Ontario

Groundwater Resources Study 3

Three-Dimensional Mapping of Surficial Deposits in the Regional Municipality of Waterloo, Southwestern Ontario

2007

Ontario

Three-Dimensional Mapping of Surficial Deposits in the Regional Municipality of Waterloo, Southwestern Ontario

Ontario Geological Survey

Groundwater Resources Study 3

by

A.F. Bajc and J. Shirota

2007

Contents

FIGURES

TABLE

PLATES

Abstract

The Ontario Geological Survey (OGS) has undertaken a project of three-dimensional (3-D) mapping of Quaternary deposits within the Regional Municipality of Waterloo in southwestern Ontario, Canada. This project is part of a broader OGS initiative designed to provide basic geoscience information for the identification, protection, preservation and sustainable use of the provincial groundwater resource.

The main objective of this project is to develop a series of protocols for detailed 3-D mapping of Quaternary deposits in the province. These protocols will be used as the basis of, and to provide standards for, similar surveys to be undertaken in other areas. Three-dimensional mapping involves the characterization of the geometry and inherent properties of subsurface deposits. This information can 1) aid in studies involving groundwater identification, extraction, protection and remediation; 2) assist with the development of policies surrounding land use and nutrient management; and 3) help to better understand the interaction between surface and groundwater systems.

This report briefly summarizes the geology of the Waterloo Region, provides an in depth discussion of the procedures and protocols involved in the construction of the 3-D geologic model and contains a brief discussion of the distribution, thickness, geometry and properties of the main units modelled. The report also contains a discussion of aquifer vulnerability and recharge. Structural contour and isopach maps, west-east and south-north cross sections at 2.5 km intervals and a depth to aquifer map that can be used to assess aquifer vulnerability and recharge areas are provided on the CD-ROM.

A companion digital data set is also being released with this Groundwater Resources Study. The data consist of 1) portable document format (PDF) versions of the contained plates; 2) comma-delimited text files of both continuous and discontinuous surfaces on a 100 m grid; 3) 100 m ESRI® ArcInfo® structural contour grids of discontinuous surfaces; 4) an abridged version of the subsurface database containing borehole location and stratigraphic information; and 5) a *.kmz* file that portrays transparent overlays of the structural contour and isopach maps, borehole locations and lithologic logs and aquifer recharge/susceptibility maps in a web-based (Google Earth™ mapping service) environment. This functionality allows for enhanced user interaction with the spatial data.

Background

Pressures directed at protecting and preserving the quality and sustainability of the provincial groundwater resource have greatly increased since the Walkerton tragedy of May 2000. One of the key recommendations contained within the report of the Walkerton Inquiry was the implementation of watershed-based, source water protection plans for all regions of the province. Source water protection plans are designed to protect human health by ensuring that current and future sources of drinking water in Ontario are protected from potential contamination and depletion. According to the United States Environmental Protection Agency, the costs of remediating contaminated groundwater can be up to 40 times greater than taking initial steps to protect water at the source.

Source water protection plans contain 1) inventories of existing and possible threats to the ground and surface water resource; 2) maps that highlight source water protection areas, areas of known and possible contamination and areas where ground and surface water is more vulnerable to contamination; 3) information on soils, geology, topography, forest cover, wetland distribution and classification, crops and water well locations; 4) a ranking of known and possible threats to surface and ground water and the identification of vulnerable areas; and 5) the establishment of regular monitoring and reporting practices.

The Regional Municipality of Waterloo (RMOW) has led the way in source water protection by developing a 10 year Water Resource Protection Strategy (WRPS) aimed at protecting and preserving water supplies in the region. Approximately 450 000 people live in the RMOW and 80% of the region's water supply is groundwater derived. The main objectives of the strategy are to 1) understand groundwater flow and identify recharge areas that contribute water to municipal wells; 2) identify potential sources of contamination, particularly those in recharge areas that contribute water to municipal wells; 3) develop and implement policies to manage land uses that may harm sources of water; and 4) develop education programs that raise public awareness of the need to protect sources of water. The region has defined well head protection areas and has rated them according to their susceptibility to contamination. This information has been used to guide land-use development policies and decisions. Other initiatives such as the Rural Water Quality and the Business Water Quality programs are cost-shared initiatives that are designed to encourage farmers and businesses to implement best-practice protocols that will help to protect and preserve surface and ground water quality. In addition, the RMOW has initiated steps to reduce the impact of road salt on its water supply.

Currently, the region is undertaking an Integrated Urban System Groundwater Optimization and Expansion project, the objective of which is to restore capacity to some existing well fields in the urban areas and to explore for new supplies in both the urban and rural areas of the region. A parallel project to generate a new three-dimensional (3-D) regional groundwater flow model has also been initiated. A good understanding of the properties and 3-D architecture of geologic materials is required for both of these projects. To this end, the Ontario Geological Survey (OGS) initiated a pilot project of 3-D mapping of Quaternary deposits within Waterloo Region. The objectives of this pilot project were to develop protocols for the construction of interactive 3-D models of Quaternary geology and derived products that could 1) aid in studies involving groundwater extraction, protection and remediation; 2) assist with the development of policies surrounding land use and nutrient management; and 3) help to better understand the interaction between ground and surface waters.

Waterloo Region was chosen for this pilot project as it is one of the largest municipal users of groundwater in Canada; relying almost exclusively on bedrock and overburden aquifers for their potable water supply. Waterloo Region also has a population that is projected to increase by an estimated 20% in the next decade. This dramatic increase will undoubtedly apply pressure to an already stressed groundwater resource. A better understanding of the geometry and inherent properties of the Quaternary sediments that overlie the bedrock surface within the region will assist with the development of source water protection plans and with the development of a geoscience-based management plan for the groundwater resource.

Regional Geologic Setting

The Region of Waterloo is located east and south of the middle of the interlake peninsula commonly referred to as southwestern Ontario (Figure 1). It is at the boundary between the Carolinian deciduous forest vegetation zone extending southward and the St. Lawrence mixed forest extending northward. It has a temperate humid climate and is just east of the area usually affected by Lake Huron lake effect winter snowstorms. It sits astride the Grand River valley and is drained by the Grand River and its major tributaries, the Conestogo and Nith rivers from the northwest and the Speed River from the northeast. Elevation ranges between 435 and 250 m asl.

PALEOZOIC GEOLOGY

Bedrock formations underlying the study area dip gently westward into the Michigan Basin. The area is underlain, east to west and oldest to youngest, by the Silurian Guelph (dolostone), Salina (dolostone, shale, salt, gypsum) and Bass Islands (dolostone) formations, with the buried Onondaga Escarpment and its caprock of Bois Blanc Formation cherty limestone underlying the western edge. The Guelph Formation outcrops along the Grand and Speed river valleys near Cambridge where it was formerly quarried. The Salina, Bass Islands and Bois Blanc formations are buried by up to 100 m of glacial deposits in the west half of the region (Figure 2).

