittlesey, and Glacial Lake Lundy as they evolved over time. Other important glacial lakes that once occurred in the Study Area are Lake Arkona, which occurred between Lake Maumee and Lake Whittlesey, and Lake Warren, which occurred after Lake Whittlesey and before Lake Lundy. The characteristics of a glaciolacustrine deposit can vary significantly depending on the proximity to the shoreline of the lake, and/or the depth of water in which material was deposited. The Study Area contains two types of glaciolacustrine deposits including alluvial, nearshore/beach deposits, and quiet water/basinal deposits. These deposits usually occur in tandem as they are connected in their depositional evolution. The characteristics and occurrences of each type are discussed below.

Nearshore/Beach Deposits

Nearshore or beach deposits are coarse grained (sand to gravel) materials that are deposited in shallow water environments and often display ripple features from wave action, and/or dune structures that result from wind action on sub-aerially exposed beach deposits. These deposits are often associated with alluvial deltaic depositional environments. As the glacial lakes receded, the surface of alluvial deposits were reworked in a beach or nearshore environment. These surficial deposits are important unconfined aquifers, extensively used for private and municipal groundwater supply.

There are three notable occurrences of reworked alluvial/beach deposits in the Study Area. The area surrounding Strathroy and Mount Brydges (the Caradoc Sand Plain) is an alluvial deposit that displays beach deposit features such as dune structures. The beach and dune characteristics indicate sub-aerial exposure of the original alluvium as Glacial Lake Warren receded over time. The second occurrence of an alluvial deposit reworked by beach or nearshore processes is further west near Wardsville and Bothwell (the Bothwell Sand Plain). The third occurrence of this deposit type is found in northeastern trending strips south of St. Thomas, extending to the edge of the Study Area south of Aylmer and Springfield. These strips are a continuation of a massive beach deposit located east of the Study Area (the Norfolk Sand Plain). This occurrence extends discontinuously as far as Chatham.

Quiet Water/Basinal Deposits

As mentioned above, the quiet water or basinal deposits occur in tandem with the beach deposits, as they represent the finer grained fraction of sediment that settles out of suspension in the lake farther from shore. These deposits typically consist of silt and clay, with minor amounts of sand. There are several small occurrences of this deposit type scattered throughout the Study Area, with a large portion of the surficial cover in the southwest portion of the Study Area (the Ekfrid Clay Plain, associated with the beach deposits described above).

Post Glacial Deposits

Organic deposits that consist of peat, muck, and marl are deposited in low-lying marshy or swampy wetland areas, and fluvial deposits consisting of sand and gravel that are deposited on modern flood plains. These deposits occur sporadically throughout the Study Area.

3.3 Bedrock Topography and Overburden Thickness

The elevation of the bedrock surface is shown on **Map 3.3**. As a result of the relatively flat topography in the Study Area, the depth to bedrock and the bedrock surface elevation maps are generally proportional to each other. The bedrock elevation is highest in the northeast portion of the Study Area and slopes downward towards Lake Erie. Consequently, the overburden thickness or depth to bedrock is greatest in the southern portion of the Study Area along the shore of Lake Erie. The bedrock elevation ranges from approximately 70 metres above sea level on the shores of Lake Erie to 330 metres above sea level in the northeast of the Study Area.

There is a prominent bedrock valley running north-south through Parkhill, Strathroy, Mount Brydges, and the area between Dutton and Shedden. This feature is highlighted on **Map 3.3**. The western edge of this bedrock valley coincides with the eastern edge of the Kettle Point formation, which forms a buried escarpment overlying the Hamilton Group formation (Johnson et al., 1992). This corresponds to a rise in bedrock elevation from 175 metres to 200 metres along the western edge of the Study Area (see **Map 3.3**). A less prominent bedrock valley is also observed in the Lucan/Birr area, that is also related to a subtle, discontinuous low in the bedrock surface.

The depth to bedrock (overburden thickness) is shown on **Map 3.4**. The thickness of Quaternary overburden deposits varies significantly over the Study Area from less than 10 metres to a maximum of 100 metres. There are two small, isolated, Paleozoic rock outcrops shown on **Map 3.2**. The bedrock crops out near St. Marys, just outside the northeast corner of the Study Area, north of Thames Centre, and west of Parkhill, along the Ausable River, near Arkona.

Generally, the overburden gets thicker from north to south in the Study Area. There are several isolated areas in which bedrock is relatively close to surface. There is an area northwest of Glencoe and Wardsville where bedrock is within 20 metres of the ground surface. Similar areas are found west of Parkhill, along the Ausable River, north of Lucan, and near St. Marys (which lies just northeast of the Study Area). These areas of thin overburden are likely related to the presence of thin clay flats (the Ekfrid and St. Clair Clay plains), that are featureless and topographically low. In the area near St. Marys, limestone bedrock outcrops accounting for the quarries and cement industry in the area. This is also an area of quiet water/basinal clay deposition.

There is a relatively thin cover of overburden in the northeast of the Study Area due to the higher bedrock elevation in this area. It is evident that the bedrock surface exerts the dominant control on overburden thickness as the topography ranges from 200 to 300 metres a.s.l. over the majority of the Study Area (except for river valleys, the shores of Lake Erie, and the Parkhill area), and the bedrock surface topography ranges from 100 to 330 metres a.s.l.

The bedrock valley highlighted on **Map 3.3** has been infilled resulting in greater overburden thicknesses which are in the order of 60 metres. Elgin County has the thickest overburden in the Study Area, with thicknesses generally ranging from 60 metres to 100 metres.

3.4 Regional Cross Sections

Six regional cross sections were developed and are shown on **Map 3.5**, **Map 3.6** and **Map 3.7**. The locations of the cross sections are shown on **Map 3.1**. The contacts for the bedrock formations were derived from oil and gas well record information.

Map 3.5 has two west-east sections: Section A-A’ extends near the northern limit of the Study Area in the Parkhill and Lucan area, while Section B-B’ extends through the middle of the Study Area extending through the Strathroy, London and Dorchester areas.

Section A-A’ illustrates that most of the water wells are bedrock wells east of Lucan, with shallow overburden wells in the Ailsa Craig area. Bedrock is dominated by the Dundee Formation underlain by the Lucas Formation which dips from east to west. The “buried escarpment” along the western edge of the Study Area is evident in the western limits of this section with significant thicknesses of the Hamilton Group and the Kettle Point Formation west of the Ausable River.

Section B-B’ indicates that both shallow overburden and deep bedrock wells occur extending from the east to Komoka and shallow wells predominate in the Strathroy area. Limestone bedrock is dominant in the east, with the Hamilton Group shales occurring at the bedrock surface near Komoka and extending west to Strathroy. The Kettle Point Formation is dominant along the western part of this section.

Section C-C’ (**Map 3.6**) is another west-east section, extending along the southern portion of the Study Area. The section illustrates the thick overburden that occurs over most of Elgin County.

This section shows that the Marcellus Formation shales occur at surface in the St. Thomas, Aylmer to Lake Erie area and is overlaid by the Hamilton Group west of St. Thomas. This section also indicates that the Kettle Point Formation is dominant along the western edge of the Study Area.

Section D-D' (**Map 3.6**) is a north-south section extending from Parkhill south to Wardsville and Rodney. Generally, basal bedrock wells are dominant in this area. The bedrock is dominated by the Hamilton Group shales which are underlain by the Dundee Formation and the Lucas Formation.

Map 3.7 contains two north-south sections: Section E-E' extending through the middle of the Study Area extending along the western part of Lucan-Biddulph through Komoka to the Dutton area; and Section F-F' located in the eastern part of the Study Area, extending from St. Marys to Thorndale, and the eastern edge of London to Lake Erie.

Section E-E' illustrates that deep bedrock wells that penetrate deep into the Lucas Formation occur in Lucan-Biddulph in the north, while shallow overburden wells predominate elsewhere along the section. Bedrock dips from north to south along this section.

Section F-F' indicates that bedrock wells installed in the Dundee and Lucas Formations are dominant in the north and overburden wells occur in the south. Bedrock dips significantly from north to south with the Dundee Formation and the Lucas Formation the most significant rock units.

4. HYDROGEOLOGY

4.1 Hydrologic Cycle and Groundwater Principles

Before proceeding with an analysis of the hydrogeology of Middlesex and Elgin, the following is a review of some of the basic concepts of groundwater flow. A Glossary of Technical Terms used in this report is presented in Section 12.

Groundwater Flow and the Hydrologic Cycle

The continuous circulation of water between ocean, atmosphere and land is called the hydrologic cycle (**Figure 4.1)**. Precipitation falls onto the watersheds in the form of rain or snowfall. A portion of this precipitation runs directly to surface water tributaries as overland flow, while some is returned to the atmosphere via the process of evapotranspiration (combination of evaporation and plant transpiration). The remaining precipitation infiltrates into the ground and becomes groundwater. The rate at which precipitation soaks into the ground is controlled by the permeability and porosity of the shallow soil layers and water table depth.

Once in the ground, the direction and rate of groundwater flow is controlled by the permeability (referred to as hydraulic conductivity) and porosity of the soil or rock material, and by the water pressure (referred to as the hydraulic head). Groundwater generally moves faster in permeable materials such as sand, gravel and fractured rock, and slower in less permeable deposits such as clay or silt.

Aquifers and Aquitards

Hydrogeological units or formations (e.g., layer of soil) that can supply adequate quantities of potable water when tapped by a well are referred to as aquifers. Typical geological units that can be good aquifers include sands, gravels, fractured limestone or sandstone. **Figure 4.1** illustrates the relationship between aquifers, aquitards and groundwater supply wells.

Geological units that are almost impermeable or have a low permeability are referred to as aquitards. While aquitards are not suitable for groundwater supply, they can protect adjacent aquifers from contamination, as they restrict migration of contaminants. Materials that often act as aquitards include clay, clayey glacial till (till is a mixture of clay, silt, sand and gravel deposited by a glacier), shale or unfractured rock.

Confined and Unconfined Aquifers

Aquifers can be defined as either being confined or unconfined. A confined aquifer is bounded or confined between two low permeability units (aquitards). An aquifer is unconfined if its upper surface is defined by the water table. In Middlesex and Elgin, the shallow surficial sand aquifers of the Caradoc Sand Plain and the Norfolk Sand Plain in south Malahide are unconfined. The bedrock aquifers in Middlesex and Elgin are confined because they are overlain by clay or till. From a groundwater management perspective, confined aquifers are usually better protected from contamination than are unconfined aquifers; however, unconfined aquifers can often produce higher quantities of groundwater.

Water Tables and Potentiometric Surfaces

In unconfined aquifers, the top saturated portion of the aquifer is defined by the water table. The slope of the water table over an area defines the direction of groundwater flow. Groundwater flows from areas of higher water table elevation to areas of lower elevation. Often the elevation of the water table surface is a subdued reflection of the topography. For confined aquifers, where there is no water table, the direction of groundwater flow is controlled by the slope or gradient in the potentiometric surface. The potentiometric surface is the imaginary surface developed by plotting and contouring the water levels or hydraulic heads in all wells that tap into the confined aquifer. Groundwater flow in the confined aquifers travels from areas of relatively high hydraulic head to areas of relatively low head. Hydraulic heads in the aquifer are determined by measuring the standing (or static) water level in wells.

Groundwater Recharge and Discharge

The terms recharge and discharge are often used to describe the direction of groundwater flow near the ground surface. Where the net direction of groundwater flow is downward, the area is under recharge conditions, while areas of net upward vertical flow are referred to as groundwater discharge zones. Identification of recharge and discharge areas within a watershed is important from a planning perspective, since contamination of recharge areas can have a wider impact on the aquifer(s). Groundwater flowing downwards can introduce contaminants from the surface into potable aquifers.

Both large scale (regional) and small scale (local) recharge and discharge zones can occur. The number and size of recharge/discharge zones depend on the watershed topography.

4.2 Hydrogeological Setting

There are three major types of aquifers in the Study Area: shallow unconfined overburden aquifers, deeper overburden aquifers, and bedrock aquifers (Goff and Brown, 1981). The most significant shallow unconfined aquifers are associated with relatively large sand plains such as the Caradoc Sand Plain (Strathroy, Mount Brydges, London), the Bothwell Sand Plain (Wardsville, Newbury) and the Norfolk Sand Plain (southern part of Malahide Township, portions of Aylmer). Intermediate depth aquifers consist of saturated sand and gravel deposits in the overburden and can be discontinuous in nature. The White Oak Aquifer located in southwest London is an example of such an aquifer. Bedrock aquifers are often at, or a few metres beneath, the overburden/bedrock interface. Bedrock aquifers in Adelaide Metcalfe and north Thames Centre and Lucan-Biddulph are examples of such aquifers.

4.3 Overburden Aquifers

4.3.1 Hydrostratigraphy

There are generally two types of overburden aquifers in the Study Area: shallow unconfined aquifers and deeper confined overburden aquifers. The overburden hydrogeology is strongly influenced by the depositional glacier environment as described in Sections 2 and 3.

Surficial Sand Aquifers

Shallow unconfined aquifers are associated with relatively large sand plains such as the Caradoc Sand Plain (Strathroy, Mount Brydges, London), the Bothwell Sand Plain (Wardsville, Newbury) and the Norfolk Sand Plain (south Malahide Township, portions of Aylmer). There are also sand deposits in south Central Elgin and Southwold Township.

As well, shallow unconfined aquifers are associated with glacial spillway deposits such as in the Fanshawe Lake area, spillway deposits near Dorchester and along the flanks of moraines, most particularly the Wyoming, Mitchell and Lucan Moraines (Huron Lobe moraines).

The surficial sand aquifer is generally less than 15 metres thick. **Map 4.1** illustrates wells less than 15 metres deep (in red). This map indicates that the areas densely covered with shallow wells coincide with the Physiography (see Section 2.3 and **Map 2.3**) and the Quaternary Geology (see Section 3.2 and **Map 3.2**). The water table is relatively shallow on the sand plain (usually within 2 to 5 metres of surface).

Table 4.1 is a summary of test pumping rates from the Water Well Records. As indicated in this table, the median pumping rate for shallow wells is 23 litres/minute, with 80% of these wells pumping between 5 litres/minute and 91 litres/minute. Because of the high permeability of these deposits, well yields can be high, but are often limited by the low available drawdown where the deposits are less thick. There are many old dug wells and sand point wells installed in the shallow unconfined aquifer that are not included in the Water Well Record database.

Water quality in shallow overburden aquifers is usually fresh but can contain high iron and manganese. Shallow overburden aquifers are susceptible to anthropogenic sources of contamination such as agricultural fertilizers and septic systems. The Ministry of the Environment collated water quality data from water wells determined to be not affected by anthropogenic sources of contamination (MOE, 1996). **Table 4.2** summarizes the results of this research for overburden wells. As well, **Figure 4.2** summarizes water quality for iron, chloride and hardness for all of the wells included in the MOE study. Iron concentrations exceeded the Ontario aesthetic standard of 0.3 mg/L in more than 50% of the wells included in the study.

<u>Intermediate Depth and Deep Overburden Aquifers</u>

Intermediate depth aquifers consist of saturated sand and gravel deposits in the overburden and are very discontinuous in nature due to glacially-related erosional and depositional conditions. Sand and gravel deposits have been identified between different till sheets such as the Port Stanley Till which overlays the Catfish Creek Till in south London and Central Elgin. However, sand and gravel deposits are also found within individual till sheets reflecting the heterogeneous nature of glacial deposits. Although these aquifers can be consistent over a few hundred metres, and can be mapped at that scale, they cannot be delineated on a regional basis.

Table 4.1
Summary of Well Pumping Rates
Overburden Wells

Flow Rate (L/min.)	All Wells	Well Depth		
		<15m	15m<well<30m	>30m
	Number of Wells			
<5	536	346	134	56
5 to 10	716	352	192	172
10 to 15	766	324	195	247
15 to 25	2022	680	667	675
25 to 50	3187	902	1133	1152
50 to 75	1016	305	357	354
75 to 100	367	185	85	97
100 to 150	237	102	53	82
150 to 250	165	84	41	40
250 to 500	97	31	28	38
500 to 1000	33	4	12	17
1000 to 2000	21	12	4	5
>2000	22	3	8	11
Pumping Rate (L/min.)				
Median	27	23	32	32
90^{th} Percentile	82	91	68	70
10^{th} Percentile	9	5	9	14

Map 4.1 graphically shows the distribution of overburden water wells between 15 metres and 30 metres in depth (purple dots) and over 30 metres thick (green dots). Generally, the intermediate depth (15 to 30 metres) category is associated with the latest glacial period and tends to have thinner aquifers. The deeper category wells (> 30 m) are associated with older glacial periods and tend to be thicker.

Locations where intermediate depth overburden aquifers occur include Southwest Middlesex, with wells installed in the Bothwell Sand Plain (former Mosa Township), north of Strathroy in the vicinity of the Seaforth Moraine, and in the Dorchester area associated with the Dorchester Moraine. As indicated in **Table 4.1**, the median pumping rate for intermediate depth overburden wells is 32 litres/minute, with 80% of these wells pumping between 9 litres/minute and 68 litres/minute.

Table 4.2
Water Quality
Overburden Wells

	Iron (mg/L)	**Sodium (mg/L)**	**Chloride (mg/L)**	**Sulphate (mg/L)**	**Hardness (mg/L)**	**Conductivity (FS)**
Shallow Overburden Wells (<15 m depth)						
Elgin County						
Number of Samples	17	15	19	13	19	16
Median	0.41	7	20	52	359	645
Minimum	<0.01	2.3	1	6	88	5
Maximum	4.4	34.5	80	140	473	970
Percentage exceeding Ontario Standards	53%	0%	0%	0%	n/a	n/a
Middlesex County						
Number of Samples	14	15	15	13	15	12
Median	0.045	9.2	14	42	311	625
Minimum	<0.01	4.7	2.5	9	110	302
Maximum	1.7	506	145	112	630	1520
Percentage exceeding Ontario Standards	36%	7%	0%	0%	n/a	n/a
Intermediate and Deep Overburden Wells (>15 m depth)						
Elgin County						
Number of Samples	25	24	25	14	25	20
Median	0.35	61.5	22.5	25.75	158	660
Minimum	0.01	0	1	0.5	26	354
Maximum	12.4	224	969	443	520	1730
Percentage exceeding Ontario Standards	56%	13%	28%	0%	n/a	n/a
Middlesex County						
Number of Samples	15	17	17	17	16	15
Median	0.65	60	12	14.5	191.5	520
Minimum	<0.01	2.5	0.05	1	32	354
Maximum	2	325	410	225	391	1270
Percentage exceeding Ontario Standards	67%	12%	12%	0%	n/a	n/a

Reference: Ministry of the Environment, 1996

Deep overburden wells are found in south London and north Central Elgin, Thames Centre, south of the 401, and in north Malahide (former South Dorchester Township). Deep overburden wells also occur in Southwest Middlesex (former Ekfrid Township) and in West Elgin and Dutton-Dunwich. These wells are shown as green dots on **Map 4.1**. The median pumping rate for deep overburden wells is 32 litres/minute, with 80% of these wells pumping between 14 litres/minute and 70 litres/minute (see **Table 4.1**).

The water quality of the intermediate depth and deep overburden aquifers is similar to shallow overburden aquifers (see **Table 4.2** and **Figure 4.2**). Sodium and chloride concentrations tend to be higher than shallow overburden aquifers while hardness levels are slightly reduced. Iron concentrations exceed the Ontario aesthetic standard of 0.3 mg/L in over 50% of the wells included in the MOE study (MOE, 1996).

Clay and Till Aquitards

Although not aquifers, the aquitards in Middlesex-Elgin are an important part of the hydrogeological setting. Lacustrine clays (e.g., the Ekfrid Clay Plain) provide protection to underlying aquifers, but limit the amount of infiltration to these aquifers.

The tills of Southwestern Ontario, unlike those of Central and Eastern Ontario, have significant proportions of clay and silt and generally have a very low permeability. Therefore, the tills also act as aquitards and protect underlying aquifers from contamination.

4.4 Bedrock Aquifers

4.4.1 Hydrostratigraphy

The two main regional bedrock aquifers are the limestone aquifer in the eastern part of the Study Area and a basal shale aquifer along the Study Area's western border. **Map 4.2** presents the areal distribution of wells installed in bedrock. The map differentiates between wells that penetrate less than 3 metres into bedrock and wells that penetrate deeper into bedrock. **Table 4.3** summarizes these wells by depth of penetration from the overburden surface, bedrock type (shale or limestone), and bedrock formation. Wells that only penetrate bedrock a few metres are most likely hydraulically connected to a layer of sand, gravel and highly fractured bedrock that often exists at the overburden-bedrock interface. These aquifers are often called “basal” aquifers or “contact” aquifers.

Wells that penetrate deeper into bedrock tap into fractures in the bedrock . These wells generally are not cased in bedrock (i.e., open hole) and it is not unusual for a bedrock well to intercept fractures over a relatively wide depth range. **Table 4.3** presents data for wells by bedrock formation (based on the interpretation of formations from the oil and gas well database) using the total depth of the well (e.g., if the total depth of the well is beneath the interpolated surface of the Lucas Formation, that well is designated a Lucas Formation well, even though it would receive groundwater from both the Lucas Formation and the overlying Dundee Formation. **Table 4.4** summarizes pumping test data for the bedrock wells using the same categories as **Table 4.3**.

Table 4.3
Summary of Bedrock Wells

Bedrock Wells	Number of Wells	Percentage of Total Number of Bedrock Wells	Penetration Below Overburden		
			Depth of Penetration	Number of Wells	Percentage of Bedrock Group
All Bedrock Wells	4155	100%	<3 m	1604	39%
			>3 m	2551	61%
By Bedrock Type					
Shale Wells	1760	42%	<3 m	895	51%
			>3 m	865	49%
Limestone Wells	2395	58%	<3 m	709	30%
			>3 m	1686	70%
By Bedrock Formation					
Kettle Point*	364	9%	<3 m	236	65%
			>3 m	128	35%
Hamilton Group*	1343	32%	<3 m	641	48%
			>3 m	702	52%
Marcellus*	53	1%	<3 m	18	34%
			>3 m	35	66%
Dundee**	1556	37%	<3 m	688	44%
			>3 m	868	56%
Lucas**	775	19%	<3 m	21	3%
			>3 m	754	97%
Deeper than Lucas**	64	2%			

**- principally shale, ** - principally limestone*

Table 4.4
Summary of Well Pumping Rates
Bedrock Wells

Bedrock Wells	Depth of Bedrock Penetration from Overburden	Pumping Rate (L/min)		
		Average Rate	Median Rate	Maximum Rate
All Bedrock Wells	all wells	54	36	3,814
	<3 m	42	32	3,178
	>3 m	56	36	3,814
By Bedrock Type				
Shale Wells	<3 m	35	23	3,178
	>3 m	38	23	3,178
Limestone Wells	<3 m	48	45	686
	>3 m	71	45	3,814
By Bedrock Formation				
Kettle Point*	<3 m	23	23	109
	>3 m	19	9	91
Hamilton Group*	<3 m	42	23	3,178
	>3 m	36	18	1,762
Marcellus*	<3 m	50	30	141
	>3 m	55	45	141
Dundee**	<3 m	47	41	454
	>3 m	49	41	454
Lucas**	<3 m	48	41	454
	>3 m	73	41	454
Deeper than Lucas**		325	48	3,814

**- principally shale, ** - principally limestone*

<u>Limestone Aquifer</u>

The **Limestone Aquifer** occurs in the northeastern part of the Study Area in the northern part of Thames Centre (former West Nissouri Township) and in Lucan-Biddulph (former Biddulph Township). The limestone aquifer is principally associated with the Dundee Formation as well as the Lucas Formation (a member of the Detroit River Group) and while wells are installed both deep into the bedrock (70% of limestone wells) and at the overburden bedrock interface (basal wells: 30% of all limestone wells), deep bedrock wells predominate. Ninety-eight percent (98 %) of the limestone wells yielded 150 litres/minute or less with a median yield of 36 litres/minute. There is only a slight difference between the median yield from basal limestone wells and deeper limestone wells (27 litres/minute compared to 36 litres/minute, respectively).