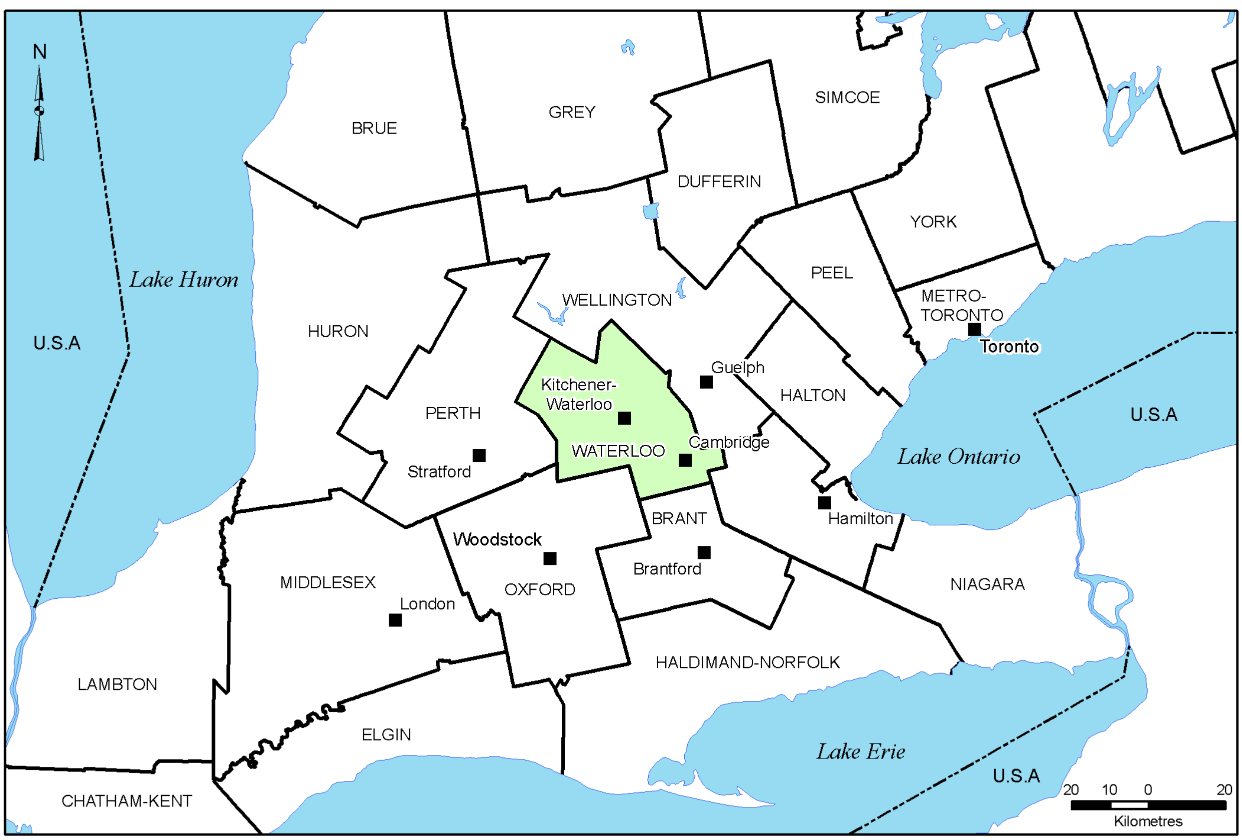


Figure 1. Location of the Regional Municipality of Waterloo in southwestern Ontario.

QUATERNARY GEOLOGY

Drift thickness within the RMOW is variable. Depths frequently exceed 30 m and occasionally are greater than 100 m, especially within the Waterloo Moraine. The bedrock surface slopes gently from an elevation of about 350 m asl in the northwest to 225 m asl in the southeast. The northwest extension of the Dundas buried valley and its tributaries into the region likely accounts for added bedrock relief.

Although the record of Michigan Subepisode (formerly Late Wisconsinan) glaciations within the RMOW is relatively well understood, the record of older glacial and nonglacial events remains fragmentary. Many publications summarizing the current status of knowledge of the Quaternary stratigraphy have been published over the past 4 decades. Most references pertinent to this study can be found in the citations of a Geological Association of Canada fieldtrip guidebook on three-dimensional mapping of Quaternary deposits in the Regional Municipality of Waterloo (Bajc and Karrow 2004).

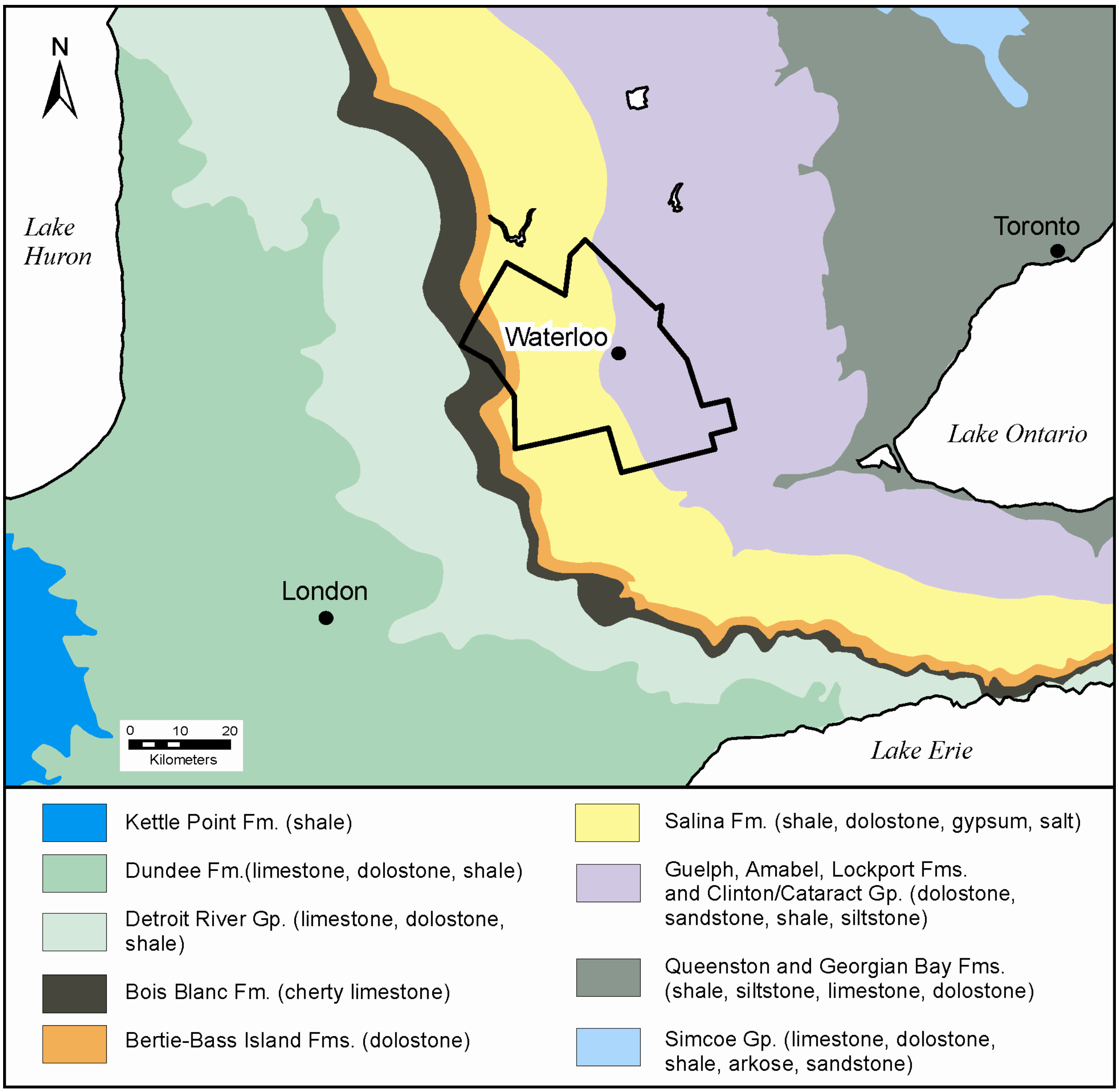


Figure 2. Bedrock geology of southwestern Ontario (*after* Johnston et al. 1991).

The Quaternary record preserved within the RMOW is characterized by repeated glacial advances of ice lobes originating from the Huron–Georgian Bay and the Erie–Ontario lake basins. Indicator clast lithologies assist with determining provenance. For example, tills originating from the Huron–Georgian Bay lobe often contain clasts of Proterozoic-age metasedimentary rocks, including jasper conglomerate, Gowganda Formation tillite and quartzites. Erie–Ontario lobe tills often contain mottled red and green Queenston Formation shales and red to white sandstones and siltstones. Grenville marble is occasionally encountered as well in Erie–Ontario lobe deposits.

Pre-Michigan Subepisode drift has been encountered at numerous locations within the RMOW. It occurs as both fine- and coarse-textured tills and stratified deposits, some of which are organic-bearing. Canning drift, a fine-textured complex of red- to mauve-coloured diamicton and glaciolacustrine deposits, has been traced as far west as the Zorra quarry north of the town of Ingersoll and eastward into the Grand River valley near Breslau. Canning Till occurs in its type section on the Nith River just west of the town of Paris. The reddish colour of this till is likely derived from Queenston Formation red shales that outcrop below the Niagara Escarpment to the east. Granules of red shale are also frequently observed within the till. An Erie–Ontario source lobe is suggested (White and Karrow 1996).

Undated organic muds overlying reddish-coloured sandy to clayey diamicton assigned to Canning drift were encountered in a borehole (OGS-03-09) on the north campus of the University of Waterloo (Bajc and Hunter 2006). A weathering profile developed in clayey Canning Till was also encountered in a borehole (OGS-04-02) south of the town of Ayr (Bajc and Hunter 2006). Wood recovered from a water well drilled near this boring location, and at an elevation similar to the top of the Canning Till, was radiocarbon dated at 42 740±1030 years BP (TO-11948). Red, stone-poor, possible Canning Till underlies alluvial deposits containing plant and mollusc remains at the Zorra quarry north of Ingersoll. Several radiocarbon dates ranging between 42.9 and 50.5 ka BP have been obtained from wood collected from this location. An inclusion of compressed peat enclosed by Catfish Creek Till and dated at 49 430±1580 years BP (TO-13283) was discovered in an OGS borehole just east of New Hamberg (OGS-03-06). Fine-textured glaciolacustrine deposits assigned to Canning drift underlie Catfish Creek Till at this location. Together, these sites suggest either an Ontario Subepisode (formerly early Wisconsinan) or Illinois Episode age for Canning Till. Additional paleoecological and radiocarbon analyses of these organic sequences may help to determine whether the sites have interstadial (Elgin Subepisode, formerly Middle Wisconsinan) or interglacial (Sangamon Episode) affinity. Alluvial channel-fill deposits containing organic remains radiocarbon dated at 40 080±1200 years BP were also recovered from a borehole on the University of Waterloo campus. Pollen and plant macrofossil remains indicate a southern boreal vegetation assemblage with climate cooler and possibly drier than present. An Elgin Subepisode nonglacial interval is inferred for this deposit (Karrow and Warner 1984).

The Michigan Subepisode is represented by the Catfish Creek Till. Catfish Creek Drift was named by deVries and Dreimanis (1960) at its type section south of London, Ontario. It occurs in the subsurface over much of southwestern Ontario and represents the deposit of the Nissouri Phase when ice pushed into southern Ohio 17 to 25 ka BP (Karrow 1988). This till is correlated with the Kent and Navarre tills of Ohio. This stony, silty to sandy till of northern provenance is often overconsolidated and forms an important marker horizon within the region (Karrow 1988). It occurs frequently in borings, roadcuts, sand and gravel pits and river bank exposures.

Exposures of Catfish Creek Till along the north shore of Lake Erie indicate an early and late phase of Catfish deposition that reflects ice flow out of the Huron and Erie lake basins. Lobal facies of Catfish Creek Till have not been reported from the Region of Waterloo; however, recent coring from the area has intersected thick successions of Catfish Creek Till with possible Huron Lobe affinity. Pebble fabrics from subglacial facies of this till generally indicate southwesterly ice flow; however, southeasterly fabrics have been reported from the western part of the region.

Following a significant retreat of ice from southwestern Ontario (Erie Phase) and the widespread deposition of glaciolacustrine deposits in the isostatically depressed lake basins, competing lobes of Huron–Georgian Bay and Erie–Ontario ice advanced into the region. Fluctuations of the ice lobes led to the deposition of multiple, lithologically distinctive till sheets and the formation of a series of subparallel end moraines (Figure 3). The sequence and age relationships of the till sheets identified to date are highlighted in Figure 4. Note that the Waterloo Moraine was constructed, in an interlobate setting, shortly after the initial breakup of Catfish Creek ice and in association with Maryhill and Stirton tills.