The water quality in the limestone wells is generally good with, of course, high hardness being a common occurrence. High iron concentrations and sulphide odours also occur. **Table 4.5** summarizes the water quality data from water wells determined to be not affected by anthropogenic sources of contamination (MOE, 1996). **Figure 4.2** also shows hardness, chloride and iron concentrations in these wells plotted against the depth of well. Iron concentrations exceeded the Ontario aesthetic standard of 0.3 mg/L in approximately 40% of the bedrock wells tested. High sodium and chloride concentrations were also more common in bedrock wells than overburden wells.

Table 4.5
Water Quality
Bedrock Wells

	Iron (mg/L)	**Sodium (mg/L)**	**Chloride (mg/L)**	**Sulphate (mg/L)**	**Hardness (mg/L)**	**Conductivity (FS)**
Elgin County						
Number of Samples	17	18	19	16	20	18
Median	0.22	47.75	44.5	7.25	152.5	610
Minimum	<0.01	11	1	1	15	346
Maximum	3.9	280	666	900	965	2635
Percentage exceeding Ontario Standards	41%	22%	21%	6%	n/a	n/a
Middlesex County						
Number of Samples	31	32	33	29	33	27
Median	0.12	40.5	10	44	178	560
Minimum	<0.01	4.7	0.5	0.5	36	261
Maximum	2.1	1080	1520	825	982	4750
Percentage exceeding Ontario Standards	35%	9%	9%	3%	n/a	n/a

Reference: Ministry of the Environment, 1996

Groundwater flow in the Limestone Aquifer is attributed to secondary porosity produced by fractures. Solution weathering caused by the migration of groundwater under-saturated with respect to calcite can increase the rock permeability by dissolving the fracture surfaces.

Shale Aquifer

The **Shale Aquifer** occurs near the western border of the Study Area extending north from the Thames River, chiefly in the municipality of Adelaide Metcalfe. The shale aquifer is principally associated with the Hamilton Group formations (see Section 3). Basal bedrock wells are more prevalent (51% of all shale bedrock wells). Based on pumping test data, well yields in the Shale Aquifer are much less in comparison to the Limestone Aquifer located to the east. Ninety-six percent (96 %) of all shale bedrock wells yielded 75 litres/minute or less, with a median yield of 9 litres/minute. The median yield for basal shale wells was 18 litres/minute, much greater than the median pumping rate for deeper shale wells (5 litres/minute). This is not unexpected because unfractured shale generally has too low a permeability to be considered an aquifer material. Groundwater from these wells comes from fractured shale and sand and gravel at the overburden/bedrock interface for basal wells or from small sandstone partings in the shale bedrock for deeper wells.

Groundwater quality from the shale aquifer is generally very poor, with high dissolved solids, and elevated chloride concentrations are prevalent. The water is also highly odourous. Generally, the shale aquifer is a marginal aquifer in terms of quantity and quality but is used because there are few overburden aquifers in this area.

4.5 Groundwater Flow

4.5.1 The Water Table

As described in Section 4.1, the water table is the surface where the fluid pressure is atmospheric, generally equivalent to the point where the voids in soil or rock are saturated with water. Water infiltrating through the ground surface moves vertically downward to the water table. Beneath the water table, groundwater can flow both horizontally and vertically. The direction and rate of groundwater movement is controlled by two factors: hydraulic gradient and hydraulic conductivity. The hydraulic gradient is the technical term for the difference in pressure or water level that causes water to flow from areas of high water level to low water level. Shallow horizontal groundwater flow generally follows the surface topography. Vertical groundwater flow is downwards when groundwater is recharging lower strata and can be upwards (discharge conditions) where deeper strata have higher water levels such as in river valleys.

To develop an understanding of groundwater flow in the Study Area, a "Water Table Map" (**Map 4.3**) was constructed using water levels recorded in shallow wells (<15 metres deep) and the location and elevation of streams and rivers in the Study Area. As this map shows, the water table mimics surface topography (see **Map 2.1**) with high elevations in the northeast and lower elevations in the southwest and south. The river and creek valleys are clearly indicated on the map as being points of locally low water table levels. Horizontal groundwater flow directions will mimic surface water flow (i.e., groundwater will flow towards the river and creek valleys).

4.5.2 Overburden Groundwater Flow Direction

Regional groundwater flow directions in the overburden were evaluated by plotting water levels from intermediate depth overburden wells (between 15 metres and 30 metres depth) and deeper overburden wells (>30 m) (**Map 4.4** and **Map 4.5**, respectively). Generally, the groundwater flow pattern is similar for both types of overburden wells, with water levels being relatively lower in the deep overburden wells. Water levels are higher in the northeast part of the Study Area, reflecting higher topography in this area. The bedrock is relatively shallow in this area (exposed in St. Marys, which is within the buffer of the Study Area). The higher water levels in the overburden may also be a reflection of higher water levels in the underlying bedrock at this location.

The other areas of higher water levels are influenced by the moraines. This phenomenon is more dominant in the intermediate depth overburden wells **(Map 4.4**). Specifically, the Mitchell and Lucan Moraines cause higher water levels in the area between Birr and Melrose in Middlesex Centre. Similarly, the Westminster and Ingersoll Moraines cause higher water levels in Thames Centre, south of the 401 south of Dorchester.

There are water elevation lows in the overburden aquifers in southeast Malahide and Bayham (located in the south-east buffer area). A similar location of lower water levels is the area around Port Stanley in Central Elgin, which is influenced by Kettle Creek. Water levels along the rest of the Lake Erie Shore are not as depressed, probably due to the topographically high bluffs along the shoreline (in particular, the area between Catfish Creek and Port Stanley).

Water levels are also depressed at the lower reach of the Thames River in the Study Area (i.e, downstream of Wardsville). This is due, in part, to lower surface elevations and also the transition from the Ekfrid Clay Plain in the east to the Bothwell Sand Plain in the west.

The last notable area of lower water levels is in the northwest corner of the Study Area (northwest part of North Middlesex). Water levels in this area are influenced by the topographically low Thedford Marsh and ultimately Lake Huron (located just beyond the buffer).

4.5.3 Bedrock Groundwater Flow Direction

Groundwater flow within the bedrock is primarily through fractures. The type of bedrock influences the number, size and frequency of fractures. Limestone is generally more permeable than shale and, therefore, is a better aquifer and requires less hydraulic gradient to move the same amount of water.

The direction of horizontal groundwater flow has been estimated through the mapping of static water level elevations in bedrock wells as recorded in the MOE Water Well Records (**Map 4.6**). All wells completed in the bedrock were used in this map. Therefore, the resulting static water level represents the average hydraulic head in all aquifers intercepted. As a result, the information is best used to assess the average direction of groundwater flow in the bedrock, with the realization that flow directions in both the lateral and vertical direction may differ within individual water-bearing bedrock horizons. It is very difficult to determine if water levels in bedrock wells are reflective of their total depth (i.e., water levels are different in deeper bedrock wells than wells that just penetrate the bedrock) because the entire thickness of bedrock is uncased (i.e., open hole).

An analysis of **Map 4.6** indicates that on a regional scale, groundwater flow generally coincides with the water table with the exception of lower levels in the north-central area of the Study Area (Lucan-Biddulph). The water level elevation in this area is similar to the water level elevation to the west in North Middlesex. It is believed that a change in bedrock formation occurs in this area, with the bedrock significantly more permeable, causing a general lowering of water levels. This phenomenon was identified to the north of the Study Area in West Perth and East Huron, where sinkholes have been identified (i.e., a karstic environment). In the Lucan-Biddulph area, there is thicker overburden than to the north where the sinkholes have been identified. The significance of this condition is further discussed in Section 4.6.

There is a slight increase in water levels along the north-west border of the Study Area, west of Strathroy at Highway 402. This may indicate an area influenced by a combination of the Seaforth Moraine (see **Map 2.1**), and an increase in the bedrock surface elevation (see **Map 2.3**) at this location.

4.6 Groundwater Infiltration and Recharge

Identification of areas of significant infiltration and groundwater recharge is important from a groundwater management perspective. Recharge areas act to replenish the aquifer and are susceptible to impacts as near surface contaminants can migrate with groundwater flow into the sub-surface and affect potable water aquifers. Contamination in recharge areas can also affect surface water quality as a result of subsequent groundwater base flow into receiving streams and wetlands.

For this study, mapping of areas of significant potential recharge and discharge has been completed by mapping areas where there is a high potential of either upward or downward vertical hydraulic gradients, based on depth to static water level data.

Mapping of the potential direction of vertical hydraulic gradients was completed by subtracting the potentiometric levels for the different well categories (intermediate depth overburden, deeper overburden and bedrock wells; **Map 4.4**, **Map 4.5** and **Map 4.6** respectively) from the water table level(**Map 4.3**). These maps show areas of potential recharge (the potentiometric surface is lower than the water table) as shades of green. Potential discharge conditions (the potentiometric surface is higher than the water table) are shown as shades of blue. Areas where there is less than 5 metres of difference between the water table and the potentiometric surface are shown as white. Wells that have been recorded in the MOE Water Well Records as flowing, indicating strong upward groundwater flow gradients, are presented as red dots.

Intermediate Depth Overburden Wells

Map 4.7 is the recharge/discharge map for the intermediate depth overburden wells (wells between 15 metres and 30 metres depth). Areas of high potential recharge (green areas) include:

- the Wyoming Moraine in the northwest part of the Study Area south of Parkhill and north of the Ausable River

C the Seaforth Moraine north of Strathroy

C the Ingersoll Moraine, particularly at the former village of Byron in northwest London , south of the Thames River

C the St. Thomas Moraine extending from north Malahide to south of St. Thomas

C in the extreme southwest corner of the Study Area, southeast of Wardsville, due west of West Lorne, related to the Blenheim Moraine in Chatham-Kent which extends from Blenheim in the west, through Ridgetown and in Kintyre.

Areas with high discharge potential (areas in blue) include:

C the north branch of the Thames River, extending from St. Marys in Perth County through north Thames Centre (former West Nissouri Township) to north Fanshawe Lake

C the Thames river in north London at the University of Western Ontario (and also a portion of Medway Creek)

C the Thames River, north of Byron, where the river bends to the north around the Ingersoll Moraine

C the Ausable River south and west of Parkhill, especially between Thedford and Arkona along the western border of North Middlesex

C Mud Creek upstream of the Parkhill Dam

C the lower portions of creeks that flow into Lake Erie including (from east to west) Big Otter Creek southeast of Aylmer; Catfish Creek between New Sarum and Port Bruce; Kettle Creek between St. Thomas and Port Stanley; and Talbot Creek east of Port Talbot in Dutton-Dunwich

C the Thames River valley between Delaware in the east and Strathburn in the west.

Deep Overburden Wells

Map 4.8 shows the recharge/discharge conditions for the deep overburden wells (greater than 30 metres depth). Recharge areas shown on this map are broader but with less pronounced differences in elevations than the intermediate depth overburden wells (**Map 4.7**), with a very notable exception. There is an area of high recharge potential in Lucan-Biddulph. This condition is also noted in the Bedrock recharge/discharge map and is discussed more fully in that section.

There is also significant recharge potential along the Wyoming Moraine northwest of Ailsa Craig. There is another area indicative of strong recharge potential at the Ingersoll Moraine, at the former village of Byron in west London, south of the Thames River (similar to that noted for the intermediate depth wells).

Discharge conditions (blue areas) for the deep overburden wells are also somewhat different than the intermediate depth wells. A discharge area is identified between Ailsa Craig and Lucan, related to the Little Ausable River to the north and the Nairn Creek to the south. Discharge areas are also indicated along the main (south) branch of the Thames River, from London east to Dorchester, with a significant area in the buffer area near Ingersoll in Oxford County at the confluence of the Thames River and the Middle Thames River.

In comparison to the intermediate depth overburden wells, there is less discharge potential along Big Otter Creek, Catfish Creek and Kettle Creek that feed into Lake Erie in the east portion of the Study Area. There is however, stronger recharge potential for Talbot Creek and a number of smaller streams that enter Lake Erie west of Iona.

Discharge conditions are also indicated along the Sydenham River at the west boundary of the Study Area, near Alvinston, in Lambton County.

Bedrock Wells

Map 4.9 shows the recharge/discharge conditions for the bedrock aquifer. As described in the review of the bedrock potentiometric surface, the water levels in the bedrock wells in Lucan-Biddulph are very low, well below the elevation of the overburden/bedrock interface. This results in a large difference between the water table elevation and the bedrock water levels indicating a very strong recharge potential for this area (the dark green area north of Lucan on **Map 4.9**) with respect to the bedrock area. **Map 4.7** indicates that a substantial portion of this area exhibits discharge conditions or neutral conditions with respect to the intermediate overburden aquifer.

Map 4.10 illustrates the difference between the water level in the bedrock and the surface of the bedrock. As this map indicates, the only area where the water level in the bedrock is beneath the bedrock surface is the Lucan area.

A similar phenomenon was identified in West Perth, Perth County and East Huron, Huron County, located north of Lucan-Biddulph. In those areas the overburden is significantly thinner and sinkholes have been identified. Sinkholes are areas of karstic (limestone with large cavities made by water solubilizing the limestone) limestone and can cause rapid recharge to the bedrock.

Cross sections through this area were prepared (see **Map 4.11**), and they graphically indicate the low water levels in the bedrock wells. As this map also indicates, there is significant overburden in the area consisting mainly of clay or till (also referred to as diamicton) which will limit the amount of recharge caused by the high positive gradient in this area. A study of the sinkholes of East Huron and West Perth is currently being conducted by the Ausable Bayfield Conservation Authority and may clarify many of the potential groundwater impact issues related to it.

4.7 Potential Groundwater Discharge Areas

Another method recommended by the Ministry of the Environment to define potential discharge areas is to plot areas where the water table (**Map 4.3**) is predicted to be above ground surface (**Map 2.1**). The rationale for this approach is that areas where the water table is predicted to be higher than ground surface represent areas where there are abrupt changes in topography near surface water since the water table map was developed assuming that the water table coincided with surface water elevations. **Map 4.12** is the result of this analysis. Overall, there are very few areas where the water table is predicted to be significantly above ground surface with a notable exception near Byron, located in west London, east of Komoka. This area does have relatively abrupt changes in topography. Overall, it is concluded that this method of identifying potential discharge areas is not applicable for the Study Area and is more suited to areas where there are larger changes in topography.

4.8 Water Supply

This section presents a summary of water wells in terms of specific capacity and a summary of the numbers used in the Study Area.

4.8.1 Specific Capacity

The distribution of specific capacities of all overburden wells is shown on **Map 4.13**. The average specific capacity of the overburden wells is 32 m^3/day/m. The analysis shows that 80 percent of wells have a specific capacity between 0.8 and 58 m^3/day/m.

Map 4.14 presents the distribution of specific capacities of all bedrock wells. The average specific capacity of the limestone wells is 31 m^3/day/m, which is similar to the overburden wells and higher than the average specific capacities for wells in the shale aquifers. The analysis shows that 80 percent of wells have a specific capacity between 0.7 and 43 m^3/day/m.

4.8.2 Distribution of Type of Wells

The percentage distribution of the different types of wells utilized in the Study Area is shown in **Figure 4.3**. Overburden wells account for 74% of the wells reviewed for this study; the remainder are bedrock wells. As this figure indicates, shallow wells are the dominant overburden well with roughly the same proportion of intermediate depth wells (between 15 metres and 30 metres in depth) and deeper overburden wells (greater than 30 metres depth).

Of the bedrock wells, 39% are basal bedrock wells (wells that penetrate the bedrock by less than 3 metres) and 61% are deep bedrock wells (wells that penetrate the bedrock more than 3 metres).

4.8.3 Distribution of Depth of Wells

Figure 4.4 presents histograms of the number of wells by depth. This figure shows that the most overburden wells are relatively shallow (<20 metres depth) and most bedrock wells are between 20 metres and 50 metres deep.

4.9 Aquifer Intrinsic Susceptibility Mapping

Generally, the intent of groundwater intrinsic susceptibility mapping is to identify areas where groundwater is relatively more susceptible to impact from surface contamination. In summary, intrinsic susceptibility mapping consists of the following components:

C Water well records are used to derive the "Intrinsic Susceptibility Index" for each well. Information from the records on soil or rock types encountered and their thickness is used

C A "K" factor is assigned for each type of soil or rock indicated in the well record. The "K" factor varies inversely with the permeability of the soil or rock. For instance, sand has a "K" factor of 2 and clay has a "K" factor of 6. The intrinsic susceptibility index for that layer is the "K" factor multiplied by the thickness of the layer.

C The "first" aquifer is identified as any consecutive grouping of aquifer type layers (e.g., sand, gravel, limestone) that is at least 2 metres thick and is at least partially saturated (i.e., the water table is above the bottom of the grouping). A consecutive grouping includes non-aquifer (e.g., clay) layers of less than 1 metre thickness.

C Aquifers are further classified as "confined" (where the water table elevation is at least 4 metres above the top of the aquifer layer) or "unconfined" (where the water table elevation is less than 4 metres above the top of the aquifer).

C The Intrinsic Susceptibility Index for the well is the sum of each layer's ISI above the top of a confined aquifer and to either the top of the aquifer layer or the water table (whichever is lower) for an unconfined aquifer.

If no "aquifer" is identified in the well record, the process is repeated using a reduced aquifer thickness criterion of 1 metre. If an aquifer is still not identified in the well record, then the ISI for that well is the sum of all ISI values for each layer in the well record.

The Intrinsic Susceptibility Map is developed by using a computer algorithm to interpolate between the ISI values calculated for each well. The ISI map has three categories: low vulnerability areas with ISI values greater than 80, moderate vulnerability areas with ISI values between 80 and 30, and high vulnerability areas with ISI values less than 30.

The MOE Terms of Reference states that the interpolation should be completed on the "indexed" scores (each well is assigned an index of 1 -high vulnerability, 2 - moderate vulnerability and 3- low vulnerability). Using indexed values eliminates any skew from high ISI values (which can be over 400 in areas with thick, low permeability overburden) caused by the interpolation algorithm. However, index values will also eliminate valid differentiation within an ISI category (e.g., ISI values of 32 and 78 both have an indexed value of 2).

4.9.1 Uncertainty Assessment of Aquifer Susceptibility

Estimation of aquifer vulnerability is not an exact science, and involves many assumptions that are necessary for a regional assessment. Some drawbacks of the method include:

- it is based on the Water Well Records which have varying levels of reliability
- since it is based on Water Well Records, wells that do not have a record (i.e., installed before 1945 or installed (e.g., hand dug) by the owner are not included in the assessment
- since the ISI is evaluated only at wells and values are interpolated between the wells, the map is more reliable in areas where there are many water wells and less reliable in areas where there are few water wells.

Because of these concerns, the aquifer vulnerability maps produced for this study are best used as a guidance tool for land use planners, and should not be used on their own to make site specific decisions. They can be used as a coarse screening tool where the groundwater vulnerability is a factor in the planning decision-making process.

In order to quantify uncertainty associated with the ISI method, the following analysis was completed:

- two different interpolation algorithms were used (Kriging and Natural Neighbour)

- use of indexed scores, non-indexed scores, and modified non-indexed scores (maximum capped at 130), and

- a sensitivity assessment consisting of randomly selecting 80% of the ISI values, interpolating the ISI areas with these data and then using the remaining 20% of the ISI values to validate the interpolated areas by comparing the calculated ISI to the ISI predicted by the interpolation algorithm for each location.

The result of the assessment of the interpolation algorithm and the scoring system are summarized in **Table 4.6**. In terms of the scoring system, the use of indexed scores results in larger high and moderate vulnerability areas. The use of the modified (by having a maximum ISI of 130) non-indexed method increases the high and moderate vulnerability areas and reduces the low vulnerability area in comparison to using the non-indexed scores.

The results indicated no significant difference between the two interpolation algorithms considered. The Natural Neighbour algorithm can only interpolate between data points and therefore has a smaller total area than the Kriging algorithm, which can extrapolate right to the buffer area boundary. As indicated in **Table 4.6**, there is less than a 2% difference in the results of the different interpolation algorithms.

Table 4.6
Summary of ISI Sensitivity Assessment

ISI Category	Indexed Scores		Non-Indexed Scores		Modified Non-Indexed Scores	
	Area (km^2)	Percentage of Total Area	Area (km^2)	Percentage of Total Area	Area (km^2)	Percentage of Total Area
Kriging Interpolation Algorithm						
High	1,196	20	897	15	1,025	17
Moderate	2,417	41	1,694	29	2,178	37
Low	2,269	39	3,291	56	2,680	46
Natural Neighbour Interpolation Algorithm						
High	1,114	19	862	15	959	16
Moderate	2,463	42	1,680	29	2,196	37
Low	2,304	39	3,339	57	2,726	46

The results of the calibration/validation assessment are presented in **Table 4.7**. This assessment consisted of randomly selecting 80% of the ISI values calculated for the wells and using that data to interpolate areas of vulnerability. The remaining 20% of the ISI values were used to compare the actual (calculated) ISI versus the interpolated ISI value.

Table 4.7
Calibration / Validation Assessment
of the Intrinsic Susceptibility Assessment

Actual ISI	**Interpolated ISI**	**Index Scores**		**Non-Indexed Scores**		**Modified Non-Indexed Scores**	
		Number of Wells	**Category Percentage (%)**	**Number of Wells**	**Category Percentage (%)**	**Number of Wells**	**Category Percentage (%)**
Kriging Interpolation Algorithm							
High	High	592	60	545	55	561	57
	Moderate	303	31	276	28	308	31
	Low	90	9	164	17	116	12
Moderate	High	118	15	101	13	100	13
	Moderate	497	62	426	53	479	60
	Low	185	23	273	34	221	28
Low	High	90	7	62	5	64	5
	Moderate	398	29	258	19	334	24
	Low	884	64	1052	77	974	71
Natural Neighbour Interpolation Algorithm							
High	High	577	59	528	54	542	55
	Moderate	321	33	287	29	324	33
	Low	87	9	170	17	119	12
Moderate	High	113	14	75	9	81	10
	Moderate	501	63	445	56	494	62
	Low	186	23	280	35	225	28
Low	High	91	7	57	4	62	5
	Moderate	408	30	256	19	350	26
	Low	873	64	1059	77	960	70

This assessment indicates that the ISI method has an accuracy in the order of 60 % (i.e., about 60 % of the interpolated ISI values matched the actual, calculated ISI value for that well location).

There was no significant difference between the interpolation algorithms used in the validation assessment. For high vulnerability areas, the indexed scoring method provided a better result. For instance, only 9 % of the validation wells with high actual ISI values had interpolated ISI values of low vulnerability.

The calibration/validation process is analogous to completing site-specific confirmatory drilling to confirm the predicted vulnerability at a location. Based on the results, it would be expected that the ISI value would be confirmed only 60 % of the time. This reinforces the conclusion that aquifer vulnerability maps produced for this study are best used as a guidance tool only, and should not be used on their own to make site specific decisions. Their use as a coarse screening tool where the groundwater vulnerability is a factor in the planning decision making process should be made with caution.

4.9.2 Results of Aquifer Susceptibility Mapping

The results of the susceptibility mapping are shown on **Map 4.15**. Several trends are identified from this map:

- areas ranked as having a high susceptibility (coloured yellow on map) coincide with the major sand plains. Most of Strathroy Caradoc is mapped as being highly susceptible, coinciding with the Caradoc Sand Plain. This extends east through the former glacial delta at Komoka Kilworth into the City of London where most of the built-up area of the city is mapped as being highly or moderately susceptible

- the extreme corner of Southwest Middlesex is also mapped as highly susceptible due to the Bothwell Sand Plain. The southern portion of Malahide extending into south Central Elgin is similarly mapped as being highly susceptible. This area is an extension of the large Norfolk Sand Plain located to the east

- the area around and to the north of Dorchester is mapped as being highly or moderately susceptible coinciding with the Dorchester Moraine

- the mostly moderately susceptible area in north Middlesex Centre between Melrose in the south and Ailsa Craig in the north is probably related to sand and gravel deposits along the flanks of the Mitchell and Lucan Moraines

C the area marked as being moderately sensitive from Shedden to east of Dutton is not related to any known surficial sand areas and may be due to a low density of water wells in this area (an indication of the uncertainty related to ISI mapping)

C throughout the map, there are several small yellow (highly susceptible) or green (moderately susceptible) areas. This is an artifact of individual wells or the interpolation algorithm used to extend the ISI values from individual wells over the entire area. As such, little importance should be attached to these areas.

To show the protection offered by use of deeper drilled wells, the ISI mapping was also completed using only wells 15 metres or greater in depth (**Map 4.16**). As expected, this map shows that the aquifers for these wells are much more protected than the analysis using all of the wells.

5. GROUNDWATER USE

5.1 Background

This section presents an overview of the different uses of groundwater within the Study Area. Groundwater is used as a potable water source to municipalities and private homes, for irrigation and livestock watering to the agricultural community, and as a non-potable source of water for manufacturing and industry. Groundwater also has an important role in sustaining natural ecological habitats by maintaining base flow to surface water and wetlands. This study identifies the major users of the groundwater resource and quantifies the volumes that are taken. From this information, a water budget assessment is performed, comparing the current demands on the groundwater system with the estimated regional groundwater recharge. The comparison is used to assess if the current groundwater demand is sustainable at the regional level.

5.2 Objectives and Scope of Work

The objectives of this section were to inventory the major groundwater users and to assess, from a regional perspective, if the groundwater supply meets the current demands. The main aspects of the assessment were to:

- identify the major groundwater users and the volume of water taken; compare current demands on the regional groundwater system with the estimated aquifer recharge; and

- inventory known water users who are regulated under Ontario Regulation 459.

5.3 Methodology

5.3.1 Approach

Details on specific approaches used in this assessment are as follows.

Evaluation of Existing Groundwater Demand

An evaluation of the existing groundwater demand was based on the protocols outlined in the MOE Terms of Reference. The approach taken was to inventory the water usage by the following categories:

- Category 1: Public Supply
- Category 2: Self Supply (Residential and Commercial/Industrial)
- Category 3: Self Supply Irrigation
- Category 4: Self Supply Livestock
- Category 5: Self Supply Industrial (manufacturing)
- Category 6: Self Supply Industrial (mining)
- Category 7: Self Supply Other.

Category 1: Public Supply, includes municipal potable water systems that use groundwater as the water source. Information was gleaned from the MOE Water Treatment Plant records, MOE Permit To Take Water (PTTW) database, Ontario Regulation 459 Engineering Reports, and MOE Groundwater Under the Direct Influence of Surface Water (GUDI) studies.

Category 2: Self Supply, includes non-municipal potable water supply wells. This category includes privately owned O. Reg. 459 communal systems, as well as non-communal systems that serve <5 residents. For residential supplies, information on water use was obtained from 2001 Statistics Canada population census data and the MOE Water Well Information System (WWIS). Commercial/Industrial usage data was supplied from the MOE Permit to Take Water database.

Category 3: Self Supply Irrigation, includes water that is primarily used by farmers for irrigation of their crops, or for orchards. This data was supplied by the Ministry of Natural Resources (MNR) at both the township and quaternary subwatershed level. Water used for golf course irrigation, as provided in the MOE PTTW database, was included in this category.

Category 4: Self Supply Livestock, includes water used for watering cattle and farm animals. This data was supplied by the Ministry of Natural Resources (MNR) at both the township and quaternary subwatershed level.

Category 5: Self Supply Industrial (Manufacturing), includes water used for cooling, food processing, and other manufacturing and industrial operations. The information source was the MOE Permit to Take Water database.

Category 6: Self Supply Industrial (Mining), includes water used for aggregate washing and quarry dewatering. Water used for enhanced oil extraction in petroleum reservoirs is also included. The information source was the MOE Permit to Take Water database.

Category 7: Self Supply Other, includes miscellaneous groundwater uses not covered in the above categories, such as groundwater remediation.

Inventorying of O.Reg 459 Regulated Water Supply Systems

These systems include any water system that supplies >50,000 litres of water per day (on more than 2 days in every 90-day period) and is capable of supplying >250,000 litres of water per day, or supplies water to more than five private residents. Examples of such systems include municipal groundwater source water supplies, and large capacity communal wells. The data sources for this information were the MOE Permits to Take Water (PTTW), and information supplied by the municipalities.

5.3.2 Data Sources and Limitations

The data sources that were used in this analysis, and their limitations, are discussed below.

MOE Permits to Take Water (PTTW)

Information on the types of commercial and industrial uses of the groundwater resource was assessed through the available MOE Permit to Take Water (PTTW) database following the protocols outlined in the MOE Terms of Reference. Under the Ontario Water Resources Act (R.S.O. 1990), a permit is required for any water taking that exceeds 50,000 litres/day. The PTTW system generally classifies the permits as being from a groundwater source, a surface water source or both. Permits classified as either having a groundwater source or both a groundwater and surface water source were used in this assessment. As instructed in the MOE Terms of Reference, PTTW that were issued for agricultural purposes, construction activities, dams and reservoir storage and wildlife conservation were precluded.

The limitations to the PTTW data set include:

- Permitted volumes are usually greater than the actual taking. Furthermore, once a permit is issued, there is no commitment on the part of the permit holder to withdraw any water. As a result, the PTTW records may over-estimate the actual quantity of water that is taken.

- PTTW records do not identify smaller takings of groundwater of <50,000 litres/day; therefore, many commercial/industrial uses cannot be identified.

- The identification of the water source is problematic for some water usages. Water takings from ponds are classed as a surface water. However, in reality much of the water flowing into the pond, especially in sand plain areas, may be groundwater base flow. For purposes of this assessment, any water source identified as a pond was considered as a groundwater source.

A survey was completed of large (>200,000 L/d) water taking permit holders to allow a comparison of the permitted water taking as shown in the MOE PTTW records, and the actual water use. The survey involved sending questionaries to 46 addresses where maximum daily water taking permits exceeded 200,000 L/d. A total of 19 responses was obtained; with six of these responses containing sufficient information to calculate the actual annual water usage. The results of this assessment are presented in **Table 5.1** .

The six complete responses represented a total maximum permitted water taking of 13,279,788 litres/day (includes both surface water and groundwater takings). The majority of these water users were related to Golf Course Irrigation. Reported actual water usage was 5,931,120 litres/day, representing only 44% of the permitted taking. Furthermore, every permit holder reported a smaller water taking than they were permitted. The implications of this assessment are that using the maximum permitted water taking value is likely to overestimate the amount of water that is actually used.

While data limitations exist, this method is deemed to provide an adequate means to identify the larger and more significant water takers in the Study Area.

2001 Population Census Data

Population statistics from the Statistics Canada 2001 census were used to estimate the number of municipal residents that may rely on groundwater as a potable water supply.

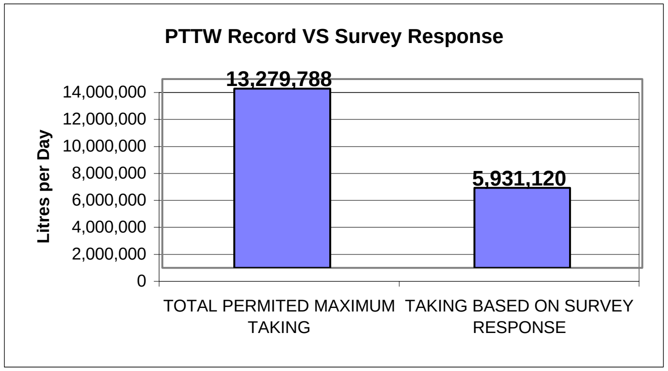
This census data set is considered high quality and accurate. Possible errors are introduced into the analysis when estimating the population of groundwater users who live in municipalities that are serviced by both municipal systems and individual wells. Errors occur when the census boundaries do not correspond to the boundary of the municipal servicing limits. This problem may result in either over or under-estimation of groundwater use.

Agricultural Water Use Data

Agricultural water use data was supplied by the Ministry of Natural Resources (MNR). The data was generated by Rob de Loe Consulting Services on behalf of the MNR (Rob de Loe, 2002). The data contains agricultural livestock watering and irrigation information by watershed derived from the

TABLE 5.1
SUMMARY OF PTTW SURVEY FOR LARGE WATER TAKINGS (>200,000 L/DAY)

PermitNo	Specific Purpose	Source Name		Maximum Litres Per Day	Days Taking Per Year	Maximum Hours Per Day	Average Hours Per Day	Litres Per Minute
01-P-1068	Golf Course Irrigation	109' Well	PTTW	1,063,764	220	13	2	1364
			Survey	640,800	180		8	1335
98-P-1099	Other - Recreational	Dingman Creek	PTTW	436,416	8	8	6	909
			Survey	17,760	12		8	37
00-P-1059	Other - Recreational	Well Points	PTTW	408,823	210	9	5	757
			Survey	62,400	77		2	520
00-P-1036	Field and Pasture Crops	Dugout Pond	PTTW	4,451,500	42	24	12	3100
			Survey	1,341,000	38		15	1490
99-P-1263	Golf Course Irrigation	Well #2	PTTW	196,387	180	24	20	
			Survey	97,920	120		12	136
99-P-1263	Golf Course Irrigation	Well #4	PTTW	49,097	180	12	10	
			Survey	48,960	120		12	68
99-P-1263	Golf Course Irrigation	Well #5	PTTW	26,185	180	12	10	
			Survey	25,920	120		12	36
99-P-1263	Golf Course Irrigation	Well #6	PTTW	292,308	180	12	10	
			Survey	294,480	120		12	409
86-P-1041	Golf Course Irrigation	Medway Creek	PTTW	2,945,808	180	24		1728
			Survey	1,326,780	114		13	1701
86-P-1041	Golf Course Irrigation	Dugout Pond	PTTW	3,409,500	180	10	5	8319
			Survey	2,075,100	168		5	6917



TOTAL PERMITED MAXIMUM TAKING	**13,279,788**	**L/day**
TAKING BASED ON SURVEY RESPONSE	**5,931,120**	**L/day**
TOTAL NUMBER OF SURVEYS	**46**	
TOTAL NUMBER OF SURVEY RESPONSES	**19**	
TOTAL NUMBER OF COMPLETE RESPONSES	**6**	

Includes both Surface Water and Groundwater Takings analysis of the 1996 Agricultural Census data. As a special request for this study, the data was also supplied at the township level.

The main limitation is that the input data was collected at the Ontario Consolidated Census Subdivision (CCS) level and interpreted through the application of agricultural water use coefficients. Because of census confidentiality reasons, the actual location of the water user (farm) is not provided, and only consolidated total water use data is available at the broader CCS level. As a result, the actual location of the water use may be applied to the wrong subwatershed in the analysis.

The raw water usage data supplied by the MNR represents the estimated total water use, including both surface water and groundwater. The proportion of water that has a groundwater source was estimated by multiplying the total water usage by a groundwater use ratio. For irrigation water, the ratio was estimated by dividing the total volume of permitted agricultural water takings using the PTTW database, by the volume of permitted agricultural water takings that are classed as either a groundwater or combined surface water/groundwater source. The resulting ratio was 0.48 for Elgin County (including St. Thomas) and 0.49 for Middlesex County (including London).

Groundwater use for livestock consumption was estimated by multiplying total water usage data provided by MNR (Rob de Loe, 2002) by water source usage ratios provided by MNR. MNR suggests using the ratios 0.93 and 0.52 for groundwater source livestock watering in the Lake Erie and Lake Huron drainage basins, respectively. For this study, the 0.93 ratio was also applied to livestock water use in all municipalities that drained predominantly into Lake St. Clair.

5.4 Findings

The estimated groundwater usage by category is shown graphically in **Map 5.1**, and tabulated in **Table 5.2**. Overall, the total estimated groundwater use is approximately 31,500,000 m^3/year.

TABLE 5.2
SUMMARY OF AVERAGE ANNUAL GROUNDWATER USAGE BY MUNICIPALITY

Municipality	Public Supply	Self Supply, Domestic (Residential)	Self Supply, Domestic (Commercial Institutional)	Self Supply, Irrigation	Self Supply, Livestock	Self Supply, Industrial (manufacturing)	Self Supply, Industrial (mining)	Self Supply, Other	TOTAL VOLUME	TOTAL BY %
	m^3/year	m^3/year	m^3/year	m^3/year	m^3/year	m^3/year	m^3/year	m^3/year	m^3/year	
MIDDLESEX COUNTY										
Thames Centre	706,275	516,940	185,157	1,081,709	374,926	0	1,963,872	0	4,828,879	15.3%
Lucan Biddulph	0	118,169	0	68	135,981	0	0	0	254,218	0.8%
Middlesex Centre	266,486	547,792	0	913,819	381,270	0	783,367	0	2,892,734	9.2%
Strathroy Caradoc	2,529,450	319,311	938,450	758,710	172,898	0	0	0	4,718,819	15.0%
North Middlesex	0	64,003	0	20,071	380,236	0	0	0	464,310	1.5%
Adelaide Metcalfe	0	208,041	0	155	336,954	0	0	0	545,150	1.7%
Southwest Middlesex	0	264,762	0	64,950	214,652	0	0	0	544,364	1.7%
Newbury	0	0	0	0	0	0	0	0	0	0.0%
ELGIN COUNTY										
Central Elgin	182,500	425,280	0	250,592	86,461	0	392,774	57,204	1,394,811	4.4%
Southwold	0	143,336	0	103,670	102,858	0	0	0	349,864	1.1%
Dutton Dunwich	0	140,908	10,310	5,704	134,869	0	0	0	291,791	0.9%
West Elgin	0	184,790	0	12,948	94,183	0	228,362	0	520,283	1.7%
Malahide	0	542,618	0	701,180	465,785	0	0	0	1,709,583	5.4%
Aylmer	0	0	0	0	0	0	0	0	0	0.0%
STUDY AREA										
CITY OF ST THOMAS	0	0	0	0	0	0	0	0	0	0.0%
CITY OF LONDON	0	319,375	2,579,229	2,013,114	73,843	294,090	7,714,526	0	12,994,177	41.2%
MIDDLESEX COUNTY	3,502,211	2,039,018	1,123,607	2,839,482	1,996,917	0	2,747,239	0	14,248,474	45.2%
ELGIN COUNTY	182,500	1,436,932	10,310	1,074,094	884,156	0	621,136	57,204	4,266,332	13.5%
Total Study Area	3,684,711	3,795,325	3,713,146	5,926,690	2,954,916	294,090	11,082,901	57,204	**31,508,983**	
Use by %	12%	12.0%	11.8%	18.8%	9.4%	0.9%	35.2%	0.2%		

The distribution of groundwater (see **Figure 5.1**) use by category is as follows:

Public Supply:	12%
Self Supply, Domestic (Residential)	12%
Self Supply, Domestic (Commercial/Institutional)	12%
Self Supply, Irrigation	19%
Self Supply, Livestock	9%
Self Supply, Industrial (manufacturing)	1%
Self Supply Industrial (mining)	35%
Self Supply, Other	<1%

The largest water users (based primarily on maximum permitted total volumes) are the quarry and mining industry, that accounts for 35% of the groundwater use. Use of groundwater for potable purposes (Public supply and Self Supply, Domestic-Residential) makes up approximately 24% of the groundwater use. A discussion of each of the main categories of groundwater usage is presented in the sections below.

5.4.1 Public Supply

The category of Public Supply includes all groundwater withdrawn by public and private water suppliers and delivered to users that do not supply their own water. In the Study Area, four municipalities operate public groundwater supply systems. These systems include:

Middlesex Centre (3 Systems: Melrose, Komoka-Kilworth, Birr)
Thames Centre (2 Systems: Dorchester, Thorndale Systems)
Strathroy-Caradoc (2 Systems: Strathroy, Mount Brydges Systems)
Central Elgin (1 System: Belmont System).

A summary of the population that is supplied by these municipal systems is shown in **Table 5.3**.

TABLE 5.3
SUMMARY OF POTABLE WATER SOURCE BY MUNICIPALITY

Municipality	Total Population	Population on Municipal Groundwater Wells	Population on Municipal Surface Water	Population on Private Wells	% Population supplied by Groundwater		
					Total	Private Wells	Municipal Wells
MIDDLESEX COUNTY							
Thames Centre	13125	5,031	0	8,093	100%	62%	38%
Lucan Biddulph	4388	0	2,538	1,850	42%	42%	0%
Middlesex Centre	14664	2,863	3,225	8,576	78%	58%	20%
Strathroy Caradoc	20706	15,707	0	4,999	100%	24%	76%
North Middlesex	7839	0	6,837	1,002	13%	13%	0%
Adelaide Metacalfe	3257	0	0	3,257	100%	100%	0%
Southwest Middlesex	7077	0	2,932	4,145	59%	59%	0%
Newbury	422	0	422	0	0%	0%	0%
ELGIN COUNTY							
Central Elgin	12360	1,788	3,913	6,658	68%	54%	14%
Southwold	4487	0	2,244	2,244	50%	50%	0%
Dutton Dunwich	3696	0	1,490	2,206	60%	60%	0%
West Elgin	5464	0	2,571	2,893	53%	53%	0%
Malahide	8809	0	315	8,495	96%	96%	0%
Aylmer	7126	0	7,126	0	0%	0%	0%
STUDY AREA							
CITY OF ST THOMAS	35210	0	35,210	0	0%	0%	0%
CITY OF LONDON	336539	0	331,539	5,000	1%	1%	0%
MIDDLESEX COUNTY	71478	23601	15954	31922	78%	45%	33%
ELGIN COUNTY	41942	1788	17659	22496	58%	54%	4%
Total Study Area	**485169**	**25389**	**400362**	**59418**	17%	12%	5%
Use by %		5%	83%	12%			

A detailed description of the water usage for each municipal system is presented in Appendix A. In addition to the systems listed in Appendix A, the City of London operates two well fields as an emergency backup to their normal piped Lake Erie and Lake Huron potable water source. The Highbury and Fanshawe well fields have a combined pumping rate capacity of 22,000 m^3/day. These well systems are not further discussed in this section, as they are seldom used.

The eight systems listed above supply a combined population of approximately 25,389, or 5% of the Study Area population of 485,169. The majority of the population (400,362 or 83% of the total population) receive their water from Lake Erie and Lake Huron. Individual private wells are estimated to supply a population of 59,418 or 12% of the total Study Area population. A summary of the attributes and water usage of the eight municipal groundwater source systems is provided below:

Thames Centre

<u>Dorchester</u>

Dorchester is located in the Municipality of Thames Centre and is supplied by five wells that pump from an unconfined overburden aquifer. In addition, two backup wells are completed in the bedrock, but are to be used for emergency purposes only, as the water quality is relatively poor. The population that is serviced by these wells is approximately 4,800. The average daily water use is 1,855 m^3/day, while the maximum daily water use is 3,979 m^3/day. The calculated water use per person is 386 litres/day, which is within the provincial average range of 270 to 450 litres/day. Dorchester is currently in the process of expanding their water treatment facilities.

<u>Thorndale</u>

Thorndale is a small community of 750 people, of which 336 residents received their potable water supply from two bedrock wells. These wells on average produce 80 m^3/day. Maximum daily demand is 461 m^3/day. The calculated per capita water use is 238 litres/day, which is less than the provincial average range of 270 to 450 litres/day.

Middlesex Centre

Birr

Birr is a small community (population of 200) within the Township of Middlesex Centre. The water supply system provides water to 18 residences (68 people) and consists of two wells that pump from a confined overburden aquifer. Water use is solely for residential purposes. The design capacity is 88.3 m^3/day. The average daily and maximum daily use has been 15.7 m^3/day and 17.4 m^3/day, respectively. Based on these rates, the calculated average daily water use per capita is 231 litres/day, which is less than the normal provincial per capita range of 270 to 450 litres/day.

Melrose

The Village of Melrose, located in the Township of Middlesex Centre, is supplied by two wells that pump a confined overburden aquifer. The wells serve a population of 217 residents. Water use is predominatly residential. The average daily water use is 56 m^3/day and the maximum daily water use is 81 m^3/day. The design capacity of the system is 277 m^3/day. The calculated average daily water use per capita is 259 litres/day, which is below the provincial average of 270 to 450 litres/day per person.

Komoka-Kilworth

The communities of Komoka and Kilworth are supplied by three wells that pump from a mainly confined overburden aquifer system. The water supply system services a population of 2,600. Water use is estimated to be 90% residential and 10% commercial/industrial. The design capacity is 1,814 m^3/day. The average daily water use is 658 m^3/day, while the maximum daily flow requirement is 1,011 m^3/day. The calculated per capita water use is 253 litres/day, which is less than the provincial average range of 270 to 450 litres/day.

Strathroy-Caradoc

Strathroy

Strathroy is the largest community within the Study Area that relies on groundwater as a potable water source. The community is supplied by 13 wells or well point networks that tap an unconfined overburden aquifer. These wells supply a community of 12,000 people with an average of 6,000 m^3/day of water. Water use is approximately 70 % residential and 30 % commercial/industrial. The design capacity is 12,476 m^3/day. The maximum daily usage is 12,252 m^3. The calculated per capita water use is 500 litres/day, which is slightly higher than the provincial average range of 270 to 450 litres/day.

Mount Brydges

Water needs in Mount Brydges are met by two wells completed in a partially confined overburden aquifer. Water use is predominantly residential. The average daily water demand is 930 m^3/day, while the maximum daily water need is 3,394 m^3/day. The calculated per capita water use is 400 litres/day, which is within the provincial average range of 270 to 450 litres/day.

Central Elgin

Belmont

The Village of Belmont is a community of 1,840 served by two wells located near the town centre. The overburden aquifer is sand and gravel and is confined by clay. The design capacity is 1,800 m^3/day. The average daily water use is 500 m^3/day, while the maximum daily water use is 1,108 m^3/day. The calculated per capita water use is 272 litres/day, which is within the provincial average range of 270 to 450 litres/day.

5.4.2 Self Supply Domestic

The water use classification of Self Supply (Domestic) consists of the following two categories:

a) Residential (residents on private individual wells)
b) Commercial/Institutional.

<u>Residential</u>

Calculation of groundwater usage through private individual wells is presented in **Table 5.2**. These estimates are based on population statistics summarized in **Table 5.3** and presented in more detail in **Appendix A**. The estimated volume of groundwater supplied by private wells is almost 3,800,000 m^3/year. A review of **Table 5.2** and **Table 5.3**, shows the following key observations:

- Overall, 12% of the population is serviced by private wells.

- Middlesex County contains the highest population who use private wells (31,922 or 45% of population), while Elgin County has the second highest population (22,496 or 54% of population).

- Municipalities where >5,000 residents receive their water from private wells include Thames Centre (8,093), Middlesex Centre (8,576), Strathroy-Caradoc (5,000), Central Elgin (6,658) and Malahide (8,495). It is estimated that the City of London has 5,000 residents in the amalgamated townships who use private wells.

- Private wells supply at least 50% of the population in nine of sixteen municipalities, with the exceptions being Lucan Biddulph (42%), Strathroy Caradoc (24%), North Middlesex (13%), Newbury (0%), Aylmer (0%), City of London (1%), and St. Thomas (0%).

- Municipalities that rely the most on private wells by percent of population include Adelaide Metcalfe (100% usage, population 3,257) and Malahide (96%, population 8,495) usage.

Commercial/Institutional

This category encompasses commercial and institutional uses such as water used for hospitals, schools, fire services, air conditioners/heat pumps and other similar uses not covered under public supply. Potable water uses by campgrounds, mobile homes parks, and other private commercial establishments, as well as recreational uses such as snow-making and swimming pool filling are also included.

Overall, approximately 3,700,000 m^3/year of groundwater is used for commercial operations, or 12% of the total groundwater use in the Study Area. The predominant use of groundwater in this category is for heat pumps for which 10 permits were issued. The City of London and Middlesex County have the largest volume of water use in this category, using approximately 3,700,000 m^3/year.

5.4.3 Self Supply Irrigation

This category includes water used for agricultural irrigation, frost protection, and irrigation of golf courses. Agriculture water use estimates were prepared by Rob de Loe Consulting on behalf of the MNR (Rob de Loe, 2002), while non-agricultural irrigation uses (mainly golf courses) were estimated based on PTTW records.

A summary of the water use estimates for agricultural irrigation, as supplied by MNR, is presented in **Table 5.3** and shown graphically in **Figure 5.2.** Irrigation water use is divided into several categories (field, fruit, vegetable and speciality crop) depending upon irrigated crop. These values represent total water use and include surface water and groundwater usage. Estimation of the groundwater component of the water use was determined following protocols outlined in Section 5.3.2.