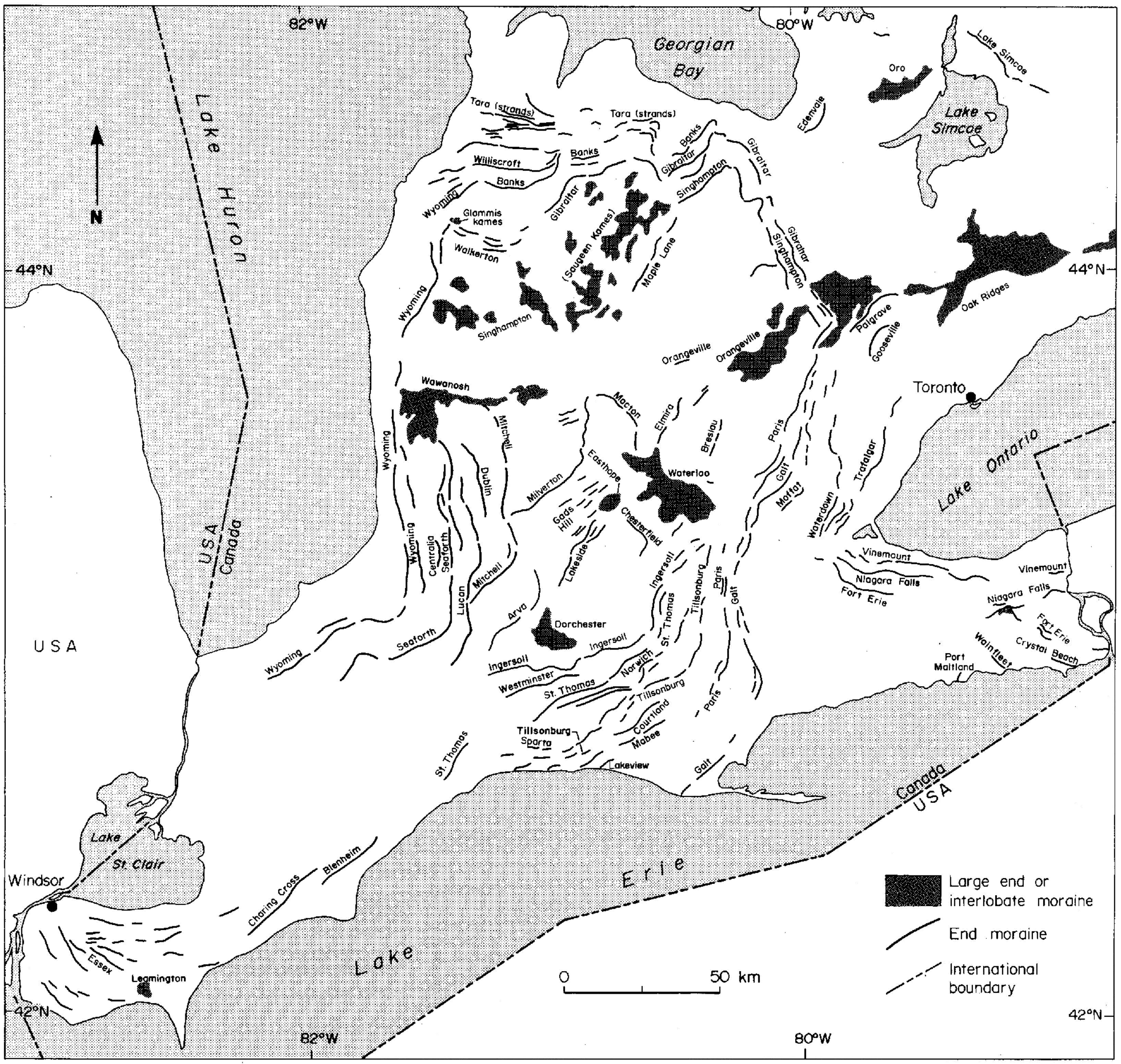


Figure 3. Moraines of southwestern Ontario (from Barnett 1991).

The Waterloo Moraine is undoubtedly one of Ontario's most significant regional aquifers and yet, few studies concentrating on its internal character, sedimentology and depositional history have been undertaken to date. F.B. Taylor (1913) was the first to recognize the Waterloo Moraine as an interlobate feature deposited along the retreating margin of the Lake Erie ice lobe in an area referred to as "Ontario Island". He described the feature as a "finely formed moraine ridge running south from Waterloo to Ayr and west to Bamberg". He also described it as a feature that was "higher and more bulky than the average".

Subsequent studies, including those of Chapman and Putnam (1951) refined the geographic extent and character of the moraine. They described it as an oblong tract of hills, most of which are composed of sandy till with lesser amounts of kame sand and gravel. Outwash deposits were observed to occupy hollows in the landscape. Chapman and Putnam (1951) also noted the peculiar preponderance of fine sand in the moraine.

As part of his Quaternary mapping of the Waterloo Moraine area 35 to 45 years ago, Karrow noted that the Waterloo Moraine was cored with fine-textured sand and gravel and was only capped locally by deposits of fine-textured till originating from both the Huron–Georgian Bay and Erie–Ontario ice lobes. Karrow recognized 2 southeast-trending ridges located west of Kitchener and surmised that they represented important ice-marginal positions. He also recognized a series of spurs or projections extending out from the moraine core to the south (Washington spur), west (Philipsburg spur), northwest (Crosshill spur) and north (Hawkesville spur) (Figure 5). The Philipsburg and Hawkesville spurs link the Waterloo Moraine to the Easthope and Elmira moraines, respectively. The relationship of these spurs to the Waterloo Moraine remained uncertain.

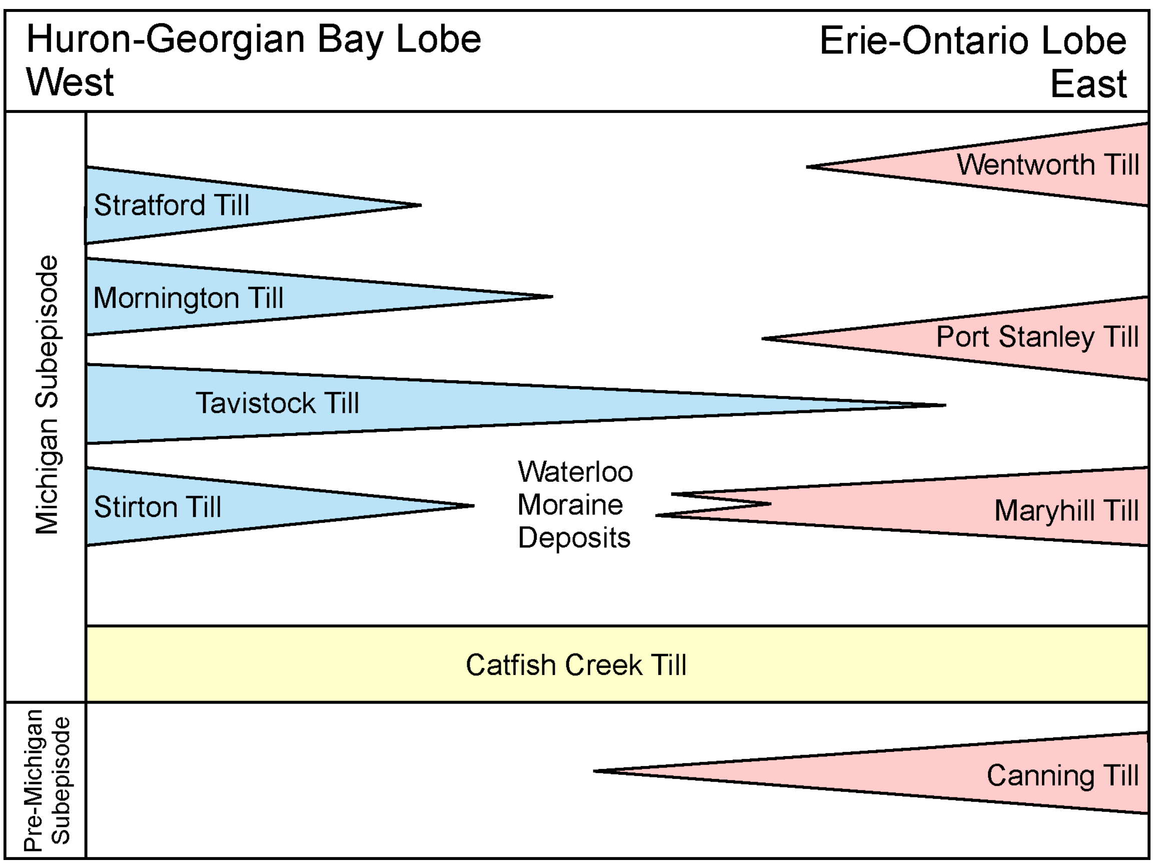


Figure 4. Time-distance diagram showing major till units in the Regional Municipality of Waterloo.

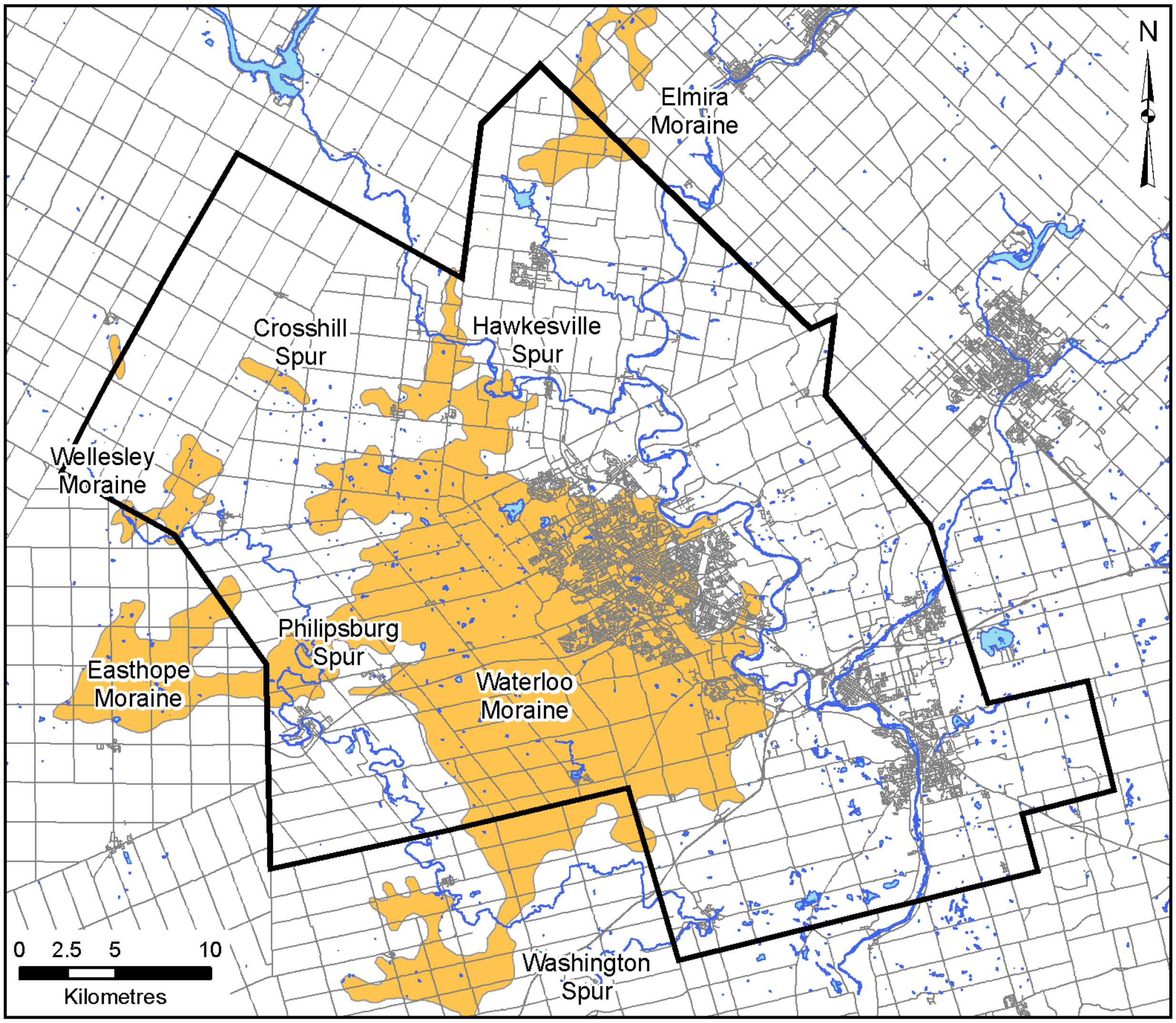


Figure 5. Location of the Waterloo Moraine in the Regional Municipality of Waterloo.

Initial concensus on the origin of the moraine favoured an interlobate setting during the initial breakup and lobation of Laurentide Ice during the latter stages of the Nissouri Phase. Barnett (1991) suggested that the Dorchester Moraine to the southwest, Easthope Moraine just west of Waterloo and the Orangeville Moraine to the northeast likely formed along this interlobate position synchronously with the formation of the Waterloo Moraine (*see* Figure 3). Karrow (1993) favoured a complex, protracted history for the formation of the moraine and suggested that most of the moraine sediments were deposited before the deposition of the Maryhill, Mornington, Port Stanley and Tavistock tills.

A number of deep-drilling initiatives during the 1980s and early to mid-1990s over the Waterloo Moraine resulted in an improved understanding of the subsurface stratigraphy of the area. Several Masters theses conducted under the supervision of Karrow (Ross 1986; Paloschi 1993; Rajakaruna 1994; Gautrey 1996) focussed on the stratigraphy and hydrostratigraphy of the moraine. Karrow and Paloschi (1996) presented the first stratigraphic section across the Waterloo Moraine and concluded that it was constructed during the Port Bruce Phase and that the bulk of the sediment comprising the moraine was associated with the Maryhill Till with which it is interbedded. Its sedimentary record contains evidence of high-magnitude meltwater discharge events with rapid sedimentation in conduits and subaquatic fan settings (Russell, Sharpe and Bajc, in press). Paleocurrents derived from fluvial bedforms trend predominantly to the west and northwest, with local inputs from the northwest and north along the Crosshill and Hawkesville spurs, respectively. Buried conduit deposits containing coarse, highly transmissive sediments likely occur in the subsurface along these trends.