Estimation of the total groundwater use for irrigation is tabulated in **Table 5.2** by municipality. The estimated total groundwater use was approximately 5,900,000 m^3/year or 19% of the total groundwater use in the Study Area. The majority of irrigation water use was in Middlesex County and the City of London. Irrigation of golf courses was a significant use of groundwater in this category.

5.4.4 Self Supply Livestock

Water use for livestock watering purposes was determined by Rob de Loe Consulting on behalf of the MNR (Rob de Loe, 2002), and is summarized in **Table 5.4**. The report indicates that approximately 3,500,000 m^3/year of water (surface and/or groundwater) is used for livestock watering. Of this amount, it is estimated that 3,000,000 m^3/year is provided by groundwater. Overall, livestock watering is estimated to make up 9% of the total use of groundwater in the Study Area. The distribution of groundwater use by livestock is tabulated in **Table 5.2**.

Based on these calculations, municipalities that use the most groundwater for livestock watering are Malahide, Thames Centre, Middlesex Centre, Adelaide Metcalfe and North Middlesex, with water use being near or above 300,000 m^3/year for each.

5.4.5 Self Supply Industrial (Manufacturing)

This category encompasses industrial producers of food products, metals, chemicals, and paper who use water, mainly in a non-potable capacity, in the manufacturing process. Only one user was identified in the MOE Permit to Take Water records for this category. The use was for food related production in London, and included a maximum permitted groundwater taking of 294,000 m^3/year. This category accounts for approximately 1% of the total groundwater usage.

5.4.6 Self Supply Industrial (Mining)

This category includes industrial users involved with the extraction and washing of minerals including aggregate production in quarries and pits, and enhancing oil field production. For this assessment, quarry dewatering has been considered as a groundwater use in this category. However, it is expected that water comes from both a groundwater and surface water source. In total, 14 permits were issued for quarry or aggregate extraction, and ranged in taking from 30,000 to

TABLE 5.4
AGRICULTURE WATER USE

Municipality	Number of Farms	Livestock (m^3/day)	Field (m^3/day)	Fruit (m^3/day)	Vegetable (m^3/day)	Specialty Crops (m^3/day)	Total (m^3/day)
Malahide	408	500,199	1,389,848	201,716	70,027	153,391	2,315,180
Central Elgin	233	92,849	360,701	77,009	34,621	171,264	736,443
Southwold	227	110,457	10,467	26,489	2,407	271,709	421,529
Dutton/Dunwich	212	144,834	6,048	52,461	1,567	0	204,910
West Elgin	243	101,142	55,887	32,428	5,567	0	195,023
Total: Elgin County	**1,323**	**949,481**	**1,822,950**	**390,102**	**114,189**	**596,364**	**3,873,085**
Southwest Middlesex	313	230,511	73,235	6,296	4,314	76,767	391,123
Strathroy-Caradoc	264	185,672	555,128	26,558	62,230	515,958	1,345,546
Thames Centre	413	402,627	110,157	15,574	2,198	141,645	672,202
Middlesex Centre	515	409,439	85,822	125,621	3,589	1,141,938	1,766,409
London	162	79,299	2,627	98,988	3,444	106,926	291,283
North Middlesex	433	736,036	16,489	74,591	4,320	30,159	861,595
Adelaide Metcalfe	266	361,849	8,777	0	1,109	0	371,735
Lucan Biddulph	149	146,028	3,837	0	1,520	0	151,384
Total: Middlesex County	**2,515**	**2,551,461**	**856,073**	**347,628**	**82,723**	**2,013,392**	**5,851,278**

Data compiled by MNR, (Rob de Loe, 2002)
Values include both surface water and groundwater source.

3,900,000 m^3/year. Two permits were issued for groundwater takings to enhance oil field production. The total permitted groundwater taking for this use is approximately 11,000,000 m^3/year, and represents 35% of the total estimated groundwater use in the Study Area.

5.4.7 Self Supply Other

The MOE category of Self Supply Other represents miscellaneous usages that cannot be easily placed in any other category. From a review of the PTTW in the Study Area, only two permits were present that were considered for this category. The permits were for remediation dewatering in Port Stanley and involved total takings of 57,200 m^3/year. This category represents <1% of the total groundwater used in the Study Area.

5.4.8 Ecological Use

Groundwater has a very important role in the environment, whether it is supplying cool water to fish habitats, maintaining water levels in a wetland or providing needed base flow to streams during times of drought.

In stream environments, base flow provides cooler uniform temperatures for fish spawning areas, and maintains needed water levels, especially during the summer and winter months when precipitation is reduced. Base flow also provides a source of clean water to streams that may be polluted from surface runoff from land activities such as field drainage, or from sewage treatment plant discharges.

Groundwater flow also helps maintain high water tables in wetland environments. High water tables are required by many fauna, flora and inhabitants of the wetland. Wetlands are often found in groundwater discharge environments. Groundwater flow is also important to the growth of specific vegetation types (e.g., forest cover) by keeping water levels within reach of root systems.

5.5 Water Budget

An evaluation of whether groundwater resources are sustainable or being depleted at the regional level can be made by comparing the quantity of groundwater used with the total volume of precipitation that infiltrates and recharges the aquifers.

The process of the hydrological cycle consists of precipitation, evaporation and transpiration that govern the flow of water within the surface and groundwater systems. The general equation describing the water budget is:

$$P=ET+R+I$$

Where
- P = Precipitation
- ET = Evapotranspiration (evaporation + transpiration)
- R = Runoff into watercourses
- I = Infiltration to the sub-surface

The combined runoff and infiltration (to groundwater) components are frequently referred to as "surplus".

The precipitation component includes rainfall, snow, hail and sleet. Evapotranspiration includes all the processes by which water becomes atmospheric water vapour. It includes evaporation from rivers, lakes, bare soil and vegetative surfaces, and from within the leaves of plants.

Runoff is that part of precipitation that travels over the ground surface and through channels to reach an outlet location

Infiltration is made up of two components:

1) Interflow or sub-surface flow, which is part of the precipitation that infiltrates the surface soil and moves laterally through the upper soil horizon toward water courses above the main

groundwater levels. It is generally a lateral flow of water in a perched saturated soil layer and it continues downslope until it reappears at the surface as seepage or springs. Parts of the sub-surface flow may enter the streams promptly, but other parts may take longer before joining the stream flow.

2) Deep percolation that recharges the groundwater and produces base flow to water courses. Base flow in water courses represents a withdrawal from the groundwater table. Although the component entering the aquifer may change the groundwater storage, generally this change is assumed to be negligible in the long term.

The water surplus infiltration was estimated by subtracting estimated regional evapotranspiration (ET) amounts from the regional annual precipitation (P). The data used was climate normals and calculated ET rates for the period between 1961 and 1990, and organized by Agriculture Canada based (Agriculture Canada, 1997) on Ecodistricts. The Study Area falls within three Ecodistricts in the following proportions: Ecodistrict 557 (6%); Ecodistrict 567 (35%); and Ecodistrict 565 (59%). A summary of the climate data is presented in **Table 5.5** and **Table 5.6** .

Table 5.5
Water Budget

	Total Precipitation (mm)			**Evapotranspiration (mm)**			**Water Surplus (mm)**		
Ecodistrict	**557**	**565**	**567**	**557**	**565**	**567**	**557**	**565**	**567**
% of Study Area within Ecodistrict	**6%**	**59%**	**35%**	**6%**	**59%**	**35%**	**6%**	**59%**	**35%**
January	105.3	57.8	71.2	0	0	0	105.3	57.8	71.2
February	74.3	53.5	59.5	0	0	0	74.3	53.5	59.5
March	70.2	70.6	74.5	0	1.1	0	70.2	69.5	74.5
April	71.8	79.4	78.8	30.3	32.4	32.5	41.5	47	46.3

	Total Precipitation (mm)			Evapotranspiration (mm)			Water Surplus (mm)		
Ecodistrict	**557**	**565**	**567**	**557**	**565**	**567**	**557**	**565**	**567**
% of Study Area within Ecodistrict	**6%**	**59%**	**35%**	**6%**	**59%**	**35%**	**6%**	**59%**	**35%**
May	76	74.7	75	72.2	73.8	74.7	3.8	0.9	0.3
June	78.4	86.2	83.4	109	112.3	112.8	-30.6	-26.1	-29.4
July	77.1	79.6	76.1	124.2	129.2	129.1	-47.1	-49.6	-53
August	93.7	93.7	93.2	109.1	114.4	113	-15.4	-20.7	-19.8
September	101.4	88.8	88.8	77.4	82.1	79.8	24	6.7	9
October	90.8	66.1	77.1	39.6	42.4	39.8	51.2	23.7	37.3
November	100.1	88.1	92.7	10.9	13.8	11.6	89.2	74.3	81.1
December	113.6	85.4	95.9	0	0	0	113.6	85.4	95.9
Annual Total	1053	923.9	966.2	572.8	601.4	593.1	480.2	322.7	369.8
Study Area Total	946.4			596.8			348.6		

The average annual precipitation for the Study Area is estimated to be 946 mm. Given that the Study Area is 4,880 km^2, the estimated annual volume of precipitation is 4,616 million m^3, and similarly, 2,912 million m^3 of water is lost to evapotranspiration. The amount of surplus remaining is equal to 1,701 million m^3. The proportion of the surplus that recharges the groundwater environment depends on the infiltration rate of the soil. The infiltration rate of the soil is not homogenous, as the soil conditions vary significantly across the Study Area. A range of 25 to 50 percent of the surplus is assumed to infiltrate, which was used to estimate an average range of recharge volumes for the Study Area (**Table 5.6)**.

Table 5.6

Recharge Volumes

% of Surplus as Recharge	Annual Volume of Recharge	Annual Runoff Volume	Average Annual Infiltration Rate
25 %	425 million m^3	1276 million m^3	87 mm
50 %	950 million m^3	951 million m^3	174 mm

A comparison of the estimated regional aquifer recharge (425 to 950 million m^3/year) with the estimated groundwater use (31.5 million m^3/year) suggests that groundwater use is <10% of the estimated recharge. Considering that the estimated groundwater use is likely conservatively high for reasons discussed in Section 5.3.2, the likelihood of regional groundwater depletion (aquifer mining) is deemed low. Nevertheless, lowering of water tables and depletion of groundwater resources can still occur at the local scale near locations of high groundwater use.

5.6 Ontario Regulation 459 Systems

These systems include any water system that supplies >50,000 litres of water per day (on more than two days in every 90-day period) and is capable of supplying <250,000 litres of water per day, or supplies water to more than five private residents. A list of O.Reg 459 systems that have been identified in this study is detailed in **Appendix A**. This list should not be considered exhaustive, as other systems are likely present that could be defined as an O.Reg 459 system.

6. CONTAMINATION ASSESSMENT

6.1 Background

The development of workable groundwater protection strategies requires some understanding of the potential risks to the resource, both in terms of the location and the severity of the threat that is posed. These risks include point sources of potential contaminants such as gas stations, dry cleaners, landfills, and manufacturing plants, as well as larger scale sources such as the agricultural use of nutrients and pesticides, and the disposal by spreading of sewage and non-sewage biosolids.

The first step in assessing the potential risks to groundwater is to catalogue the various potential contaminant sources, and attempt to assign a geographic coordinate to each source. These data can then be used in conjunction with maps of aquifer vulnerability or intrinsic susceptibility to highlight areas that are at particular risk. The regional potential contaminant inventory (PCI) can also be used to identify potential contaminant sources that fall within local wellhead protection areas (WHPAs), so that these sources can be followed up in greater detail.

While a thorough PCI will typically identify and map hundreds or thousands of potential contaminant sources across a region, not all activities involving the production, storage, use or disposal of hazardous substances will result in groundwater contamination.

6.2 Objectives and Scope of Work

The overall objective of this portion of the Groundwater Study was to develop an inventory of potential contaminant sources across the Study Area, and assign a geographic coordinate to each source where possible. A secondary objective was to develop and detail the methodology used in conducting this inventory, such that the procedure can be repeated when newer or more accurate data become available.

The PCI includes data from all levels of government, as well as a number of commercial sources. The specific tasks involved in developing the PCI included:

- The collection and compilation of information from various sources including private, local, provincial and federal agencies,

- A QA/QC review of the data to remove spurious, duplicate, incorrect or out-of-date information.

- Data management and display using ArcView™ and MS Access™.

- Geocoding of the potential contaminant sources, and the generation of a variety of potential contaminant source maps.

6.3 Methodology for Middlesex and Elgin Potential Contaminant Inventory

The primary task for the PCI involved researching, assembling and geocoding various potential contaminant sources, from a variety of public and private databases and other sources. The following sections describe in some detail the various data sources compiled, including a discussion of the quality and reliability of the data (where known). The methodology used to assign geographic coordinates to each dataset (geocoding) is also detailed.

6.3.1 Public Potential Contaminant Databases

MOE Database CD

The MOE provided a CD containing a compilation database made up of the following individual datasets:

- TSSA Fuel Storage Tanks
- MOE PCB Storage Sites
- MOE Waste Disposal Site Inventory
- MOE Spills.

No metadata or descriptions of the fields were provided with these datasets, and except for the waste disposal sites, no geographic coordinates were given. The accuracy of the locations of the waste disposal sites is not known. The accuracy of the locations of the other three datasets is discussed under the Geocoding section.

MOE Waste Generator Database

Regulation 347 of the Ontario EPA defines a waste generation site as any site, equipment and/or operation involved in the production, collection, handling and/or storage of regulated wastes. A generator of regulated waste is required to register the waste generation site and each waste produced, collected, handled, or stored at the site. This database contains the registration number, company name and address of registered generators as well as the types of hazardous wastes generated.

Geographic coordinates were assigned to these records by manual geocoding, with reference to the street address and postal code contained in the database.

Review of MOE Site Records

A wide variety of reports held in the MOE Southwest Regional Office in London, Ontario were examined. These reports covered a wide variety of topics, including annual landfill monitoring, site investigations, environmental assessments, remedial action plans, groundwater supply studies and other topics. Those reports considered pertinent to groundwater protection were entered into a database, which included information on the site location, a description of the report, the report's author and client, and the type of information contained within. Geographic coordinates (UTM NAD 83) were assigned to each report by reference to maps and figures included in each report.

6.3.2 Commercial Databases

In addition to the available MOE databases and reports, a number of commercial datasets were obtained and, where necessary, geocoded. The datasets were ordered from EcoLog Environmental

Risk Information Services (ERIS) Ltd., and the descriptions of each dataset below are taken from EcoLog's published material:

Anderson's Waste Disposal Sites (1930-2000)

The Anderson database uses historical documentation to locate and characterize the likely positions of former waste disposal sites in Ontario. It aims to identify those sites that are missing from the MOE's Waste Disposal Site Inventory. The Anderson database provides revisions and corrections to the positions and descriptions for sites listed in the MOE database. In addition to historical waste disposal facilities, the database also identifies certain auto wreckers and scrap yards that have been extrapolated from documentary sources.

Geographic coordinates were provided for each site by DMTI Spatial Street Network (as described in Section 6.3.3), hereafter referred to as DMTI Spatial.

National PCB Inventory (1988-1998)

Environment Canada's National PCB inventory includes information on in-use PCB containing equipment in Canada including federal, provincial and private facilities. All federal out-of-service PCB containing equipment and all PCB waste owned by the federal government or by federally regulated industries such as airlines, railway companies, broadcasting companies, telephone and telecommunications companies, pipeline companies, etc., are also listed.

Geographic coordinates were provided for each site by DMTI Spatial.

Inventory of Coal Gasification Plants (to 1988)

This inventory of all known and historical coal gasification plants was collected by the MOE. It identifies sites that produced and continue to produce or use coal tar and other related tars. This information is effective to 1988, but the program has since been discontinued.

Geographic coordinates were provided for each site by DMTI Spatial.

Pesticide Register (1988-1998)

The MOE maintains a database of all manufacturers and vendors of registered pesticides.

Geographic coordinates were provided for each site by DMTI Spatial.

6.3.3 Geocoding Methods

In order to use the information contained in the MOE Contaminant Database, an effort was made to assign geographic coordinates to each unique point. The Fuel Storage Tanks, PCB Sites, and Spills data were located solely by street address, postal code, primary intersection, or general descriptions. The following section describes the methodology used to convert these various location descriptions into UTM easting and northing coordinates (geocoding).

The contaminant information was geocoded against the following base data:

- Six Digit Postal Code Polygons: A commercial product purchased from DMTI Spatial Inc., this is a GIS polygon layer where each polygon corresponds to one of Canada Post's unique six-digit postal codes.

- DMTI Spatial Street Network: This is a commercial product that contains street segments that are typically attributed with street name and the range of addresses that are located along that segment (block).

The address fields in the MOE database were often incomplete or incorrectly entered, and a significant effort was made to parse the address fields properly prior to geocoding.

The initial approach was to attempt to match the six-digit postal codes to the DMTI postal code database, with geocoded locations assigned the UTM coordinate of the postal code polygon centroid.

Because rural postal code polygons are quite large, only urban postal codes were used at this initial stage.

The second technique used was to geocode against the DMTI street segment layer. Again, the precision of this technique varied considerably, but was, in general, accurate to a particular block. Finally, a combination of street address and postal code attributes was used, typically to provide a more precise location in rural areas.

The success of the geocoding effort was variable, and was generally dependent on the quality of data in the MOE Contaminant Database. **Table 6.1** provides a summary of the level of success, and a semi-quantitative assessment of the precision of the assigned coordinates.

Table 6.1
Geocoding Summary

Database	Very Good	Good	Poor	Not Geocoded	Total
TSSA Fuel Storage Sites	340	0	110	24	474
Provincial PCB Storage Sites	69	0	6	104	179
MOE Spills Database				358	358
WSIS Landfills	191			172	363

6.4 Geographic Distribution of Potential Contaminant Sources

The distribution of potential contaminant sources across the Study Area is shown on **Map 6.1**, with the London area shown in greater detail on **Map 6.2**. Not surprisingly, the majority of the point contaminant sources such as gas stations, PCB storage sites, dry cleaners and manufacturing facilities are located in and around the urban areas, particularly London and St. Thomas.

Landfill sites are more broadly distributed, with both active and closed landfills in all area municipalities.

6.5 Relative Risks

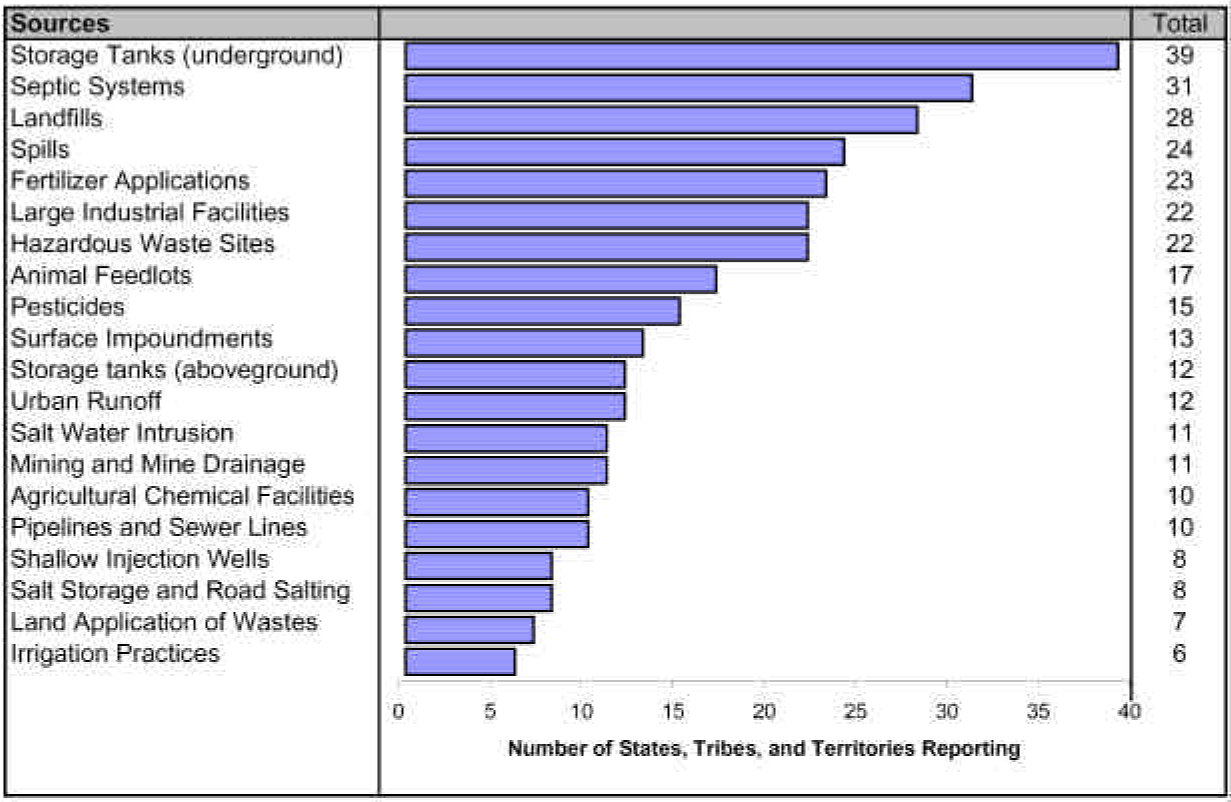
Potential contaminant inventories for an area the size of Middlesex and Elgin Counties will typically identify hundreds or even thousands of potential contaminant sources. Potential contaminant source maps can often create a false impression of the degree of risk to groundwater aquifers and local drinking water resources. In order to characterize the actual risks, and to highlight those potential contaminant sources requiring the immediate attention of groundwater managers, some method of ranking the relative risks is needed.

There have been several attempts made, primarily in the United States, to develop a relative ranking system for potential threats to groundwater. These rankings are applied to relatively broad categories of land use activities, and do not generally take into account either site-specific differences in operations, equipment or the type of materials used. The rankings also ignore the importance of site-specific conditions such as the vulnerability of local aquifers.

Nevertheless, such ranking systems, particularly when combined with maps of aquifer vulnerability and WHPAs, can help to focus groundwater protection efforts on the most serious risk areas, and make the best use of limited municipal resources. The rankings developed by the Virginia and California Environmental Protection Agencies (EPAs) were reviewed to come up with a generalized risk ranking for the Middlesex and Elgin PCI. **Table 6.2**, provided at the end of this section, outlines the major land use activities, and the relative risk ranking applied to each one. Where possible, this ranking utilizes North American Industry Classification System (NAICS) codes, recognizing that some land use activities will not have a corresponding NAICS code.

Unfortunately, the existing contaminant databases do not contain sufficient data to apply the relative risk ranking methodology to the results of the Middlesex and Elgin PCI. This is because most of the data sources used to compile the PCI do not contain NAICS codes.

Figure 6.1
Major Sources of Groundwater Contamination



Source: US EPA National Water Quality Inventory, 2000 Report to Congress; 841-R-02-001

6.6 Specific Risks from Selected Land Use Activities

Through a regular survey of state EPAs, the U.S. EPA has developed a list of the major potential sources of groundwater contamination in the USA (**Figure 6.1** above). While survey results for Canada are not available, the similarity between the two countries in terms of industrial, commercial and agricultural practices suggests that the results are likely representative of the major groundwater contaminant sources in Canada as well. As shown on **Figure 6.1**, underground storage tanks (USTs) were the most frequently cited source of groundwater contamination. The list includes both large (e.g., landfills) and small (e.g., septic systems) point sources, as well as a number of non-point sources (e.g., urban runoff and fertilizer applications). However, the sources are not correlated to general land use. A comparison of rural versus urban environments is likely to present variations in the major sources cited. For example, septic systems, animal feedlots, and widespread application of fertilizers and pesticides are more likely sources of groundwater contamination in a rural setting; while USTs, landfills and large industrial facilities are contaminant sources often associated with an urban environment.

The remainder of this section provides a more detailed discussion of some of the more significant potential sources of groundwater contamination in the Study Area, including:

- the application of agricultural and non-agricultural nutrients
- road salt storage and application
- landfills, and
- industrial and commercial chemical usage.