If one looks at the published 1:50 000 scale Quaternary geology maps for the Region of Waterloo, the Waterloo Moraine is classed as being composed of ice-contact sand with lesser amounts of ice-contact gravel. This rather nongenetic classification was based almost exclusively on geomorphology since exposures within the moraine were limited. With the recent developments in subsurface imaging techniques, such as ground penetrating radar and seismic reflection, and the availability of high resolution, digital elevation models coupled with an abundance of continuously cored boreholes within the moraine, a better understanding of depositional environments is possible.

The Waterloo Moraine has been described as a hummocky to rolling tract of land. Much of the hummocky terrain is, in fact, interpreted as erosional or dissected in origin. Dissection likely occurred during and shortly following retreat of the Erie–Ontario ice lobe from the region as proglacial lakes drained and base levels fell.

Some of the rolling terrain has also been described as palimpsest. Karrow (1993) reports that portions of the moraine have been overridden by late-stage ice advances from the Erie–Ontario and Huron–Georgian Bay ice lobes. The thin, lobate nature of these ice sheets resulted in the deposition of thin blankets or sheets of till on the moraine with the preservation of the underlying morainic topography. Most exposures of diamicton capping the moraine appear to show structures indicative of mass flow deposition either beyond or under a floating ice margin rather than by actively advancing ice with the deposition of lodgement till. This may help to explain why the rolling character of the moraine is preserved in areas where diamicton occurs on surface. The melting of buried ice blocks within these areas may also help to explain some of the topography. Kettle depressions occur throughout the core of the Waterloo Moraine as well as the associated spurs.

Detailed inspection of sand and gravel pit exposures and new and archived drill core from the moraine has resulted in a better understanding of the depositional environments associated with the Waterloo Moraine. A complex mosaic of quiet water basinal, subaquatic fan, deltaic, braided stream and kame/kettle depositional environments are recognized in the sedimentary record. Few sand and gravel pit exposures actually display ice-contact features such as faults and chaotic bedding. Deposits and features associated with stranded blocks of ice are, however, locally represented by kames, kettle depressions and well-defined ice-contact slopes.

Glaciolacustrine environments appear to dominate the sediment record within the moraine. The close association of Maryhill Till with glaciolacustrine deposits suggests that the ice was advancing into and retreating out of a glacial lake. The fine texture of Maryhill Till is also suggestive of glacial overriding of glaciolacustrine sediments. Glacial lake deposits occur at some of the highest points in the moraine including Mannheim and St. Agatha. They have also been found in the Crosshill and Hawkesville spurs, as well as in the Wellesley and Elmira moraines. The lake into which these sediments were deposited was likely supported on all sides by ice of the Erie–Ontario and Huron–Georgian Bay ice lobes. Most paleocurrents obtained from planar cross-beds, trough cross-beds and steeply-dipping foreset beds within the moraine indicate paleoflow towards the west to northwest, consistent with an Erie–Ontario source lobe for the moraine. Chapman and Dell (1963) noted an abundance of calcite in the sands of the Waterloo Moraine and similarly suggested an eastern source area below the Niagara Escarpment where Ordovician limestones are common. Although a large glacial lake is inferred by the presence of glaciolacustrine deposits in the moraine, no shoreline features have been recognized.

Continued retreat of the Erie–Ontario and Huron–Georgian Bay ice lobes following deposition of the Waterloo Moraine resulted in rapid drainage of the lake into which the moraine was deposited. The lake most likely drained southward down the Grand River valley into high level lakes in the Erie basin. Strong dissection of the morainic deposits occurred at this time. Outwash deposits of sand and gravel accumulated in the valleys of the Grand, Conestogo, Nith and Speed rivers as the Erie lobe retreated eastward out of the region. A late stage readjustment/advance of the Erie lobe to a position marked by the Paris and Galt moraines resulted in the deposition of coarse-textured Wentworth Till upon Grand River outwash deposits. Organic and alluvial deposits accumulated in local depressions and along water courses throughout the region following the retreat of ice from the region. These deposits are generally shallow and discontinuous.

Construction of a 3-D Geologic Model

Building a three-dimensional model of Quaternary geology for Waterloo Region was undertaken in 4 important stages: 1) data compilation and standardization; 2) acquisition of new geological and geophysical data; 3) development of a conceptual geological model; and 4) data preparation, interpretation, synthesis and presentation.

DATA COMPILATION AND STANDARDIZATION

Several databases have been created and/or obtained from internal and external sources as part of the data compilation exercise. These databases include 1) borehole logs of monitoring and/or production wells acquired from the Water Services Division of the RMOW; 2) a geotechnical databank originally created by the Geological Survey of Canada (GSC) in the early 1970s and updated and uploaded to a Microsoft® Access® database format in the late 1990s by the Department of Environmental Studies at the University of Waterloo; 3) a database of shallow sediment logs captured from hand written field notes acquired by Dr. P.F. Karrow as part of his Quaternary mapping investigations within the region over the last 4 decades; 4) a similar database of shallow sediment exposure logs acquired by Bajc as part of field studies carried out during the summers of 2002 and 2003; 5) a high resolution suite of borehole logs acquired from government reports, theses and unpublished consultants reports housed at the RMOW; and 6) the Ontario Ministry of the Environment (MOE) water well database.

The project database also contains a detailed interpretation of about 350 archived borehole geophysical records collected by faculty and staff of the University of Waterloo and various consultants working in the region over the past 3 decades. The interpretation was facilitated by calibrating recently cored and geophysically logged boreholes within the region against the archived geophysically logged boreholes that, for the most part, lack high quality sediment records. The geophysically derived logs contributed to the modelling process by marking important contacts between clayey and coarse-textured sediments that were often missed in the mud rotary logs.

Not surprisingly, most of the databases from which data were retrieved were structured differently and utilized terminology inconsistent with that proposed for three-dimensional mapping in southern Ontario. Terminology in each database was standardized in accordance with material codes developed for the seamless surficial geology map of southern Ontario (Ontario Geological Survey 2003). Each unique combination of terms used to describe a sediment layer was then translated to populate primary, secondary and tertiary material attribute fields in the working database. The original sediment descriptions were retained in a separate field to allow for inspection during the interpretation phase. The z-values of the borehole collars were extracted from the provincial digital elevation model (DEM) which has a 10 m resolution.

Once the databases were standardized, they were appended and filtered to remove duplicate records and data points with compromised location and elevation attributes. To date, the working copy of the three-dimensional database for Waterloo Region contains greater than 17 000 data points and 73 000 sediment layers. Approximately half of the records are classified as "definitive", meaning they were logged by a trained geoscientist. These definitive boreholes consist of monitoring wells, engineering testholes, large natural and man-made exposures and cored borings. The average depth of these definitive boreholes is just under 16 m and only 15% of these records (711 of 4795 records) are greater than 30 m in depth. The data set also contains the logs of 110 cored boreholes, 13 of which were completed as part of this project and most of which extend into bedrock. These "golden spikes", as they have been commonly referred to, are an invaluable source of stratigraphic information and are essential for the development and verification of the conceptual geological model. These records are used to build the model in areas lacking high quality information as well as to bolster the model in well-understood areas.