6.6.1 Application of Agricultural and Non-Agricultural Nutrients

The storage and application of nutrients on agricultural and rural lands can present a significant risk for biological and nitrate contamination of groundwater, particularly in areas of high aquifer vulnerability. Nutrients are typically applied as manure, fertilizer, or non-agricultural bio-solids from wastewater treatment plants and septic systems. The operation of domestic septic tile beds can also release biological contaminants and nitrate, as well as other household chemicals, into the shallow subsurface.

There is little information available on the location or rates of agricultural nutrient application in the form of manure or fertilizer.

There are a number of wastewater treatment plants across the Study Area, although only one plant (Chatham Street plant in Bayham) was identified where biosolids are spread on agricultural land. The municipality would not provide the location of the spreading sites. Other wastewater treatment plants in Southwest Middlesex, Strathroy Caradoc, and West Elgin dispose of their biosolids in lagoons. The locations of these lagoons were not determined with sufficient accuracy to include them on the PCI map. Many of the other wastewater treatment plants in the Study Area are quite new, and have not yet had to dispose of biosolids.

Private septic systems are present outside of the areas serviced by municipal sewers. These tend to pose the greatest concern in rural subdivisions, where homes have both individual septic systems and individual domestic water wells.

6.6.2 Road Salt Storage and Application

Road salts are used as de-icing and anti-icing chemicals for winter road maintenance. Environment Canada has determined that road salts in sufficient concentrations pose a risk to plants, animals and the aquatic environment (Environment Canada, 2001). Currently, the federal government is developing measures to manage the risks associated with road salts. A proposed Risk Management Strategy for Road Salts, outlining how Environment Canada plans to deal with road salt, is expected to be available by the end of 2003 (Environment Canada, 2002).

Road maintenance applications include chloride salts such as sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$) and potassium chloride (KCl), brines used in road de-icing/anti-icing, and additives commonly used in road salts (ferrocyanides). These salts can enter the surface water, soil and groundwater and may impact on soil properties, roadside vegetation, wildlife, groundwater, aquatic habitat, and surface water.

Road salt contamination is a concern in areas of high use on roadways and along major expressways as well as near point contamination from salt storage areas, due to impacts on surface and groundwater. According to Environment Canada (2001), most of the claims from property owners against transport authorities are related to contamination of well water from salt released into groundwater. In stormwater drainage, salt is transported to surface waters such as creeks, rivers, lakes and can impact aquatic species. Plants can also be exposed to road salt through the soil, air and runoff water. In sensitive areas, road salt application can affect nearby crops and trees (Environment Canada, 2002).

In the Middlesex and Elgin Study Area, there are at least 25 municipal salt storage facilities, as well as a number of MTO facilities. **Maps 6.1** and **Map 6.2** show the location of known salt storage sites across the Study Area.

6.6.3 Landfills

Landfills may contain a wide variety of domestic, industrial and commercial wastes. As precipitation percolates through a landfill, it comes into contact with these wastes and produces leachate. The composition of leachate depends on the nature of the waste within a landfill, but typically contains elevated concentrations of nitrogen (ammonia and/or nitrates), sodium, chloride, boron, and iron, and has an elevated chemical and biochemical oxygen demand (COD/BOD). If leachate migrates out of a landfill, it may pose a threat to surface and/or groundwater.

Older landfills were often located in former gravel pits or quarries, in ravines, or on marginal land such as wetlands. These sites provide little in the way of natural protection for either groundwater or surface water, and the nature of the waste within these landfills is generally not well known.

Landfills that have been active in the past 15 to 20 years are generally better documented and monitored, and are often engineered to prevent the migration of leachate to groundwater or surface water. Where these more recent landfills have adversely impacted the environment, mitigation measures have often been put into effect.

In addition to the risks posed by known landfills, there are likely to be a number of historical landfills and waste dumps for which the location is not known, or which have not been assessed for potential environmental impacts.

Within the databases available for Middlesex and Elgin, there are 107 landfill records in the MOE WDSI database. However, some landfills have more than one record attached to them, so that the actual number of recorded landfills is probably less than 100. The majority of these are closed waste disposal sites rather than active sites. The MOE database CD provided for the study did not distinguish between active and closed waste disposal sites. Active waste disposal sites, as shown on **Maps 6.1** and **Map 6.2**, were identified based on information provided in the MOE Waste Disposal Site Inventory (June 1991). The EcoLog ERIS database identified 313 sites, 238 of which were labelled "dumps", 73 "auto junkyards" and an additional two as "incinerators". The locations of the various sites by database and type are shown on **Map 6.1**, with the London area highlighted on **Map 6.2**.

6.6.4 Industrial and Commercial Chemical Use

While industrial and commercial chemical use encompasses a wide variety of potential threats to groundwater, the most common potential contaminant sources are fuel storage tanks, historical use and disposal practices, and spills.

Fuel Storage Tanks

Fuel and related products such as lubricating oils and solvents are stored and used at a wide variety of commercial, industrial and agricultural facilities (as well as some private homes), either in aboveground storage tanks (ASTs) or underground storage tanks (USTs). These tanks, and the associated piping, can present a threat to groundwater either through catastrophic failure or, more commonly, through slow leaks that may go unnoticed for months or years.

The most common use of USTs, and therefore a common source of resultant contamination, is at retail fuel outlets. Historically, the standards for UST construction and use did not require the incorporation of leak protection (e.g., double walls, corrosion resistance) or leak testing. In some cases, USTs were not removed when former retail fuel outlets were converted to other uses.

Because the Ontario Drinking Water Standards for contaminants such as fuels and their breakdown products is quite low (often in the ppb range), only a small volume of contaminant is needed to affect a large volume of groundwater.

The distribution of fuel storage tanks across the Study Area is also shown on **Map 6.1** and **Map 6.2**.

Historical Practices

The historical industrial and commercial use of chemicals was generally conducted with little knowledge of the potential risks to the environment, and to groundwater contamination in particular. Practices such as strictly auditing the volume of chemicals to identify losses, building secondary containment around storage tanks, using ASTs instead of USTs, and properly disposing of hazardous chemicals were not common prior to the 1980s.

In the absence of good environmental management practices, industrial chemicals were often released to the environment through leaks in storage tanks and piping, or leaks in machinery combined with cracked concrete floors or leaking floor drains. Historical disposal practices for liquids and empty storage containers often involved pouring waste chemicals on the ground, diverting them to unlined disposal lagoons or landfills, or burning them in unlined outdoor burn pits.

The solvents perchloroethylene (PCE) and trichloroethylene (TCE) are two of the more common industrial chemicals that pose a significant risk to groundwater. PCE is widely used as a dry-cleaning fluid, while TCE is a common degreaser and is widely used in industrial applications. Both TCE and PCE are denser than water, and tend to sink through an aquifer until they reach a low permeability horizon, providing a persistent, long term source of groundwater contamination.

Spills

Even with modern best management practices for handling and disposing of chemicals, accidental releases of chemicals are still common. Often, the amount spilled is small, or response actions are sufficiently fast, so that the environmental impacts of such spills are mitigated. However, in the case of larger spills, or undetected slow releases, there may be significant potential for groundwater impacts.

Unfortunately, the MOE Spills database is incomplete, and is particularly difficult to geocode. As such, it is difficult to assess the degree of risk to groundwater posed by the spills incidents recorded in this database.

6.7 Contaminant Pathways

6.7.1 General

While many of the deeper aquifers across the Study Area are generally well protected from surface contamination by overlying fine-grained sediments (clays and silts), this natural protective layer can be breached by manmade structures and excavations. These structures can provide a pathway for contamination to move rapidly through the confining layer, substantially increasing the vulnerability of the deeper aquifers. The principal manmade contaminant pathways of concern are improperly constructed or decommissioned wells, and deep excavations or tunnels for foundations and sewers.

6.7.2 Improperly Constructed or Abandoned Water Wells

The MOE water well database lists over 20,000 wells in Middlesex and Elgin, and this list is unlikely to be comprehensive. Wells drilled prior to the 1950s, and most dug wells, are almost certainly not included, so the actual number of wells within the Study Area is probably in excess of 30,000.

Ontario Regulation 903/90 requires that all wells have a water-tight annular seal (cement or bentonite) between the well casing and the bored hole, from ground surface to a depth of at least 3 metres, to prevent the inflow of surface water into the aquifer. The regulation also requires that any water well that is no longer being used or maintained for future use, be decommissioned (abandoned) by a licensed well contractor.

The MOE water well database does not include a field indicating whether or not the well has an annular seal. This information should have been recorded on the original well log, but in practice these records are often incomplete. Because of this, there is no simple method for identifying wells that do not have proper annular seals, and so may pose a significant risk to groundwater.

Improperly abandoned wells may pose a greater risk to groundwater than wells without proper annular seals, since the full open diameter of the casing is often available as a pathway for surface contaminants to migrate into groundwater aquifers. Most well owners are unaware of the legal requirements or proper procedures regarding the decommissioning of abandoned wells, and many property owners may be unaware of the presence of improperly decommissioned wells on their lands.

Until recently, it was common practice for abandoned wells to be destroyed by bulldozers or other heavy equipment during grading operations when a previously rural property was developed for urban use. Domestic wells are also frequently abandoned without proper decommissioning when municipal water services are extended into an area. An informal survey suggests municipalities do not require proper decommissioning of private wells as a condition of connecting to municipal water supplies.

Maps of areas with municipal water services were not available in digital format for most areas. However, the City of St. Thomas provides an example of what can be done with this type of data. Using the project GIS, 28 wells were identified where the location plotted within the area of the City serviced by municipal water. While some of these may be monitoring, remediation, or municipal supply wells that are still in use, the majority are likely to be domestic wells which may not have been properly decommissioned. The occurrence of water wells within the groundwater capture zones identified for the municipal wells is discussed in Section 7.3.

Table 6.2: Risk Ranking for Major Land Uses

Primary NAICS Code	Industrial Classification	Golder Risk Ranking	USEPA Ranking	Potential Contaminant Type: Microbiological	Nitrate/Nitrite	Volatile Organics	Synthetic Organics	Inorganic Chemicals	Radioactive
2122	Metal Ore Mining	Very High	Very High			✓		✓	
2123	Non-Metallic Mineral Mining and Quarrying	Very High	Very High			✓			
3241	Petroleum and Coal Products Manufacturing	Very High	Very High			✓	✓	✓	
3251	Basic Chemical Manufacturing	Very High	Very High						
3252	Resin, Synthetic Rubber, and Artificial and Synthetic Fibres and Filaments Manufacturing	Very High	Very High			✓	✓		
3253	Pesticide, Fertilizer and Other Agricultural Chemical Manufacturing	Very High	Very High		✓		✓		
3259	Other Chemical Product Manufacturing	Very High	Very High			✓	✓		
3261	Plastics Product Manufacturing	Very High	Very High			✓	✓		
3262	Rubber Product Manufacturing	Very High	Very High			✓	✓		
3314	Non-Ferrous Metal (except Aluminum) Production and Processing	Very High	Very High			✓		✓	
3322	Cutlery and Hand Tool Manufacturing	Very High	Very High			✓		✓	
3323	Architectural and Structural Metals Manufacturing	Very High	Very High			✓		✓	
3329	Other Fabricated Metal Product Manufacturing	Very High	Very High			✓		✓	
3335	Metalworking Machinery Manufacturing	Very High	Very High			✓		✓	
4162	Metal Service Centres	Very High	Very High						
4184	Chemical (except Agricultural) and Allied Product Wholesaler-Distributors	Very High	Very High						
4471	Gasoline Stations	Very High	Very High			✓	✓		
5622	Waste Treatment and Disposal	Very High	Very High	✓	✓	✓	✓	✓	
5629	Remediation and Other Waste Management Services	Very High	Very High	✓	✓	✓	✓	✓	
8123	Laundry Services	Very High	Very High			✓			
1121	Cattle Ranching and Farming	High	High	✓	✓				
1123	Poultry and Egg Production	High	High	✓	✓				
1129	Other Animal Production	High	High	✓	✓				
3211	Sawmills and Wood Preservation	High	High			✓	✓		
3212	Veneer, Plywood and Engineered Wood Product Manufacturing	High	High			✓	✓		
3219	Other Wood Product Manufacturing	High	High			✓	✓		
3221	Pulp, Paper and Paperboard Mills	High	High			✓	✓		
3325	Hardware Manufacturing	High	High			✓		✓	
3327	Machine Shops, Turned Product, and Screw, Nut and Bolt Manufacturing	High	High			✓		✓	
3344	Semiconductor and Other Electronic Component Manufacturing	High	High			✓		✓	
3351	Electric Lighting Equipment Manufacturing	High	High			✓		✓	
3353	Electrical Equipment Manufacturing	High	High			✓		✓	
3359	Other Electrical Equipment and Component Manufacturing	High	High			✓		✓	
3362	Motor Vehicle Body and Trailer Manufacturing	High	High			✓		✓	
3363	Motor Vehicle Parts Manufacturing	High	High			✓		✓	
3364	Aerospace Product and Parts Manufacturing	High	High			✓		✓	
3366	Ship and Boat Building	High	High			✓	✓	✓	
3371	Household and Institutional Furniture and Kitchen Cabinet Manufacturing	High	High			✓			
3372	Office Furniture (including Fixtures) Manufacturing	High	High			✓			
3379	Other Furniture-Related Product Manufacturing	High	High			✓			
4111	Farm Product Wholesaler-Distributors	High	High						
4121	Petroleum Product Wholesaler-Distributors	High	High			✓			
4411	Automobile Dealers	High	High						
4821	Rail Transportation	High	High	✓	✓	✓	✓		✓
4831	Deep Sea, Coastal and Great Lakes Water Transportation	High	High						
4841	General Freight Trucking	High	High	✓	✓	✓	✓		✓
4842	Specialized Freight Trucking	High	High						
4851	Urban Transit Systems	High	High						
4852	Interurban and Rural Bus Transportation	High	High						
4853	Taxi and Limousine Service	High	High						
4854	School and Employee Bus Transportation	High	High						
4855	Charter Bus Industry	High	High						
4859	Other Transit and Ground Passenger Transportation	High	High						
4861	Pipeline Transportation of Crude Oil	High	High			✓	✓		
8111	Automotive Repair and Maintenance	High	High			✓			
1112	Vegetable and Melon Farming	Medium	Moderate	✓	✓			✓	
1114	Greenhouse, Nursery and Floriculture Production	Medium	Moderate	✓	✓			✓	
1119	Other Crop Farming	Medium	Low	✓	✓			✓	
1132	Forest Nurseries and Gathering of Forest Products	Medium	Moderate	✓	✓			✓	
1151	Support Activities for Crop Production	Medium		✓	✓			✓	
1152	Support Activities for Animal Production	Medium		✓	✓			✓	
1153	Support Activities for Forestry	Medium		✓	✓			✓	
2131	Support Activities for Mining and Oil and Gas Extraction	Medium				✓			
2213	Water, Sewage and Other Systems	Medium	Moderate	✓	✓	✓	✓		
2311	Land Subdivision and Land Development	Medium	Moderate						
3111	Animal Food Manufacturing	Medium	Moderate	✓	✓	✓			
3112	Grain and Oilseed Milling	Medium	Moderate		✓	✓			
3113	Sugar and Confectionery Product Manufacturing	Medium	Moderate		✓	✓			
3114	Fruit and Vegetable Preserving and Specialty Food Manufacturing	Medium	Moderate		✓	✓			

Table 6.2 continued

Primary NAICS Code	Industrial Classification	Golder Risk Ranking	USEPA Ranking	Potential Contaminant Type					
				Microbiological	Nitrate/Nitrite	Volatile Organics	Synthetic Organics	Inorganic Chemicals	Radioactive
3115	Dairy Product Manufacturing	Medium	Moderate	✓	✓	✓			
3116	Meat Product Manufacturing	Medium		✓	✓	✓			
3117	Seafood Product Preparation and Packaging	Medium	Moderate	✓	✓	✓			
3118	Bakeries and Tortilla Manufacturing	Medium	Moderate		✓	✓			
3119	Other Food Manufacturing	Medium	Moderate		✓	✓			
3121	Beverage Manufacturing	Medium	Moderate		✓	✓			
3122	Tobacco Manufacturing	Medium			✓	✓			
3131	Fibre, Yarn and Thread Mills	Medium				✓	✓	✓	
3132	Fabric Mills	Medium				✓	✓	✓	
3133	Textile and Fabric Finishing and Fabric Coating	Medium				✓	✓	✓	
3149	Other Textile Product Mills	Medium				✓	✓	✓	
3162	Footwear Manufacturing	Medium				✓	✓		
3169	Other Leather and Allied Product Manufacturing	Medium				✓	✓		
3222	Converted Paper Product Manufacturing	Medium				✓	✓		
3231	Printing and Related Support Activities	Medium				✓	✓		
3255	Paint, Coating and Adhesive Manufacturing	Medium				✓	✓		
3256	Soap, Cleaning Compound and Toilet Preparation Manufacturing	Medium				✓	✓		
3273	Cement and Concrete Product Manufacturing	Medium	Moderate						
3311	Iron and Steel Mills and Ferro-Alloy Manufacturing	Medium				✓	✓	✓	
3312	Steel Product Manufacturing from Purchased Steel	Medium				✓		✓	
3313	Alumina and Aluminum Production and Processing	Medium				✓		✓	
3315	Foundries	Medium				✓		✓	
3321	Forging and Stamping	Medium				✓		✓	
3324	Boiler, Tank and Shipping Container Manufacturing	Medium				✓		✓	
3326	Spring and Wire Product Manufacturing	Medium				✓		✓	
3328	Coating, Engraving, Heat Treating and Allied Activities	Medium				✓		✓	
3331	Agricultural, Construction and Mining Machinery Manufacturing	Medium				✓		✓	
3332	Industrial Machinery Manufacturing	Medium				✓		✓	
3333	Commercial and Service Industry Machinery Manufacturing	Medium				✓		✓	
3334	Ventilation, Heating, Air-Conditioning and Commercial Refrigeration Equipment Manufacturing	Medium				✓		✓	
3336	Engine, Turbine and Power Transmission Equipment Manufacturing	Medium				✓		✓	
3339	Other General-Purpose Machinery Manufacturing	Medium				✓		✓	
3341	Computer and Peripheral Equipment Manufacturing	Medium				✓		✓	
3342	Communications Equipment Manufacturing	Medium				✓		✓	
3343	Audio and Video Equipment Manufacturing	Medium				✓		✓	
3345	Navigational, Measuring, Medical and Control Instruments Manufacturing	Medium				✓		✓	
3346	Manufacturing and Reproducing Magnetic and Optical Media	Medium				✓		✓	
3352	Household Appliance Manufacturing	Medium				✓		✓	
3369	Other Transportation Equipment Manufacturing	Medium				✓		✓	
4152	New Motor Vehicle Parts and Accessories Wholesaler-Distributors	Medium	Moderate						
4153	Used Motor Vehicle Parts and Accessories Wholesaler-Distributors	Medium	Moderate						
4163	Lumber, Millwork, Hardware and Other Building Supplies Wholesaler-Distributors	Medium	Moderate						
4413	Automotive Parts, Accessories and Tire Stores	Medium	Moderate						
5621	Waste Collection	Medium	Moderate	✓		✓	✓	✓	
6215	Medical and Diagnostic Laboratories	Medium		✓		✓	✓		✓
6221	General Medical and Surgical Hospitals	Medium		✓		✓	✓		✓
8122	Funeral Services	Medium	Moderate	✓	✓	✓			
2211	Electric Power Generation, Transmission and Distribution	Low				✓	✓		
3271	Clay Product and Refractory Manufacturing	Low				✓	✓		
3272	Glass and Glass Product Manufacturing	Low						✓	
4812	Non-Scheduled Air Transportation	Low				✓			
4862	Pipeline Transportation of Natural Gas	Low				✓	✓		
7212	RV (Recreational Vehicle) Parks and Recreational Camps	Low	Low						
8112	Electronic and Precision Equipment Repair and Maintenance	Low	Low						

7. MUNICIPAL WELLHEAD PROTECTION

Wellhead Protection planning can be defined as establishing management zones around a water supply well field. Establishing a wellhead protection plan involves completing the following tasks:

- susceptibility assessment
- delineation of wellhead protection areas
- inventory of potential contaminant sources
- management of potential and existing contaminant sources to ensure protection of the wellfield.

There are nine municipal groundwater supply systems in Middlesex- Elgin: Dorchester, Thorndale, Birr, Melrose, Komoka-Kilworth, City of London Stand-by wells at Fanshawe, Strathroy-Mount Brydges, Highbury Avenue, and Belmont. The Strathroy-Mount Brydges and Belmont well systems have had detailed wellhead protection studies completed on them and are not included in this study. An assessment of the City of London Highbury well system was not included in the Terms of Reference for this Study. Granton has a small groundwater system, but this is scheduled to be decommissioned in 2004.

7.1 Wellhead Protection Area Delineation

Wellhead protection areas are defined geographical limits most critical to the protection of the well field. There are several methods that can be used to delineate groundwater capture zones, which form the wellhead protection areas. These methods are listed below in order of increasing complexity and detail

- arbitrary fixed radii
- calculated fixed radii
- simplified variable shapes
- analytical methods
- numerical modelling.

Complex methods are appropriate to analyze complex hydrogeologic settings which have been thoroughly characterized by hydrogeological investigations (e.g., pumping tests, borehole drilling). Less complex methods can be used as screening methods or for areas where the geology is not overly complex or for areas where the hydrogeological setting has not been investigated in detail.

7.1.1 Numerical Modelling

The United States Geological Survey (USGS) numerical groundwater flow model MODFLOW (McDonald and Harbaugh, 1988) was used to develop a numerical model of the hydrogeological setting for all wellfields. MODFLOW is a three dimensional, finite difference groundwater flow model which solves the groundwater flow equation for each cell within a grid with respect to each cell surrounding it. The program also is able to simulate other hydrologic processes such as areal recharge, rivers and lakes. A pre-processor and post-processor computer program developed for MODFLOW called VISUAL MODFLOW (Guiger and Franz, 1990), was used to develop the model and obtain graphical output.

An adjunct particle tracking program to MODFLOW called MODPATH was used to delineate the areas contributing groundwater to the wellfield and also used to establish TOT areas.

The methodology consists of the following components:

Conceptual Model - A conceptual model for each wellfield was developed from the Water Well Records. Water well information was used within an approximate 10 km by 10 km area around the wellfield. For the Fanshawe Wellfield, a previous study had investigated the wellfield area and produced geological cross-sections. This information was then reviewed and geological cross-sections were developed based on the well information. These geological cross-sections for each wellfield are in **Appendix B**. This information was used to delineate the extent of the wellfield aquifer. As well, the upper limit and lower limit of the aquifer was defined at particular well locations and this information was used to develop the aquifer top surface and bottom surface that is used in the numerical model.

Static water elevations from the water wells located within the wellfield aquifer were also reviewed and plotted within the area of the wellfield. Static water levels indicate the direction of groundwater movement in the aquifer and therefore have a significant influence on model development and the wellhead area delineation. Static water levels recorded on Water Well Records can be difficult to assess because the wells were drilled at different times (basically over a 50 year period) and static water elevations vary with time. Some static water elevation data may be erroneous in that the driller may have recorded a level that may not have had sufficient time to recover to a true static level after well drilling and development activities. For these reasons, static water elevations from certain wells were selected to reflect the condition at the wellfield. **Appendix B** contains a listing of all of the wells used for calibration for each wellfield.

Numerical Model Development - A numerical model was developed based on the conceptual model. In MODFLOW, a Study Area (Domain) is defined by a set of boundary conditions (e.g., constant head and no flow). Within the domain area, a grid is constructed with the intention of having the smallest cells in the area of greatest interest, thus providing better accuracy to the model. Layers are used to simulate confined, unconfined, or a combination of confined/unconfined conditions. Cells within the grid can be defined to behave like drains (e.g., wells, streams, etc.). Areal recharge and evapotranspiration can also be simulated. Aquifer properties such as hydraulic conductivity and porosity are assigned for each cell in the domain. Boundary conditions such as a "no flow" boundary or a constant head boundary are specified on a cell-by-cell basis.

The program computes flow between adjacent cells and determines the rate of movement of water to and from the groundwater system ("storage"). Flow is calculated based on hydraulic conductivity, cross-sectional area perpendicular to flow and hydraulic gradient. Input parameters include grid spacing, layer types and aquifer properties (e.g., hydraulic conductivity and storativity). Output, in the form of hydraulic head and drawdown values, is generated for each cell in the grid.

Numerical Model Calibration - Model calibration is a heuristic (trial and error) process where the model output parameters (chiefly water levels predicted by the model) are compared to measured static water levels from the Water Well Records. The model input parameters (aquifer properties and recharge) are then adjusted so that the error between water level prediction and the measured levels is minimized. Boundary conditions were not adjusted in the calibration process. **Appendix B** contains plots of measured versus modelled water levels in the wells.

Municipal Well Simulation - Information from the municipal supply wells such as pumping rate, well depth etc., was taken from information provided by the municipality (e.g., Engineers' Reports, hydrogeology investigation studies, etc.).

Time of Travel Assessment - After the numerical model was calibrated and the effects of the municipal well simulated, time-of-travel estimates are computed using particle tracking. Particle tracking was completed using an adjunct computer program to MODFLOW called MODPATH. Groundwater velocities were calculated using the simulated water level data, hydraulic conductivity and porosity for each cell and travel times were computed based on the groundwater velocity and the geometry of the cell. Backward tracking particles originating at the well were used to map the 2-year, 5-year and 25-year time-of-travel capture zones.

The time of travel estimates are shown projected to the ground surface. It is emphasized that the time of travel is within the aquifer and in the case of some systems modelled, it takes significant time for water to migrate from the ground surface through the low permeability clayey silt aquitard to the aquifer (i.e., greater than 100 years). Therefore, for some systems emphasis of protection policy should centre mainly on maintaining the integrity of the protective aquitard and less on the land use that occurs at the ground surface.

7.1.2 Wellhead Delineation Uncertainty and Limitations

The delineation of wellhead protection areas is based on a number of assumptions and estimates based on point data such as lithology from water wells and pumping test data. Examples include the assumption that hydraulic properties do not vary within a hydrostratigraphic unit (i.e., the aquifer or the aquitard). The boundary conditions are also assumptions based on the conceptual model. Each model was developed using the available data and the results represent a reasonable estimate based on that data. Improvements in the model can be made based on additional information that may become available in the future. Even with this uncertainty, the wellhead delineation process provides a good indication of the source of the water for each water supply which can facilitate good water resource protection policy.

7.2 Results of Wellhead Protection Area Delineation

The results for each of the six municipal groundwater supply systems are presented in this section. An overview of each system is first given followed by a description of the hydrogeology and other factors that influence groundwater movement. The results of the modelling are then presented. The detailed documentation including conceptual model development, cross sections and numerical model calibration are provided in **Appendix B**.

7.2.1 Dorchester Water Supply System

The Dorchester Water Supply System consists of six wells concentrated in a wellfield located in the south part of the village. The wells tap a relatively shallow unconfined sand and gravel aquifer approximately 10 metres thick. The wells range in depth from 9.1 metres to 12.2 metres.

The average flow demand for the Dorchester system is 1,855 m^3/day. The water quality is generally good with treatment consisting of disinfection and sequestration of iron and manganese. The pumping rates used in modelling the Dorchester wellfield are summarized in **Table 7.1.**

Table 7.1
Dorchester Wellfield Pumping Rates

Average Rate (m^3/day)	Permitted Rate (m^3/day)	Calibration Period Rate (m^3/day)	Future Rate for Delineation Zones (m^3/day)
1855	5400	1855	3500

At the wellfield, the aquifer is underlain by silty clay till ranging in thickness from 5 to 16 metres with an increasing content of gravel, cobbles and boulders nearer the bottom of the strata. Bedrock (Dundee formation) underlies the silty clay aquitard, and is found at a depth below ground surface ranging from 21 metres to 28 metres. The well field is located north of the Ingersoll Moraine, with the sand and gravel related to glacialfluvial spillway deposits that often occur on the flanks of moraines. **Map B.1 (Appendix B)** contains geological cross-sections for the Dorchester area.

The Ingersoll Moraine consists of low permeability clayey silt to silty clay till. Underlying the Port Stanley Till is the Catfish Creek Till. There may be a small seam between the two till sheets, but it is assumed that the main unconfined aquifer does not extend into the Ingersoll Moraine.

The model was constructed using the Thames River and the Mill Pond as constant head boundaries and the Dorchester Creek as a "river" type boundary. The model extends south to the Ingersoll Moraine.

Table 7.2 summarizes the hydrogeologic parameters used in the modelling. The relatively high recharge rate reflects the low lying Dorchester Swamp which occurs at surface.

Table 7.2

Dorchester Wellfield Hydrogeologic Parameters

Parameter	Minimum Value	Maximum Value	Calibrated Value
Hydraulic Conductivity Unconfined Aquifer	8×10^{-5} m/s	1×10^{-3} m/s	5×10^{-4} m/s
Porosity Unconfined Aquifer	0.2	0.35	0.25
Recharge	200 mm/year	350 mm/year	300 mm/year

The results of the model are shown graphically on **Map 7.1**, which shows the 2-year, 5-year and 25-year time-of -travel capture areas. The protection areas bend to the east at the inferred limit of the

Ingersoll Moraine. The Wellhead Protection Area also intercepts Dorchester Creek, well within the 2-year travel time zone, consistent with previous studies that indicated that generally the water in the aquifer was recently recharged.

In terms of wellhead protection planning, this is considered to be a vulnerable water supply aquifer and protection planning should go beyond the wellhead areas and include the Dorchester Swamp, to protect the water quality in the aquifer, as well as Dorchester Creek, which could potentially "short-circuit" to the well.

7.2.2 Thorndale Water Supply System

The Thorndale water supply system consists of two bedrock wells and services 336 residents in the southeast portion of the hamlet. These wells, on average, produce 80 m^3/day. The wells are located quite close together (within 10 metres) and quite deep (>30 m) and tap a limestone aquifer. The aquifer is protected by a thick aquitard consisting of relatively low permeability clay and silt soils. **Table 7.3** contains the pumping rates for the Thorndale well system.

Table 7.3
Thorndale Wellfield Pumping Rates

Average Rate (m^3/day)	Permitted Rate (m^3/day)	Calibration Period Rate (m^3/day)	Future Rate for Delineation Zones (m^3/day)
80	409	80	200

The hydrogeology of the Thorndale area is dominated by the Stratford Till Plain to the north of the wells. Surficial sand and gravel deposits west of Thorndale do not significantly affect the limestone aquifer. The groundwater flow direction is from the northeast to southwest. It is inferred that most of the recharge to the bedrock aquifer occurs far to the northwest where the overburden thins and eventually crops out at St. Marys. **Map B.2 (Appendix B)** contains geological cross-sections for the Thorndale area.

There was not a significant amount of information available regarding the hydraulic characteristics of the Thorndale wells. Therefore, conservative assumptions regarding hydraulic characteristics were used at the start of the calibration process. The Thames River to the west of Thorndale was used as a constant head boundary. Cross sections prepared for this wellhead indicate that the overlying till aquitard is consistent in thickness throughout the till plain area (i.e., away from the Thames River).

The hydrogeologic parameters used in the model are summarized in **Table 7.4.** The low porosity is reflective of limestone. An effective porosity of 0.02 was used in defining the capture areas.

Table 7.4

Thorndale Wellfield Hydrogeologic Parameters

Parameter	Minimum Value	Maximum Value	Calibrated Value
Hydraulic Conductivity Aquitard Bedrock Aquifer	 2×10^{-7} m/s 5×10^{-7} m/s	 1×10^{-8} m/s 1×10^{-5} m/s	 5×10^{-8} m/s 5×10^{-6} m/s
Porosity Aquitard Bedrock Aquifer	 0.15 0.04	 0.30 0.15	 0.20 0.10
Recharge	25 mm/year	5 mm/year	10 mm/year

The results of the model are shown on **Map 7.2**. The groundwater capture zones are oriented to the northeast (i.e., in the upgradient groundwater flow direction). The time-of-travel areas are generally wider than what is expected for a relatively small water supply system in bedrock. This is due to the conservatively low estimate of hydraulic conductivity used at the start of the calibration process.

Although the wellhead time-of-travel zones are relatively large, it is emphasized that they represent travel times in the deep limestone aquifer. The time of travel for water to move from ground surface through the low permeability aquitard is estimated to be greater than a hundred years. Therefore, emphasis of protection policy should centre mainly on maintaining the integrity of the protective aquitard.

7.2.3 Birr Groundwater Supply System

The Birr groundwater supply system provides water to only 18 residences (68 people) and consists of two wells that pump from a confined overburden aquifer. Water use is solely for residential purposes and there are no plans to expand the system. The average daily and maximum daily use has been 15.7 m^3/day and 17.4 m^3/day, respectively. **Table 7.5** summarizes the pumping rates used to model the Birr system. There are no plans to expand this system.

Table 7.5
Birr Wellfield Pumping Rates

Average Rate (m^3/day)	Permitted Rate (m^3/day)	Calibration Period Rate (m^3/day)	Future Rate for Delineation Zones (m^3/day)
16	88.3	16	16

The wells are 49 metres deep and tap a 3 metre thick sand and gravel layer. Overlying this aquifer are low permeability clay and till soils that provide significant protection to the aquifer.

The geological cross-sections prepared for this system indicate that the aquifer at this depth is typical for the area and was assumed to be horizontally extensive. Because there are no nearby boundary conditions for this deep aquifer (and the system is relatively very small), boundary conditions (constant head) were set to the east and west based on measured static elevations from the Water Well Records.

Table 7.6 summarizes the hydrogeologic parameters used in the model.

Table 7.6

Birr Wellfield Hydrogeologic Parameters

Parameter	Minimum Value	Maximum Value	Calibrated Value
Hydraulic Conductivity Aquitard Aquifer	 1 x 10^{-7} m/s 5 x 10^{-5} m/s	 3 x 10^{-6} m/s 3 x 10^{-4} m/s	 1 x 10^{-6} m/s* 2 x 10^{-4} m/s
Porosity Aquitard Aquifer	 0.25 0.20	 0.35 0.35	 0.30 0.25
Recharge	7 mm/year	50 mm/year	9 mm/year

*vertical hydraulic conductivity values assumed to be 10% of horizontal hydraulic conductivity.

The results of the model are shown on **Map 7.3**, and the time-of-travel zones are relatively small, directly related to the low flow rate for the small system. The time of travel for water to move from ground surface through the low permeability aquitard is estimated to be greater than a hundred years. Therefore, emphasis of protection policy should centre mainly on maintaining the integrity of the protective aquitard.

7.2.4 Melrose Groundwater Supply System

The Melrose water supply system consists of two wells that pump from a confined overburden aquifer and provide water to 217 residents. The average daily water use is 56 m^3/day (se **Table 7.7)** and the maximum daily water use is 81 m^3/day. The design capacity of the system is 98 m^3/day. There are no plans to expand the water supply system.

Table 7.7

Melrose Wellfield Pumping Rates

Average Rate (m^3/day)	Permitted Rate (m^3/day)	Calibration Period Rate (m^3/day)	Future Rate for Delineation Zones (m^3/day)
56.4	554	60	60

The two water supply wells are 23.8 metres and 24.7 metres deep and tap a sand and gravel aquifer approximately 4 metres thick.

The geological cross sections (see Appendix B) for this system indicate that the aquifer is consistent in depth in the immediate vicinity of Melrose but there are shallow and deeper wells utilized further away from Melrose.

The Thames River, located southeast of Melrose, was used as a constant head boundary and a no flow boundary was used roughly coinciding with the watershed boundary between the Thames River and Sydenham River northwest of Melrose. The hydrogeologic parameters used in the Melrose model are detailed in **Table 7.8.**

Table 7.8
Melrose Wellfield Hydrogeologic Parameters

Parameter	Minimum Value	Maximum Value	Calibrated Value
Hydraulic Conductivity Aquitard Aquifer	 1×10^{-8} m/s 5×10^{-5} m/s	 2×10^{-7} m/s 3×10^{-4} m/s	 5×10^{-8} m/s* 1×10^{-4} m/s
Porosity Aquitard Aquifer	 0.25 0.20	 0.35 0.35	 0.30 0.25
Recharge	40 mm/year	120 mm/year	55 mm/year

*vertical hydraulic conductivity values assumed to be 10% of horizontal hydraulic conductivity.

Map 7.4 illustrates the results of the groundwater capture zone delineation. The time-of-travel areas are oriented in a southeast to northwest direction (i.e., in the upgradient groundwater flow direction), and are similar to the Birr system (relatively small narrow areas).

The time of travel for water to move from ground surface through the low permeability aquitard is estimated to be greater than fifty years. Therefore, emphasis of protection policy should centre mainly on maintaining the integrity of the protective aquitard.

7.2.5 Komoka-Kilworth Groundwater Supply System

The communities of Komoka and Kilworth are supplied by three wells that pump from a confined overburden aquifer system. The wells are located between the communities of Kilworth and Komoka and are located approximately 100 metres north of the Thames River. The water supply system services a population of 2,600. The average daily water use is 658 m^3/day, while the maximum daily flow requirement is 1,011 m^3/day. **Table 7.9** summarizes the pumping rates used in the Komoka-Kilworth groundwater model.

Table 7.9

Komoka Wellfield Pumping Rates

Average Rate (m^3/day)	Permitted Rate (m^3/day)	Calibration Period Rate (m^3/day)	Future Rate for Delineation Zones (m^3/day)
658	6546	700	1500

Well 1 is 30 metres deep, Well 2 is screened from 18.9 metres to 22.0 metres depth and Well 3 is screened from 19.2 metres to 22.5 metres. Overlying the sand and gravel aquifer are approximately 12 metres of till and clay soils, which are overlain by a sequence of clay and sand soils. The geological cross sections prepared for this system indicate that groundwater use and well depths are quite variable. Upgradient from the wells in the village of Komoka there is a shallow unconfined sand aquifer that is not very thick (less than 5 metres). Underlying the surficial sands are clay and till soils with intermediate depth aquifers intercepted on a sporadic basis (i.e., varying depth and thickness).

For the purpose of the modelling assessment , it was assumed that the intermediate depth aquifer was areally consistent throughout the upgradient direction. The Thames River was used as a constant head boundary in the overlying aquitard and a no flow boundary was used in the aquifer (i.e., groundwater was assumed to flow from both north and south directions into the Thames River valley). A "no flow" boundary was assumed to the northwest of Komoka roughly coinciding with the watershed divide between the Thames River and the Sydenham River (see **Map 2.2**). **Table 7.10** has a summary of the hydrogeologic parameters used.

Table 7.10

Komoka Wellfield Hydrogeologic Parameters

Parameter	Minimum Value	Maximum Value	Calibrated Value
Hydraulic Conductivity Aquitard Aquifer	 1 x 10^{-7} m/s 5 x 10^{-5} m/s	 1 x 10^{-6} m/s 3 x 10^{-4} m/s	 7 x 10^{-7} m/s* 1 x 10^{-4} m/s
Porosity Aquitard Aquifer	 0.25 0.20	 0.35 0.35	 0.30 0.25
Recharge	100 mm/year	160 mm/year	130 mm/year

*vertical hydraulic conductivity values assumed to be 10% of horizontal hydraulic conductivity.

Map 7.5 shows the results of the groundwater capture zone delineation. This map indicates that the time-of-travel areas extend from the wellhead upgradient to just east of the built-up area of Komoka. The model did not predict that groundwater would flow from the Thames to the wells (i.e., no flow reversal was predicted).

The major source of uncertainty associated with capture zone delineation is not associated with the numerical model hydraulic parameters, but with the conceptual model. Specifically, the assumption of a continuous aquifer throughout the area is not supported by the lithology recorded in the water wells. It is not possible, however, to reasonably define the areas where the aquifer is present or changes in elevation with the information available in the Water Well Records. Therefore, it is recommended that a wider area be taken until sufficient information is acquired on the hydrogeology of the area. This approach was used in the potential contaminant source review documented in Section 7.3.

7.2.6 Fanshawe Groundwater Supply System

The City of London operates a stand-by wellfield just east of Fanshawe Lake. The system consists of six high capacity wells (each capable of pumping more than 3,200 litres/minute). The wells are all installed within 300 metres of each other and are installed at depths ranging from 9.1 metres to 14.8 metres. The aquifer consists of gravel to gravelly sand and is unconfined. **Table 7.11** shows the pumping rates for the Fanshawe system.

Table 7.11
Fanshawe Wellfield Pumping Rates

Average Rate (m^3/day)	Permitted Rate (m^3/day)	Calibration Period Rate (m^3/day)	Future Rate for Delineation Zones (m^3/day)
- (Standby Well)	23000	0	10000 for 10 days

The sand and gravel aquifer is in a clay till bowl-like depression and, therefore, is limited in areal extent. The clay till rises to the north at Sunningdale Road and to the south, north of the Thames River. **Appendix B** contains detailed cross sections of the area. A transient analysis was necessary due to the problems with the limits of the aquifer and the high rates at which the stand-by wells are to be pumped at for a relatively short emergency period (the planning scenario is for the wells to pump for less than 5 days). **Table 7.12** summarizes the hydrogeologic parameters for the Fanshawe model.

Table 7.12

Fanshawe Wellfield Hydrogeologic Parameters

Parameter	Minimum Value	Maximum Value	Calibrated Value
Hydraulic Conductivity Unconfined Aquifer	8×10^{-5} m/s	4×10^{-4} m/s	1×10^{-4} m/s
Porosity Unconfined Aquifer	0.2	0.35	0.3
Recharge	120 mm/year	260 mm/year	190 mm/year

Map 7.6 shows the wellfield and an approximate wellhead protection boundary from the transient analysis. Since the wells are to be pumped for a short duration, the travel time areas are more of a function of the natural groundwater flow pattern (i.e., non-pumping conditions) in this area.

7.3 WHPA Potential Contaminant Source Assessment

7.3.1 Methodology

Following the definition of the municipal well capture zones, an inventory of existing and potential contaminant sources was conducted for each WHPA. This assessment included three components: a review of existing inventories, using information detailed in the Regional Potential Contaminant Source Inventory (Section 6.3); a land use survey, using available parcel mapping provided by the Municipalities of Middlesex Centre and Thames Centre; and a field survey carried out primarily in Spring 2003 and based on visual inspections from public thoroughfares within the WHPA, noting potential contaminant sources. The MOE water well database was reviewed for records of wells located in the capture zone and not in use, either as a result of "poor water quality" or insufficient water supply. "Poor water quality" was identified from information in the MOE water well database as salty, sulphur, mineral, gas or iron. As noted in Section 6.7.2, improperly abandoned wells, as well as improperly constructed existing wells, pose a risk to groundwater supplies as they represent a potential conduit from the surface to the aquifer. No information on the actual condition of existing or abandoned wells could be obtained from the MOE water well database.

Potential contaminant sources in the WHPA's were identified using the North American Industry Classification System (NAICS) codes. **Table 7.13** below lists the potential contaminant sources identified and the corresponding NAICS code. The locations of the potential contaminant sources are shown on **Maps 7.1** to **7.6**.

Table 7.13
Summary of Potential Contaminant Sources (NAICS)

ID #	NAICS CODES	DESCRIPTION
(1)	111; 112	Agriculture (crop and/or animal production)
(2)	311119	Animal food manufacturing (including feed mills)
(3)	111421	Nursery and tree production
(4)	444220	Nursery stores and garden centres
(5)	713910	Golf and country clubs
(6)	418390	Agricultural chemical & farm supplies (distributor)
(7)	812220	Cemetery
(8)	562212; 562210 (CAN only)	Solid waste landfill
(9)	562920	Recyclable materials recovery facility
(10)	423930; 415310 (CAN only)	Recyclable materials wholesaler (auto salvage yard)
(11)	212321; 212323 (CAN only)	Sand and gravel quarrying
(12)	486110	Petroleum pipelines
(13)	447110	Gasoline Station
(14)	422710	Bulk Fuel Storage
(15)	4411	Automobile dealers (new and/or used)
(16)	811111	General automotive repair
(17)	488490	Support activities for road transportation
(18)	221320	Sewage treatment facilities
(19)	48211	Rail transportation

7.3.2 Dorchester WHPA

Land use and potential contaminant sources in the area of the capture zone delineated for the Dorchester well field are shown on **Map 7.1**. The capture zone extended in a southeast direction predominantly encompassing agricultural lands in the north, with patches of wooded land, grading into exclusively forested areas towards the southeast. Several tributaries of the Thames River were identified in various portions of the capture zone. Highway 401 crossed the southeastern portion of the capture zone. The Dorchester water treatment facility, a recently constructed, state-of-the-art plant, was located in a wooded area within the northern portion of the capture zone. In addition, the Dorchester Swamp, an area zoned as a significant (locally and in some locations provincially) wetland area, encompasses a large portion of the capture zone. These environmentally protected areas are unlikely to undergo future development. A single commercial property, identified as a tree farm, was located in the northwest portion of the capture zone, adjacent to Dorchester Road. The tree farm included a greenhouse, a residential building, and equipment shed, with the majority of the property undeveloped. The lands immediately surrounding the capture zone were dominated by agricultural properties and wooded "green field" areas. In addition, two ASTs were identified immediately west of the capture zone. The first, a fuel AST associated with a residential property, was located along Regional Highway 32, while the second, also a fuel AST, was observed in association with a tobacco farm along Donny Brook Drive.

MOE well records for 18 wells were identified within the 25-year capture zone. None of these wells were identified as not in use or having poor water quality. The Intrinsic Susceptibility Index Map (**Map 4.15**) indicates this area has a high susceptibility ranking.

According to information obtained from the Municipality of Thames Centre, the properties located within the capture zone are serviced by private septic systems.

7.3.3 Thorndale WHPA

Land use and potential contaminant sources in the area of the capture zone delineated for the two Thorndale wells are shown on **Map 7.2**. An elliptical capture zone extended north-northeast across County Road 27, encompassing predominantly agricultural lands and a wooded green field area. The headwaters of a Wye Creek tributary are located in the eastern portion of the capture zone. Residential properties were also present in the southern portion of the capture zone, adjacent to the Thorndale well supply building, within the 2-year time-of-travel zone. The Thorndale Operations

Centre (Municipality of Thames Centre), consisting of a two-bay garage with attached offices, a storage shed and snow removal equipment, was located east of the well supply building, on County Road 27. Along the southern wall of the Operations Centre, there were two diesel fuel pumps, indicating the presence of two associated USTs. A fuel AST was also located along the western wall of the Operations Centre. In addition, a mixture of sand and salt for winter road maintenance was stored in a shed north of the garage. A residence with three large barns was located on the north side of County Road 27, west of Heritage Road, near the perimeter of the capture zone. One fuel AST was identified west of the barns. The lands immediately surrounding the 25- year capture zone were also dominated by agricultural activities, with additional residential properties located to the southeast. Other commercial or industrial properties and potential contaminant sources indicated on **Map 7.2** are located more than 0.5 km beyond the capture zone and are not discussed herein.

MOE well records for ten wells were identified within the 25-year capture zone. None of these wells were identified as not in use or having poor water quality. This area has mainly a low susceptibility index ranking (**Map 4.15**) with a few small areas of moderate susceptibility.

According to information obtained from the Municipality of Thames Centre, the properties located within the capture zone are serviced by private septic systems.

7.3.4 Birr WHPA

Land use and potential contaminant sources in the area of the capture zone delineated for the Birr wells are shown on **Map 7.3**. The capture zone extended east, across Highway 4, through a residential/commercial area and into agricultural lands, with Medway Creek transecting the zone. Commercial properties in the capture zone consisted of a bookstore and a general store. The general store included an adjacent picnic area and a former gas bar. The owner of the general store indicated that the existing fuel USTs were removed in April 2003. All gas pumps had been previously removed, although the concrete island remained. A small cemetery was located within the 2-year capture zone. An AST was observed in association with a farm in the southern portion of the capture zone. The lands immediately surrounding the capture zone were dominated by agricultural and residential properties, with the following noted exceptions. A second small cemetery was located west of the capture zone. To the north, along Highway 4, there were two commercial properties, one occupied by a furniture store, the other vacant.

The TSSA database indicated a fuel storage location, immediately north of the general store, on the southeast corner of the intersection of Highway 4 with Thirteen Mile Road. It is considered likely that this record corresponded to the former fuel USTs at the general store.