During the interpretation phase of the project, it became evident that some of the material description translations required modification. Cored boreholes in the vicinity of lesser quality water wells drew these issues to the authors' attention. In some cases, global changes to the translation were implemented and in other situations, changes were made to the translation on a layer by layer basis.

ACQUISITION OF NEW GEOLOGICAL AND GEOPHYSICAL DATA

Field activities during the fall of 2002 and summer of 2003 were dedicated primarily to the acquisition of high resolution geophysical data sets. Ground penetrating radar (GPR) and seismic reflection surveys were undertaken at strategic locations within the RMOW to better understand the three-dimensional geometry and depositional environments of subsurface sediments. Ground penetrating radar is best suited to areas of dry, granular materials where, under optimal conditions, sounding depths can reach 20 to 25 m. Conversely, seismic reflection is best suited to terrains with fine-grained, water-saturated surface sediments where subsurface structural resolution can reach the meter scale and sounding depths of 100 m are not uncommon.

Ground Penetrating Radar Surveys

Over 16 km of GPR profiles were acquired at 14 sites throughout the region during the fall of 2002 and the summer of 2003. Most test sites were situated within the Waterloo Moraine. One site was located in the Elmira Moraine at the north end of Woolwich Township and 2 sites were situated over glaciofluvial deposits within the Grand River valley. All GPR lines were surveyed twice using both 50 MHz and 100 MHz transmitters. One short transect line within the Top of the Hill Aggregates pit was also surveyed with 200 MHz transmitters (Figure 6). Generally, the higher the frequency of the source energy, the better the resolution of subsurface geology. Penetration depths are, however, compromised using the higher frequency antennae. Penetration depths of 10 to 20 m are not uncommon using the 50 MHz transmitters and decline to 8 to 15 m using the 100 MHz transmitters.

The primary objective of the GPR surveying was to assist with the determination of depositional environments in the upper portion of the Waterloo Moraine sediments. Sites were chosen on the basis of surface morphology and consisted of hummocky terrain, ridges, gently undulating terrain and plains. Areas of hummocky terrain and ridges generally displayed variably scaled channelized systems indicative of deposition in a glaciofluvial and/or subaquatic fan environment. There is very little evidence to support an ice-contact depositional environment. Faults and chaotic bedding are infrequently observed on the GPR profiles. First order reflectors are generally flat-lying and commonly truncated along slopes and valley walls. Much of the apparent hummock topography is therefore interpreted as erosional in origin.

Channelized deposits often occupy depressions at the bases of knolls, hummocks and ridges indicating incision of pre-existing deposits and their subsequent redistribution in topographic lows. In general, gently undulating terrain and plains display variable internal structures. Flat-lying parallel reflectors are interpreted to represent deposition in basinal glaciolacustrine settings. Channelized reflectors on flat plains indicate deposition in shallow braided streams or deltaic environments.

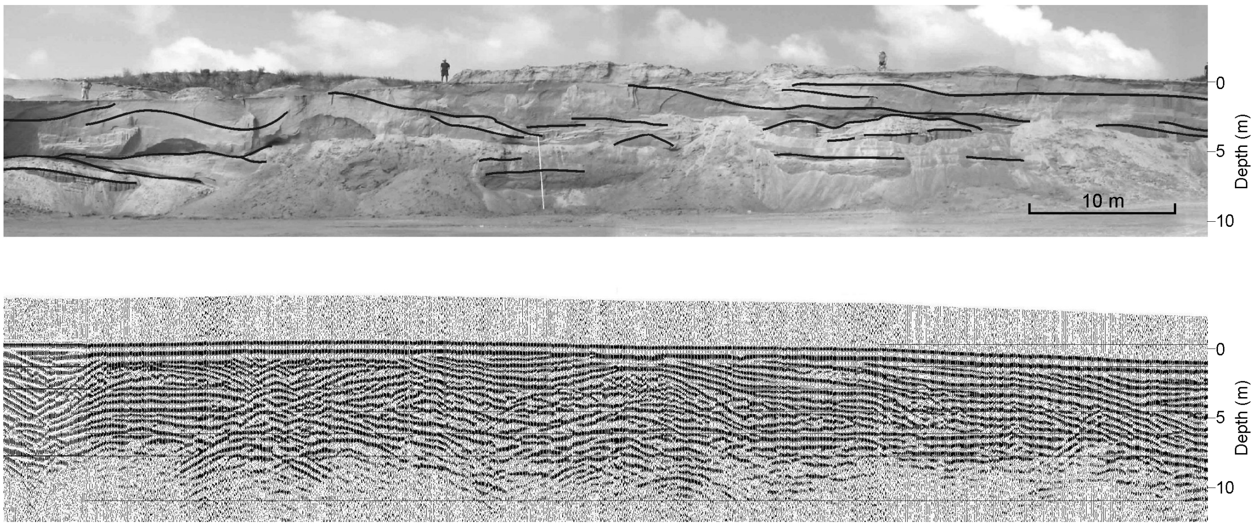


Figure 6. Ground penetrating radar response over an 8 to10 m high exposure of distal subaquatic fan sediments. Radar frequency: 200 MHz.

Seismic Reflection Surveys

High resolution seismic reflection surveys were conducted during the summer of 2003 in collaboration with the Geological Survey of Canada (GSC) as well as by a contractor (Geophysical Applications, GAPS) based out of Guelph, Ontario. Both surveys employed the common midpoint method (CMP) which is an adaptation of methods used by the petroleum industry (Pullan and Hunter 1999). The major difference between the 2 surveys was in the seismic source used. GAPS employed a 12 gauge buffalo gun fired at a meter depth whereas the GSC used their newly acquired Minivibe, a tractor-mounted vibrator similar to that used in the petroleum industry (Figure 7). The main advantages of using the vibrator is that the energy source is delivered into the ground from the road surface which can either be paved or gravel. Locates are not required for buried utilities as is the case using the buffalo gun. The Minivibe is also capable of being switched over into shear wave mode. Shear wave surveys have been shown to be effective in terrains where gas occurs at depth and may provide better results in areas where low velocity surface layers exist and the groundwater table is at great depth.

In order to determine the best locations for CMP profiling, GAPS undertook a series of 48 channel refraction profiles throughout the region. Receivers were spaced at 4 m and shots were fired at the midpoint of each spread as well as at 1.5 and 3.0 m off each end. A total of 19 profiles were collected and evaluated in terms of quality of response, number of reflectors and depth to bedrock. Results tended to be better in areas where fine-textured sediments occur on surface. Some of the test spreads within the Waterloo Moraine proved to yield very poor results due to the presence of a thick, low velocity layer at surface. On the basis of the results of the 19 test spreads, 9 sites were chosen for detailed reflection profiling. Five sites, totalling 4.89 km were surveyed by GAPS and 6 sites totalling 7.2 km were surveyed by the GSC. Approximately 1 km of survey line was duplicated using the buffalo gun and Minivibe to compare and contrast the responses obtained.