MOE well records for three wells were identified within the 25-year capture zone. None of these wells were identified as not in use or having poor water quality. The Intrinsic Susceptibility Index Map (**Map 4.15**) indicates that the majority of the area has a moderate susceptibility ranking with small areas of low susceptibility.

According to information obtained from the Municipality of Middlesex Centre, the properties located within the capture zone are serviced by private septic systems.

7.3.5 Melrose WHPA

Land use and potential contaminant sources in the area of the capture zone delineated for the two operating Melrose wells are shown on **Map 7.4**. The capture zone extended northwest through a residential subdivision, crossing Vanneck Road and into agricultural lands, to its terminus northwest of Gold Creek Drive. A small water treatment plant, operated by the Municipality of Middlesex Centre, was located within the 2-year capture zone, adjacent to the residential subdivision of Wynfield Estates. A residential fuel AST was located within the 5-year capture zone. Northwest of the property, Oxbow Creek crossed the 5-year capture zone. Two oil pipelines crossed the northern portion of the 25-year capture zone. No commercial or industrial operations were observed within the capture zone. Areas within and immediately surrounding the capture zone, which were not occupied by residential properties, were generally arable land, with some livestock observed to the east along Sunningdale Road, as well as to the south along Vanneck Road. A car sales and service garage was located south of the capture zone, along Vanneck Road. Also south of the capture zone, there were two residential fuel ASTs; one located along Vanneck Road, adjacent to the car sales and service facility, and the other located west of the intersection of Vanneck Road with

Highway 22. In addition, a cemetery was located on the southwest corner of the aforementioned intersection.

MOE well records for seven wells were identified within the 25-year capture zone. None of these wells were identified as not in use or having poor water quality. This area has a combination of high and moderate Intrinsic Susceptibility Index Ranking (**Map 4.15**).

According to information obtained from the Municipality of Middlesex Centre, the properties located within the capture zone are serviced by private septic systems.

7.3.6 Komoka WHPA

Land use and potential contaminant sources in the area of the capture zone delineated for the Komoka well field are shown on **Map 7.5**. The capture zone extended to the northwest predominantly encompassing agricultural and recreational lands, with residential properties in the southeast corner. The Thames River flowed along the southeastern boundary of the 2-year time-of-travel zone. Two rail lines, Canadian National and Canadian Pacific, crossed the north and central portions of the capture zone, respectively. Oxbow Drive crossed the northern portion of the capture zone, between the two rail lines. Agricultural lands predominated along Oxbow Drive, with an active gravel pit and two cemeteries located just beyond the western portion of the capture zone. In addition, a golf course was under development on the parcel of land occupying the southwestern corner of the intersection of Oxbow Drive with Coldstream Road, in the northeast portion of the capture zone. Further south along Coldstream Road, a livestock herd was identified. A business park and residential area (community of Kilworth) were located near the eastern boundary of the capture zone, along Glendon Drive. The central portion of the capture zone primarily consisted of agricultural lands and several ponds, associated with former gravel pits. Residential properties within the community of Komoka were located just beyond the western boundary of the capture zone. Also within Komoka, a block of commercial/industrial properties was located along Glendon Drive and Tunks Lane, including: an auto repair garage, with a former fuel pump island; a garden centre; and a feed mill. Agricultural lands occupied the remainder of the commercial/industrial block. There was a residential fuel oil AST along Glendon Drive, near a former gravel pit. Komoka

Provincial Park was located adjacent to the southern portion of the capture zone. The lands adjacent to the capture zone were generally dominated by gravel extraction operations, both historical and active, as well as agricultural lands and additional residential properties.

MOE records indicated that several active and/or closed landfill sites were located just outside the northwest portion of the capture zone.

MOE well records for 45 wells were identified within the 25-year capture zone. One of these wells was described as having poor water quality (i.e., sulphurous) and 11 wells were reportedly not in use. The locations of wells identified as having "poor water quality" and/or "not in use" are shown on **Map 7.5**. The Intrinsic Susceptibility Index Map (**Map 4.15**) indicates this area has portions of moderate and high susceptibility.

According to the Municipality of Middlesex Centre, the properties located within the capture zone are serviced by a municipal sewer system.

7.3.7 Fanshawe WHPA

Land use and potential contaminant sources in the area of the capture zone identified for the Fanshawe stand-by supply well field are shown on **Map 7.6**. The capture zone extends north, along Clarke Road, predominately encompassing the Fanshawe Golf Course in the east, and active gravel pits in the west. In the central portion of the capture zone, along Clarke Road, immediately north of the well field, there was a plot of agricultural land. In addition, there were three residential buildings on the east side of Clarke Road, also central within the capture zone. A fuel AST was present on the northern-most of the three residential properties located along Clarke Road, south of the intersection with Sunningdale Road. A high pressure oil pipeline was identified running nearly perpendicular to Clarke Road, north of the capture zone, then turning parallel to Clarke Road and passing outside the eastern boundary of the capture zone. The lands immediately adjacent to the capture zone were dominated by additional gravel extraction operations to the north, south, southeast and west, as well as additional recreational lands associated with the Fanshawe Golf Course to the east and south. Arable cropland was also observed to the northeast and northwest.

An MOE record indicated that a solid waste disposal site was located north of the capture zone, along Clarke Road. This record is believed to correspond to a solid waste recycling depot and processing facility operated under two separate Certificates of Approval (AO40146 and 7474-5E3QC8, as obtained from the company president), on both sides of Clarke Road.

MOE well records identified 34 wells within the 25-year capture zone. The locations of wells identified as "not in use" are shown on **Map 7.6**. The Intrinsic Susceptibility of this area is high to moderate (**Map 4.15**).

According to information obtained from the City of London, the properties located within the capture zone are serviced by private septic systems.

8. GROUNDWATER MANAGEMENT ISSUES AND MEASURES FOR MIDDLESEX AND ELGIN

8.1 Introduction

The previous Sections in this report summarize the data and analyses completed to develop a good understanding of the groundwater resources in the Middlesex-Elgin Study Area. A final goal of the study was to develop a groundwater management strategy. For many study participants, this final step was of significant interest as it focuses on how to apply the regional groundwater resource information and how to protect water resources for current and future generations.

The Groundwater Resource Management Strategy for Middlesex and Elgin was developed with reference to, and within the context of, the existing regulatory and non-regulatory framework in Ontario. It builds on the extensive foundation of legislation, policies and programs already in place for water resource protection. It also recognizes that water resource protection, like many environmental issues, requires an integrated, multi-sector approach, involving partnerships and the effective coordination of resources between municipal, provincial and federal levels of government, conservation authorities, health units, and interest groups.

The Strategy consists of several elements which are briefly described below in Section 8.2. The groundwater resource management principles are then presented in Section 8.3. Other elements of the Strategy are presented in detail in **Appendix D** and **Appendix E**.

8.2 Overview of the Groundwater Resource Management Strategy

Groundwater Resource Management Principles

The first element of the Strategy consists of a set of "first principles" of groundwater resource management identified during the course of the study. They are based on the predominant issues and common themes that emerged from among the various groundwater protection issues and measures discussed, and they are considered fundamental to any groundwater protection strategy, regardless of local conditions and issues (see Section 8.3). These first principles include:

- utilize planning tools for smart growth
- adopt a watershed approach with Conservation Authority leadership
- better enforcement of existing rules
- coordination of activities among government and agencies
- encourage a "living strategy" with continuous improvement
- build upon and expand non-regulatory programs.

Existing Regulatory and Non-Regulatory Context for Groundwater Protection in Ontario

A wide variety of provincial and federal laws, regulations and standards are already in place that are relevant to the management and protection of water resources in Ontario. A number of influential provincial reports have also recently been issued, including the Report of the Walkerton Inquiry and the Report of the Advisory Committee on Watershed-based Source Protection Planning. In addition, various non-regulatory programs have been developed throughout Ontario, such as educational programs, stewardship activities, and funding initiatives that have a key role to play in groundwater protection and management.

In developing the Groundwater Resource Management Strategy for Middlesex and Elgin, it was recognized that this existing regulatory and non-regulatory regime provides a good basis for the wise management of water resources. Many water protection goals can be achieved by municipalities, conservation authorities, agricultural associations, health units and provincial departments through effective application of the existing rules and resources without "reinventing the wheel".

A summary of the key laws, regulations, reports and programs was, therefore, developed as the second element of the Strategy. Like other elements of the Strategy, it is intended to serve as an initial reference or "sourcebook" when dealing with specific groundwater protection issues. It will need to be revised and updated as new regulatory requirements or non-regulatory programs are introduced. The summary of the existing regulatory and non-regulatory context is presented in detail in **Appendix D** and addresses the following:

C federal programs and initiatives related to water resource management
C provincial legislation
C key provincial policies and reports
C non-regulatory programs.

Existing Groundwater Protection Policies in Middlesex and Elgin

The third element of the Groundwater Resource Management Strategy consists of a review of the relevant policies and zoning restrictions contained in selected examples of the current Official Plans and Zoning By-laws for Middlesex and Elgin Counties, and their lower-tier municipalities. Similar to the summary of the provincial context, this review is provided as background information and as a basis for policy change and improvement. The review is included in **Appendix D**.

Model Groundwater Protection Initiatives in Other Ontario Municipalities

Several municipalities in Ontario have developed "model" policies and programs related to the protection of groundwater resources, including policies to protect wellhead zones, recharge or infiltration areas, and areas vulnerable to contamination. Policies to prevent contamination are also incorporated. In this fourth element of the Middlesex-Elgin Groundwater Resource Management Strategy, examples of these model policies are highlighted. This information is also included in **Appendix D** and presents a discussion of the Oak Ridges Moraine Conservation Plan and descriptions of model policies from the following municipalities:

C County of Oxford
C Region of Peel
C Region of Waterloo
C Regional Municipality of Halton
C County of Brant.

Groundwater Management Issues and Measures for Middlesex and Elgin

The fifth element of the Groundwater Resource Management Strategy outlines specific groundwater resource management measures for Middlesex and Elgin. First, land uses and activities that typically could affect groundwater resources anywhere within the Study Area are described. The following land uses and activities are defined in terms of their potential to affect groundwater resources:

- water well construction, maintenance and decommissioning
- septic tank construction and maintenance
- underground storage tanks
- oil and gas wells
- land application and storage of nutrients
- application of pesticides and herbicides
- use of road salt on highways
- spills
- aggregate extraction and reclamation
- intensive livestock operations
- solid waste landfills
- drainage and water taking
- stormwater retention/detention facilities
- irrigation pits and ponds
- groundwater mining, and
- water use during periods of drought.

For each use or activity, examples of potential protection measures are then summarized including:

- the provincial role, if any, in the regulation of that use or activity
- the municipal regulatory options, i.e., the regulatory "tools" that could be used by the municipalities to protect groundwater in relation to the use or activity
- the non-regulatory initiatives that could contribute to the specific protection goals.

The additional measures needed to protect important groundwater features are then described, including measures for the wellhead protection areas within the Study Area, significant recharge/infiltration areas, and the ISI areas where groundwater is particularly susceptible to contamination from surface activities.

The groundwater management issues and associated protection measures listed above are summarized in **Table 8.1** at the end of this Section and presented in detail in **Appendix E**.

8.3 General Principles for Groundwater Resource Management

In conducting the research and consultation activities undertaken in developing the Groundwater Resource Management Strategy for Middlesex and Elgin, a number of common threads and predominant themes have emerged among the many groundwater issues and protection measures identified. They represent the "first principles" of groundwater resource management and would be applicable in implementing any groundwater protection strategy, regardless of the local conditions and specific issues being addressed. These first principles are considered fundamental to any other individual or specific groundwater management measures and include the following:

C **Utilize planning tools for smart growth:** The existing land use planning regime in Ontario provides both the policy direction and mechanisms for a "multiple barrier" approach to groundwater protection. The Provincial Policy Statement issued under the Planning Act promotes wisely managed growth resulting in communities which are environmentally and economically sound, and specifically refers to the need to protect or enhance the quality and quantity of groundwater and surface waters. Municipal Official Plans, secondary plans, subwatershed plans, and stormwater management master plans can provide or contribute to overall policies for the management, wise use and protection of water resources. Zoning By-laws, development controls, site plans and by-laws for property standards, water use, and tree-cutting can play a key role at the issue or site-specific level. This can include directing growth to urban areas and rural settlement areas, to lands that are suitable for development. It would also involve implementation of servicing policies that encourage development on full or communal services, and discourage multi-lot development on individual services.

Some municipalities, such as Halton and Peel, prohibit communal services because they are concerned that they will be forced to assume control and ownership of the systems.

- **Adopt a watershed approach with Conservation Authority leadership:** Water resources - both surface and groundwater - are best understood, monitored, managed, protected and enhanced from a watershed ecosystem perspective. This allows comprehensive consideration of water balance, water quantity, and water quality, as well as water-related natural features, terrestrial resources, aquatic life, and other key ecosystem indicators. Groundwater resource management plans and activities should be undertaken within a watershed framework. The 36 Conservation Authorities in Ontario were founded on the watershed approach to resource management and, with local municipal support, they have provided leadership in water resource management for more than half a century. Their established structure and base of expertise provides a foundation for a continued leadership role in water resource management and, with appropriate funding and resources, they would be well placed to lead the development and implementation of a watershed-based approach to groundwater protection.

- **Better enforcement of existing rules:** An extensive array of laws and regulations already exist that specify requirements relevant to the protection of water resources. Additional resources for and improved enforcement of the existing regulatory requirements would be very beneficial in achieving groundwater resource management goals.

- **Coordination of activities among government and agencies:** Various federal and provincial government departments, municipalities, conservation authorities, and health units have responsibilities related to water resource management and protection. Improved communication and coordination of effort among these responsible parties, including working agreements, partnerships, and data and resource sharing, would result in more efficient use of available resources and greater effectiveness in management of the groundwater resources.

- **Encourage a "living strategy" with continuous improvement:** A groundwater resource management strategy will, at any point in time, be the product of the technical data available, the environmental context, and the laws and regulations in place during its development. Updates and improvements will be needed through further studies and ongoing monitoring to allow for appropriate refinements and improvements. Establishment of a regional Groundwater Strategy Implementation Committee would assist in the continuous improvement process.

- **Build upon and expand non-regulatory programs:** Regulation and enforcement have a role to play in providing safeguards for the environment and in ensuring the remediation of negative effects. However, non-regulatory initiatives are often more influential in raising awareness of environmentally sound practices and behaviours, and in encouraging such practices to become part of day-to-day activities. There are many non-regulatory programs in Ontario aimed at improving practices that have the potential to impact on water resources. These include the educational programs, stewardship activities, and funding initiatives that have been or are being undertaken by conservation authorities, agricultural associations, health units, and community groups, either individually or in partnership with provincial or municipal organizations. With appropriate funding and resources, these groups have the depth of experience and local knowledge needed to continue to develop and deliver these important non-regulatory components of groundwater protection and management.

TABLE 8.1

Middlesex-Elgin Groundwater Study: General Principles for Groundwater Management	
General Principle	**Description**
Utilize planning tools for smart growth	The existing land use planning regime in Ontario provides both the policy direction and mechanisms for a "multiple barrier" approach to groundwater protection. The Provincial Policy Statement issued under the Planning Act promotes wisely managed growth resulting in communities which are environmentally and economically sound, and specifically refers to the need to protect or enhance the quality and quantity of groundwater and surface waters. Municipal Official Plans, secondary plans, subwatershed plans, and stormwater management master plans can provide or contribute to overall policies for the management, wise use and protection of water resources. Zoning by-laws, development controls, site plans and by-laws for property standards, water use, and tree-cutting can play a key role at the issue or site-specific level. This can include directing growth to urban areas and rural settlement areas, to lands that are suitable for development. It would also involve implementation of servicing policies that encourage development on full or communal services, and discourage multi-lot development on individual services.
Adopt a watershed approach with Conservation Authority leadership	Water resources - both surface and groundwater - are best understood, monitored, managed, protected and enhanced from a watershed ecosystem perspective. This allows comprehensive consideration of water balance, water quantity, and water quality, as well as water-related natural features, terrestrial resources, aquatic life, and other key ecosystem indicators. Groundwater resource management plans and activities should be undertaken within a watershed framework. The 36 Conservation Authorities in Ontario were founded on the watershed approach to resource management and, with local municipal support, they have provided leadership in water resource management for more than half a century. Their established structure and base of expertise provides a foundation for a continued leadership role in water resource management and, with appropriate funding and resources, they would be well placed to lead the development and implementation of a watershed-based approach to groundwater protection.

TABLE 8.1

Middlesex-Elgin Groundwater Study: General Principles for Groundwater Management	
General Principle	**Description**
Better enforcement of existing rules	An extensive array of provincial laws and regulations already exist that specify requirements relevant to the protection of water resources. Additional resources for and improved enforcement of the existing regulatory requirements would be very beneficial in achieving groundwater resource management goals.
Coordination of Activities among government and agencies	Various federal and provincial government departments, municipalities, conservation authorities, and health units have responsibilities related to water resource management and protection. Improved communication and coordination of effort among these responsible parties, including working agreements, partnerships, and data and resource sharing, would result in more efficient use of available resources and greater effectiveness in management of the groundwater resources.
Encourage a "living strategy" with continuous improvement	A groundwater resource management strategy will, at any point in time, be the product of the technical data available, the environmental context, and the laws and regulations in place during its development. Updates and improvements will be needed through further studies and ongoing monitoring to allow for appropriate refinements and improvements. Establishment of a regional Groundwater Strategy Implementation Committee would assist in the continuous improvement process.
Build upon and expand non-regulatory programs	Regulation and enforcement have a role to play in providing safeguards for the environment and in ensuring the remediation of negative effects. However, non-regulatory initiatives are often more influential in raising awareness of environmentally sound practices and behaviours, and in encouraging such practices to become part of day-to-day activities. There are many non-regulatory programs in Ontario aimed at improving practices that have the potential to impact on water resources. These include the educational programs, stewardship activities, and funding initiatives that have been or are being undertaken by conservation authorities, agricultural associations, health units, and community groups, either individually or in partnership with provincial or municipal organizations. With appropriate funding and resources, these groups have the depth of experience and local knowledge needed to continue to develop and deliver these important non-regulatory components of groundwater protection and management.

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
Wells, Septic Systems and Tanks			
Water Well Construction, Maintenance and Decommissioning	Regulation 903	municipalities could use their powers related to development approvals and servicing to ensure that the requirements of Regulation 903 are being followed within the municipality	develop a closer working relationship with MOE to focus their efforts on particularly troublesome local areas
	Healthy Futures for Ontario funding	municipalities could require proof of proper abandonment of unused water wells, monitoring wells or boreholes as a condition of development approval (i.e. for demolition permits, applications for consent, site plan approvals and subdivision approvals)	identify a group member to act as a local education and liaison representative regarding well drilling and decommissioning programs within the region

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
	It is recommended that the Provincial role with respect to well construction, maintenance and decommissioning be improved by:	municipalities could require proof of proper abandonment of unused water wells, monitoring wells or boreholes as a precondition for hook-up to a municipal water system; for hook-up of an existing hamlet this would require proof of decommissioning of all the individual wells; grants for municipal water hook-ups could include funding for well decommissioning, with provision to amortize the cost over several years	develop an abandoned well identification and location program in conjunction with MOE to identify specific wells which require decommissioning
Water Well Construction, Maintenance and Decommissioning (cont'd)	allocating more staff and resources to the inspection of well drilling activities	a deposit system could be introduced whereby a deposit is paid prior to the drilling of investigative wells or boreholes on municipal lands or for municipal projects; the deposit would be returned once proper decommissioning has occurred	provide educational forums on the need for and methods of well construction and decommissioning
	providing funding to identify wells which need to be decommissioned	municipal inspection duties for septic systems could be extended to/coordinated with inspection of wells	develop working relationships with water suppliers, municipalities, and other groups to educate residents and industries on well decommissioning needs and programs, and on the vulnerabilities of shallow wells

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
	continue funding programs for upgrades and decommissioning under the Clean Water Program and the OFA through the Healthy Futures for Ontario program	municipalities could request to be given the responsibility of inspecting wells under Regulation 903; for example, the Township of North Grenville in eastern Ontario	initiate a mechanism whereby well test data collected by the Health Unit can be provided to the municipality for monitoring purposes.
	providing educational materials to well drilling firms, residents, municipalities, organizations, and industries regarding the MOE role and the needs and advantages inherent in proper well construction		
	developing an education program which details the vulnerabilities of shallow wells		
	developing closer ties and communication with municipal water systems to notify residents and industries which connect to public water supplies of the decommissioning requirements		
	instituting requirements for proper plugging of test holes similar to the rules for wells		

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
	requiring pump installers to report pump locations and old wells to the Ministry, and to ensure that pump replacement and well retrofits are done properly.		
Septic System Construction and Maintenance	Part 8 of the Building Code, Building Code Act; Ontario Water Resources Act	A primary role for municipalities in minimizing septic system risks to groundwater is to use municipal planning tools, including Official Plans, zoning by-laws and development controls, to implement the "smart growth" principle noted earlier in this report. This would facilitate "doing things right in the first place" by directing growth to serviced areas or areas with optimum subsurface conditions.	development and funding of a program to evaluate and repair existing non-functional septic tanks
		Muncipalities can require both a minimum lot size and minimum lot frontage	coordination with existing septic tank education programs
		Municipality to require additional study prior to authorizing septic system permits or approvals to address local geology or water quality issues.	developing studies to evaluate the impact of closely spaced septic tanks on groundwater and surface water quality
			public education on the proper maintenance and safe utilization of septic tanks, and regarding the disposal of hazardous materials into septic systems

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
Underground Storage Tanks	Transportation of Dangerous Goods Act (Canada)	municipal regulatory option would be to use municipal powers related to development approvals and servicing to ensure that the provincial requirements are being followed within the municipality	develop a working relationship with the TSSA to assist in the process of identification of underground tank owners and registration of the tanks
	Dangerous Goods Transportation Act (Provincial)	municipalities could require proof of proper installation, registration, upgrading or removal of any underground storage tanks as a condition of development approval (i.e. for applications for consent, site plan approvals and subdivision approvals), or as a precondition for hook-up to a municipal water system.	identify a staff or group member to act as a local education and liaison representative regarding existing requirements, in particular the rules under the *Technical Standards and Safety Act* and the Fire Code
	Technical Standards and Safety Act, 2000		provide educational forums on the need for and methods of proper underground storage tank installation, maintenance and removal.
	Fire Protection and Prevention Act, 1997		
Oil and Gas Wells	*Oil, Gas and Salt Resources Act* administered by the Ministry of Natural Resources	regulatory options for municipalities vis a vis oil and gas wells are similar to those mentioned in previous sections	maintenance of an ongoing liaison with local Ministry of Natural Resources staff for the exchange of information
	Ontario Regulation 245/97 titled "Exploration, Drilling and Production", issued under the *Oil, Gas and Salt Resources Act*	ensure that the provincial requirements are being followed within the municipality via use of municipal powers related to development approvals and servicing	maintenance of a database regarding both old and active oil and gas wells.

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
	R.R.O. 1990, Regulation 341 titled "Deep Well Disposal", issued under the Environmental Protection Act		
	the *Ontario Energy Board Act*, *1998* administered by the Ministry of Energy, and		
	Ontario Regulation 210/01 titled "Oil and Gas Pipeline Systems", issued under the *Technical Standards and Safety Act, 2000*.		
Use of Nutrients and Chemicals			
Land Application and Storage of Nutrients	Bill 81, Nutrient Management Act	Powers under the *Planning Act* to regulate where agricultural and related activities take place, subject to provincial policy statements and the *Farming and Food Production Protection Act 1998*	develop working relationships and, where appropriate, agreements with landowners, OMAF, and MOE to focus their efforts on locally important issues and areas of local concern
		Powers to regulate with respect to operations or activities not addressed by the regulations (e.g. smaller operations)	identify a local education and liaison representative for nutrient management programs to be a point of contact for information, education, or potential violations

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
		It is recommended that municipalities be involved in implementation duties such as review and approval of nutrient management plans and the maintenance of registries of nutrient management plans and strategies. At a minimum, municipalities should have ongoing access to this data.	provide educational forums for organization members, farmers, industries, and the general public on effective nutrient management practices
Application of Pesticides and Herbicides	Pest Control Products Act (Federal)	eliminate use of pesticides for certain uses through by-laws	additional financial resources for Best Management Practices (BMPs) could be established at the municipal level to encourage and achieve environmental responsibility in agricultural production.
	Ontario's Pesticides Act	institute requirements for all property owners who apply pesticides to complete education and testing regarding pesticide use comparable to that required of farmers.	Environmental Farm Plan was developed by OFEC to help farmers assess the environmental risk associated with their current farm practices, and to reduce this risk through the adoption of BMPs.
	Environmental Protection Act (the EPA)		municipalities, conservation authorities and other groups could continue to support the existing urban area programs that promote "pesticide free" lawns and alternative ground covers, in conjunction with water conservation measures.
	Ontario Water Resources Act (the OWRA)		

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
	Nutrient Management Act		
Use of Road Salt on Highways	MTO guidelines	municipalities could consider alternatives to road salting	A review of County road salting activities to ensure optimum road salt application rates are used, however, safety of the travelling public should be paramount.
		use of these control mechanisms to minimize road salt impacts to water supplies could provide a foundation for future management plans.	Reductions in salting rates and transitions to the use of road-salt alternatives (e.g. sand) should only be undertaken where safety permits. This review should include the overall objectives of road maintenance, including the appropriateness of "bare pavement" objectives.
		appropriate separation distance between major salt applications areas (e.g. Highway 401) and new development based on groundwater supply	Water quality monitoring sites could be established near major roads and highways.
		in the absence of an appropriate separation distance between a development and a major salt application area, a satisfactory supporting groundwater quality study should accompany the development application.	

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
Spills	MOE and owner of material are primarily responsible in the event of a spill	Municipalities could use development approval powers to ensure that emergency response teams and protocols will be in place for any new development with the potential for chemical spills.	special spill management protocols may be required in WHPAs vs non-WHPA areas. A spill responder group, consisting of the County Fire Co-ordinator, Local Fire Departments, and County and Township Officials could be established to discuss spill response in WHPAs.
	Fire department may be called upon if property or lives are endangered	Municipal response teams and protocols should be developed in conjunction with fire departments and other emergency service personnel.	review response scenarios involving first responders (such as local fire department, police etc) to ensure that response protocols are clearly understood, and the response system is a streamlined as possible.
	Environmental Protection Act, 1990, administered by the MOE		
	Ontario Water Resources Act, 1990, administered by the MOE		

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
Large Agricultural and Industrial Operations			
Aggregate Extraction and Reclamation	Aggregate Resources Act - R.S.O. 1990, c.A8., Ministry of Natural Resources (MNR)	Municipalities have a role that is subsidiary to the provincial role in that the zoning by-laws, growth management strategies, and official plans for the municipality are reviewed by the provincial MNR in granting permits and licences.	initiatives that can be employed by aggregate operations may include consulting local environmental or conservation groups in the region before or during aggregate extraction activities.
Intensive Livestock Operations	Bill 81, Nutrient Management Act	same as for "Land Application and Storage of Nutrients"	same as for "Land Application and Storage of Nutrients"
	Farming and Food Production Act, 1998		
	Provincial Policy Statement under the Planning Act		
Solid Waste Landfills	Environmental Assessment Act	Official Plan, zoning, site plan approvals	Landfill liaison committees
	Environmental Protection Act		Financial compensation to host community and/or property owners
	Planning Act		

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
	other requirements as applicable under Building Code, Fire Code, Ontario Water Resources Act and Occupational Health and Safety Act		
		Drainage and Water Taking	
Field Tile Drains	Drainage Act - R.S.O. 1990, c. D. 17	current role of municipalities in construction or alteration of field tile drainage systems is to ensure that the system follows the approved design before connecting the drainage systems to the municipal drain system.	create a simple effective drainage system that permits the required work to be completed in the fields, while minimize the inhibition of natural recharge.
	Tile Drainage Act - R.S.O. 1990, c. T.8	water from municipal drains that discharge to surface water bodies must meet the Provincial Water Quality Objectives (PWQO's), and as a result, the water quality of the water from field drains must be considered.	A well engineered drainage system could include a simple valving system that allows the amount of water and period of drainage to be controlled by shutting off or controlling the flow through the drainage system.
	Agricultural Tile Drainage Installation Act - R.S.O. 1990, c. A.14.		drainage system could discharge to an irrigation pond, minimizing the amount of water needed to be pumped from an external source in the summer months, while allowing for some groundwater recharge.

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
			Establishing natural recharge areas such as re-creation of historic wetland areas by the province, municipalities, as well as privately could reduce the stress placed on the groundwater environment from the unnatural inhibition of recharge.
Stormwater Retention/Detention Facilities	Stormwater Quality Best Management Policies, 1991, MOE	Land use regulations imposed by the municipality under the Planning Act is a regulatory control on stormwater management issues.	diligence on the part of the engineering team and those responsible for approving the designs of stormwater management systems is important in creating a system that minimizes, or potentially benefits the local environment.
		The municipality should be actively involved in conjunction with the MOE in granting permits for completing stormwater management works.	Incentives potentially put forth by municipal or provincial authorities to encourage "wise" stormwater management is a possible non-regulatory initiative.
Irrigation Pits and Ponds	Ontario Water Resources Act - O.Reg.285/99 Permit to Take Water	Municipalities are concerned with the implementation of irrigation systems as they can pose environmental damage, as well as damage to public and private property.	Owners of irrigation systems can employ a number of strategies to make efficient use of the water used for irrigation

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
	MTO - Permit to Construct	Policies could be imposed in the future by municipalities, that would be consistent with the Best Management Practices put forth by the Provincial Government.	The *Best Management Practices* provided by the Ministry of Agriculture and Food should be consulted and considered when implementing and operating an irrigation system.
	Conservation Authorities Act - R.S.O. 1990, c.27		Development of irrigation schedules and rural peer groups could benefit farmers and minimize environmental impacts associated with irrigation practices.
	Ministry of Agriculture - Best Management Practices		
Groundwater Mining	No official regulatory mechanisms present, Ontario Water Resources Act - O.Reg. 185/99 broadly addresses use of groundwater and its conservation	No official municipal regulatory mechanisms in place that deal directly with the issue of groundwater mining.	High volume water users should consider their choice of facility location and water supply in order to avoid long term water supply issues such as diminished yield as a result of groundwater mining.
		Planning Act gives municipalities the authority to use official plans and zoning by-laws to regulate water use.	Established water users can also help to avoid groundwater mining issues by becoming familiar with their water supply system, their consumption, and learn to monitor water levels.

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
		Careful land use and growth management plans are essential in curbing over consumption of groundwater thus preventing groundwater mining.	Diligence in monitoring groundwater supplies can identify problems in the early stages and prevent significant damage by altering water use appropriately.
		Facilities that use high volumes of water should be located in areas designated to be used industrially or commercially by zoning by-laws and official plans with appropriate long term water supply and treatment capacity.	Education programs to encourage the conservation and wise use of water should also be implemented to discourage groundwater mining and other forms of overuse.
Water Use During Periods of Drought	There are no provincial controls on water use during periods of drought.	Lawn watering bans are often imposed by municipal bodies when it becomes apparent that the rate of consumption is going to exceed the capacity of the municipal system to supply water to their residents	initiatives can be taken by the general public, farmers, commercial operations, and industry. During periods of drought, the onus should be placed on all water users to limit unnecessary water use to a minimum.
			Use of simple water conservation measures such as rain barrels, cisterns for lawn irrigation, trickle irrigation systems, and the use of grey water for cosmetic watering should be encouraged on the municipal scale possibly with incentives.

Table 8.1 (cont.)

Middlesex-Elgin Groundwater Study: Summary of Groundwater Management Issues and Measures			
Category/Issue	**Provincial Role**	**Municipal Regulatory Options**	**Non-Regulatory Initiatives**
			Fact sheets could be distributed with an emphasis on saving the consumer money, while stressing efficient and proper watering practices.
Groundwater Resource Features: Wellhead Protection Areas, Significant Recharge Areas, ISI Areas		Conventional zoning approach: Control or prohibit higher-risk land uses in wellhead capture zones, sensitive groundwater resource areas	Provide signage in wellhead protection areas to raise awareness
		Performance zoning approach: Require site-specific studies for higher-risk land uses in wellhead capture zones, sensitive groundwater resource areas	Include information about local groundwater resource features as part of education programs.
		Install sentry wells in wellhead protection areas	
		Prepare contingency plans for alternative drinking water supplies, and spill response plans	
		Purchase lands in sensitive groundwater resource areas	
		Provide compensation to land owners where land use restrictions are imposed.	

9. SUMMARY

This section summarizes the major findings of the study:

1) Groundwater in Middlesex and Elgin is highly influenced by the glacial geology of the area. The sand plains, clay plains and moraines in the Study Area all effect groundwater resources in terms of recharge, protection of underlying aquifers and/or discharge to surface water.

2) Within Middlesex and Elgin, there are three main types of potable water aquifers: shallow unconfined overburden aquifers, intermediate to deep overburden aquifers that are protected by overlying low permeability clay and till soils, and bedrock aquifers. Approximately 75 percent of all water wells pump from overburden aquifers.

3) The two major bedrock aquifers include a limestone aquifer located in the north-central part of Middlesex County and a shale aquifer located near the western border of Middlesex. The limestone aquifer produces adequate quantities of groundwater which is generally of good quality (with elevated water hardness). The shale aquifer is more marginal and typically produces less water with poorer water quality.

4) The overburden aquifers can be divided into three aquifer types: Surficial unconfined sand and gravel aquifers are associated with sand plains (glacial lake origin) or former glacier meltwater streams. There are also aquifers found below low permeability soils like clay and till referred to as intermediate depth confined overburden aquifers and deeper overburden confined aquifers. These aquifers tend to be relatively local in nature and cannot be mapped on a regional basis.

5) Groundwater flow is influenced by topography and the surface water drainage system, but regional flow is generally from northeast to southwest in the bedrock. The bedrock flow system is similar to the overburden system with an exception in north Middlesex, mainly in Lucan-Biddulph, where water levels in bedrock wells are quite low, below the

overburden/bedrock interface. This is a regional condition also identified in Perth County and Huron County, north of Lucan-Biddulph.

6) Groundwater recharge areas were identified to be mainly associated with the moraines in the area, which tend to be topographical highs. The Lucan-Biddulph area was also identified as a recharge area as a result of the low water level in the bedrock. Discharge areas are in the stream and river valleys, notably the Thames River and the incised creeks that feed into Lake Erie (Catfish Creek, Kettle Creek and Talbot Creek as well as the Ausable River along the western border of North Middlesex).

7) Aquifers vulnerable to contamination have been identified using the Ministry of the Environment Intrinsic Susceptibility Index (ISI) method. Aquifers that are most vulnerable to impacts are the surficial sand and gravel aquifers. These cover a large part of south Malahide and Central Elgin, almost all of Strathroy-Caradoc as well as a significant part of the City of London, and the Dorchester area. Deeper aquifers are much better protected than shallow aquifers.

8) Overall, the total estimated groundwater use is approximately 31,500,000 m^3/year, of which the main uses are:

Public Supply	12%
Self Supply, Domestic (Residential)	12%
Self Supply, Domestic (Commercial/Institutional)	12%
Self Supply, Irrigation	19%
Self Supply, Livestock	9%
Self Supply, Industrial (manufacturing)	1%
Self Supply Industrial (mining)	35%
Self Supply, Other	<1%

The largest groundwater users (based primarily on maximum permitted volumes) are the quarry and mining industries, that account for 34 % of the water use. Use of groundwater for potable purposes makes up approximately 29 % of the groundwater use.

9) An inventory of potential contaminant sources across the Study Area was developed and a geographic coordinate was assigned to each source where possible. A detailed methodology was developed and documented when conducting this inventory, such that the procedure can be updated when newer or more accurate data become available. The distribution of potential contaminant sources across the Study Area indicated that the majority of the point contaminant sources such as gas stations, PCB storage sites, dry cleaners and manufacturing facilities are located in and around the urban areas, particularly London and St. Thomas. Landfill sites are more broadly distributed, with both active and closed landfills in all area municipalities. Comments on spreading agricultural and non-agricultural (biosolids) nutrients, road salting practices, landfills and industrial and commercial chemical usage are provided.

10) Wellhead protection areas around six municipal groundwater supply systems were identified. Three of these systems, Thorndale, Birr and Melrose, are relatively small systems and the source aquifers are protected by an aquitard consisting of a thick layer of clay and silt soils. Protection planning for these systems should centre on maintaining the integrity of the aquitard with the decommissioning of unused water wells and the proper construction of new wells being the major issues. The aquifer for the Dorchester well system is unconfined and receives water from Dorchester Creek with a relatively short travel time. Protection planning for this system should include land uses along the margins of the Dorchester swamp and also maintaining a viable ecosystem for the Swamp. The Komoka-Kilworth water supply aquifer is somewhat protected from surface contaminants, but is in an area of complex geology. Protection planning for this area should include both land use considerations as well as maintaining the integrity of the clay soils overlying the aquifer.

11) Groundwater management and protection in Middlesex and Elgin are the responsibility of several levels of government, public organizations and the general public. Groundwater

resource management measures for Middlesex and Elgin were developed according to two areas of consideration. First, land uses and activities that could affect groundwater resources within the Study Area were considered. Secondly, specific groundwater resource features were defined and described including wellhead protection areas, water recharge areas, and ISI areas. A summary of the management strategy is presented in Section 8.

10. RECOMMENDATIONS

This section presents the major recommendations from this study. Additional recommendations on completing data gaps identified during this study are presented at the end of the individual appendices.

1. The groundwater management strategies outline is this report should be considered for implementation. A Groundwater Study Implementation Committee, in some form, should be considered . The intent of this committee is to coordinate between area municipalities water resource protection measures.

2. It is recommended that the GIS environment that has been established for this project be used to update the data as new information becomes available. To meet this end, a long-term maintenance plan would be required to maintain the currency of the GIS and many of the study findings to facilitate future updates of the groundwater management strategy. The long-term maintenance plan could involve updates to the GIS at the municipal level, conservation authority level or provincial level. Consistent data standards should be maintained between partnering agencies in order to facilitate the sharing of applications that may be developed. Standards are available for parcel mapping (i.e., Teranet) and municipal infrastructure (i.e., the Ontario Good Roads Association' s MIDS, Municipal Infrastructure Data Standard), which are independent of application software and platform. Alternative standards, described as "object models', are alternatively available through core GIS software such as ArcInfo 8.

3. Accurate estimation of actual water usage through the existing PTTW records is difficult. Efforts should be made to monitor the actual water used by the large water takers so that a more realistic accounting of the water demand can be determined.

4. Monitoring wells should be installed in select areas to record groundwater levels over time. The data can be collected to assess long-term trends in aquifer storage and to act as an early warning system for aquifer over pumping. Wells should be placed in the primary

overburden and bedrock aquifers identified in this study. Priority can be given to installing wells near communities that rely on private wells. Some of the wells that were installed through the new Provincial Groundwater Monitoring Network may meet these needs.

5. It is recommended that a network of monitoring wells be installed in rural agricultural areas to assess and monitor the presence of nitrates, pesticides and bacteria in the groundwater. Wells should be interspersed between low and highly vulnerable areas in order to assess the contribution that agriculture has to groundwater impairment.

6. Consideration should be given to updating the database of potential and known contaminated sites on a regular basis as further data becomes available. The database that is generated in this study is not exhaustive and will become outdated with time. The database could be expanded to include zoning information for land uses that may pose a risk to the groundwater resource.

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12. GLOSSARY OF TECHNICAL TERMS

Adsorption The attraction and adhesion of gas, vapour or dissolved matter by the surface of a solid.

Advection The movement of solutes by transport in flowing groundwater.

Anisotropy The condition in which the hydraulic conductivity of an aquifer varies with the direction of groundwater flow.

Aquiclude A saturated, poorly permeable unit that does not yield water freely to a well or spring. However, it may transmit water to or from adjacent aquifers.

Aquifer Rock or sediment unit that is sufficiently permeable to supply water to wells.

Aquifer, confined An aquifer that is bound above and below by a formation with significantly lower hydraulic conductivity.

Aquifer, perched A region in the unsaturated zone where percolating water accumulates above an impermeable or nearly impermeable layer.

Aquifer, semiconfined An aquifer confined by a low-permeability layer that can transmit some groundwater.

Aquifer, unconfined An aquifer in which the upper boundary (water table) is a water surface at atmospheric pressure (the water table).

Aquitard A low-permeability unit that contains water but does not readily yield water to pumping wells. Aquitard can restrict contamination movement.

Artesian condition Groundwater that is under pressure when tapped by a well and is able to rise above the level at which it is first encountered. It may or may not flow out at ground level. The pressure in such an aquifer commonly is called artesian pressure, and the formation containing artesian water is an artesian aquifer or confined aquifer. See flowing well

Artificial recharge A process where water is put back into groundwater storage from surface water supplies.

Base flow	Streamflow that results from groundwater seeping into a stream.
Bedrock	The solid rock beneath the soil and superficial rock. A general term for solid rock that lies beneath soil, loose sediments, or other unconsolidated material.
Boring	A hole advanced into the ground using a drilling rig.
Cementation	The filling of voids in a sediment by the precipitation of materials such as silica, calcite, and iron oxide.
Diamict or **diamicton**	Generic, non-specific term used for any poorly sorted mixture of clay, silt, sand, gravel and/or boulders regardless of origin.
Diffusion	The process by which transport in a fluid occurs as a result of differences in concentration.
Digital computer model	A model of groundwater flow in which the aquifer is characterized by numerical equations, with specified values for boundary conditions.
Discharge	The volume of water that passes a given location within a given period of time.
Discharge point	A location at which groundwater flows out of an aquifer.
Dispersion	The spreading and mixing of chemical constituents in groundwater caused by diffusion and mixing due to microscopic variations in velocities between the pores.
Drainage Basin	The land area where precipitation runs off into streams, rivers, lakes and reservoirs. Also called a watershed.
Drainage divide	A boundary line along a topographically high area that separates two adjacent drainage basins.
Drawdown	A lowering of the groundwater surface caused by pumping. The difference between the static water level and the pumped water level.

Effective porosity	The amount of porosity available for fluid flow.
Equipotential line	A line along which the pressure head of groundwater in an aquifer is the same.
Equipotential surface	A surface in a three-dimensional groundwater flow field on which the total hydraulic head in the aquifer is the same.
Evaporation	The process of liquid water becoming water vapor, including vaporization from water surfaces, land surfaces, and snow fields, but not from leaf surfaces. See transpiration.
Evapo-transpiration	The sum of evaporation and transpiration.
Finite-difference model	A digital computer model based upon a rectangular grid that sets the boundaries of the model and the nodes where the model will be solved.
Flowing well/spring	Well or spring that taps groundwater under pressure so that water rises without pumping. If the water rises above the surface, it is known as a flowing well.
Glacial-lacustrine sediments	Silt and clay deposits formed in lakes that received meltwater from glaciers.
Glacial till	A mixture of clay, sand, gravel, boulders and sediment deposited by melting glacial ice; usually resistant to groundwater flow.
Groundwater, confined	Groundwater under pressure that is significantly greater than atmospheric. This water is bound above by a unit with a hydraulic conductivity distinctly lower than that of the material in which it occurs.
Groundwater flow	The movement of water through porous material in the saturated zone.

Groundwater mining Removing groundwater at rates that exceed that of natural recharge.

Groundwater, perched Unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

Groundwater, unconfined Water which occurs in an aquifer with a water table.

Hardness A measure of the concentration of divalent cations in water, mainly calcium and magnesium.

Head, total The sum of the elevation head, the pressure head, and the velocity head at a given point in an aquifer.

Heterogeneous Non-uniform in structure or composition.

Homogeneous Uniform in structure or composition.

Hydraulic gradient The rate of change in total head per unit of distance of flow in a given direction.

Hydrogeology The study of the interrelationships of geologic materials and sub-surface water.

Hydrograph A graph that shows some property of water as a function of time.

Hydrologic cycle The cyclic transfer of water vapor from the earth's surface via evapotranspiration into the atmosphere, from the atmosphere via precipitation back to earth, and through runoff into streams, rivers, and lakes, and ultimately into the oceans.

Hydrostratigraphic unit A formation, part of a formation, or group of formations in which there are similar hydrologic characteristics that allow for grouping into aquifers and associated confining layers.

Infiltration The flow of water from the land surface into the sub-surface.

Infiltration capacity	The maximum rate at which water can enter the soil.
Isotropy	The properties of a medium are equal in all directions.
Karstic terrain	A landscape characterized by the chemical solution weathering of calcareous and dolomitic rock (limestone and dolostone) resulting in the development of larger vertical and horizontal fractures and vugs near surface. This weathering is caused by the migration of groundwater undersaturated with respect to calcite and dolomite causing an increase in the permeability of rock by dissolving fracture surfaces.
Leaky confining layer	A low-permeability layer that can transmit water at sufficient rates to provide some recharge to a well pumping from an underlying aquifer.
Milligrams per litre	A unit of the concentration of a constituent in water which represents 0.001g of constituent in 1 litre of water.
Observation well	A well drilled in a selected location for the purpose of observing aquifer parameters such as water levels and pressure changes.
Piezometer	A tube or pipe used to measure water-level elevations.
Pore space	The volume between mineral grains in a porous medium.
Porosity	The percentage of the total rock or soil space the constitutes pore spaces.
Potentio-metric map	A contour map of the potentiometric surface of a hydrogeologic unit.
Potentio-metric surface	The potential level to which water will rise in a well that penetrates a confined aquifer.
Pumping cone	A depression in the groundwater table or potentiometric surface that develops around a well that has been pumped.
Pumping test	A test that is conducted to determine aquifer or well characteristics.

Recharge area	Regions where the flow of water is directed downward with respect to the water table.
Recharge boundary	An aquifer system boundary that adds water to the aquifer such as streams and lakes.
Recovery	The rate at which the water level in a well rises after a pump has been shut off.
Rock, igneous	A rock formed by the cooling and crystallization of a molten magma.
Rock, metamorphic	A rock formed by the alteration of pre-existing rock by heat, pressure, and/or chemically active fluids.
Rock, sedimentary	A rock formed from the weathered products of pre-existing rocks that have been transported, deposited and lithified.
Run off	The amount of precipitation, snowmelt or irrigation water that reaches streams, rivers, drains or sewers.
Saturated zone	A sub-surface zone in which all openings in a soil or rock formation are filled with water.
Specific capacity	The amount of water that can be pumped from a well divided by the decrease in water level of the well at the time of pumping. It is a measure of the productivity of the well.
Static water level	The level or elevation of water in a well that is not affected by pumping. The static water level represents the water pressure in the rock that is exposed by the well to pumping. The water level will depend upon the water pressure (head) in the aquifer and the atmospheric pressure.
Storativity	The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.
Theoretical well yield	Specific capacity of a well multiplied by the available drawdown. Theoretical well yield is usually less than the actual yield capabilities of the well.

Till	Specific term used for any poorly sorted mixture (see diamict) of clay, silt, sand and gravel, often with large boulders deposited directly by glacial ice.
Till Plain	Flat topography underlain by till. Sometimes undulating and drumlinized. Very common in glaciated terrains.
Transmis-sivity	The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient.
Turbidity	The amount of solid particles that are suspended in water and cause light rays to scatter, producing a cloudy appearance.
Unsaturated zone	A soil or rock zone above the water table, extending to the ground surface, in which the pore spaces are only partially filled with water.
Volatile organic compound (VOC)	An organic compound that is highly mobile in groundwater and readily volatilized into the atmosphere.
Water table	The top of the saturated zone.
Well casing	A solid piece of pipe, typically steel or PVC plastic, inserted in the borehole to keep the well open.
Well development	The process whereby a well is pumped or surged to remove any fines from the formation in the vicinity of the well.
Well, fully penetrating	A well drilled to the bottom of an aquifer to draw water from the entire aquifer thickness.
Well interference	The condition occurring when the area of influence of a water well comes into contact with or overlaps that of a neighbouring well. For example, two wells pumping from the same aquifer will cause interference.
Well, partially penetrating	A well which draws water from only a portion of the total thickness of the aquifer.

Well screen	A filtering device used to keep sediment form entering a water well.
Well yield	The quantity of water that can be produced by a well. Often reported as litres per minute or gallons per minute.