From the 9 shallow seismic reflection sections collected in the Waterloo area, the following observations can be made. A thick sequence of high-velocity tills exist over much of the area and presents a number of challenges for seismic reflection profiling. The frequency of the seismic data is generally not high enough to allow resolution of particular units within high-velocity till sequences. In some areas, the tills have been eroded and are overlain by tens of meters of normally consolidated sediments; in general, better resolution of the overlying stratigraphy can be achieved in these areas. The bedrock surface can be observed in most areas, though it can be difficult to image beneath the thick high-velocity till sequence. An interpretation of the complex variation of velocity with depth is currently emerging through the interpretation of downhole seismic borehole logs. These logs improve the ability to properly process and interpret the seismic sections.

Figure 7. A GSC-operated Minivibe seismic profiling survey in Wellesley Township.

Overburden Drilling and Borehole Geophysical Surveys

A total of 13 PQ (8-9 cm) diameter continuous cores, 9 of which were obtained in 2003 using a Christensen mud rotary drill and 4 in 2004 using a rotosonic drill, were acquired from areas in the region lacking high quality subsurface information. Where possible, 2 to 3 m of competent bedrock was recovered at each drill site. All core is currently stored in the Mannheim water treatment facility in the Regional Municipality of Waterloo. Core was visually logged either in Sudbury or in the field and representative intervals sampled for combinations of grain size and carbonate analysis. Boreholes were sited at strategic locations along seismic reflection profiles as well as in areas lacking high quality subsurface information. Two and a half inch diameter threaded, flush-joint PVC piping was inserted down each hole prior to removal of the drill casing and sealed in place with bentonite grout. Five foot (1.5 m) slotted screens were inserted in some of the boreholes to allow for continuous groundwater monitoring by the GRCA or RMOW water services section.

The GSC and University of Waterloo conducted detailed downhole geophysical logging including natural gamma, induction conductivity, magnetic susceptibility, neutron, gamma-gamma density, spectral density ratio, temperature and temperature gradient and p- and s-wave velocity. Interpretive characteristics of each sonde can be found in Bajc and Karrow (2004).

Detailed logs of the OGS boreholes are contained in Ontario Geological Survey, Miscellaneous Release—Data 205 (Bajc and Hunter 2006). Figure 8 displays an example of one of these logs.

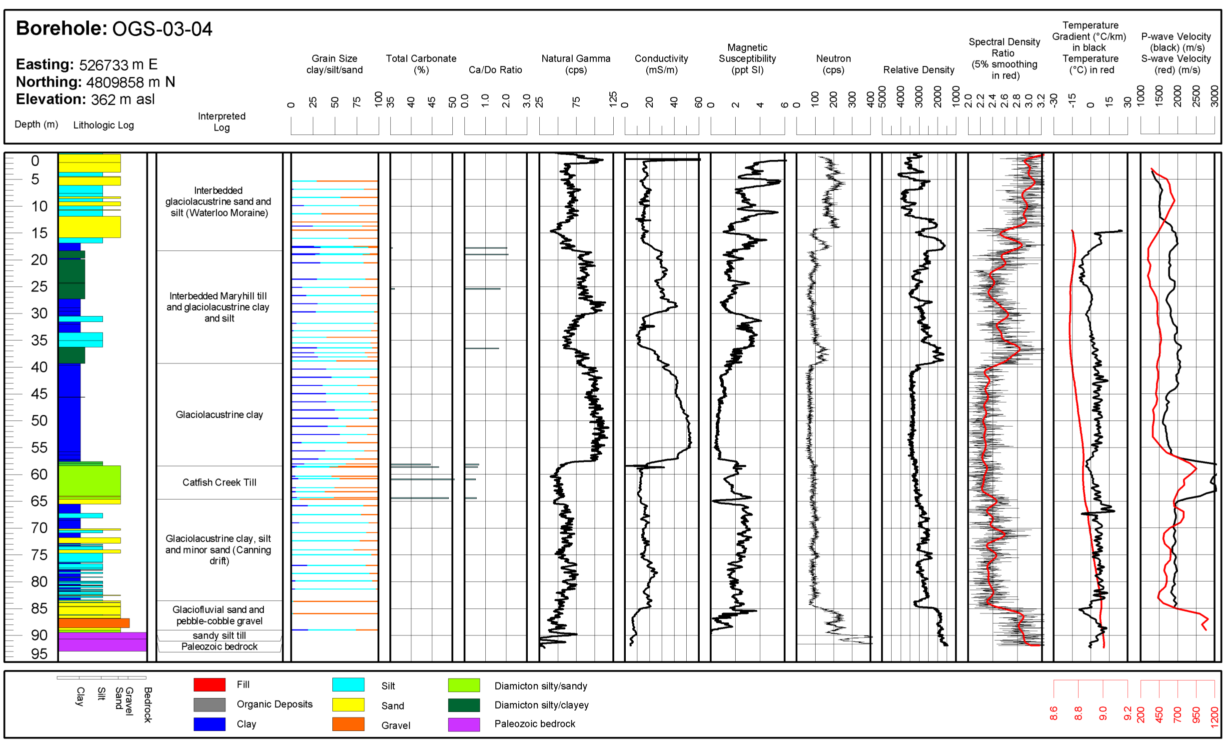


Figure 8. An example of lithologic and geophysical logs for OGS borehole OGS-03-04.

DEVELOPMENT OF A CONCEPTUAL GEOLOGICAL MODEL

The development of a conceptual geological model for the interpretation of new and archived subsurface data was undertaken following a review of all published information on the Quaternary geology of Waterloo Region. Additional insights were gained by examining all available sediment exposures within the region, relogging of selected archived core, acquisition of seismic reflection and ground penetrating radar data and continuous coring of strategically placed boreholes. The conceptual geological model developed for the Region of Waterloo consists of an aquifer/aquitard sequence with 19 hydrostratigraphic layers (Table 1). Many of the layers have limited aerial extent, their outer edges defined by the limits of ice advance or the elevation of meltwater channels and lacustrine inundation. The model building process involved subdivision of the Quaternary sequence to as high a level of detail as possible, bearing in mind that units could be merged if data quality prevented their full definition from a regional perspective.

Table 1. Listing of the 19 hydrostratigraphic units modelled within the Regional Municipality of Waterloo and their corresponding lithostratigraphic equivalents and lithologic descriptions. Search radii used for geostatistical processing of picks data also included.

Hydrostratigraphic Unit	Lithostratigraphic Unit	Lithology	Search Radius (m)
ATA1	Whittlesey clay	Silt and clay	1000
AFA1	Whittlesey sand	Very fine to coarse sand	500
ATA2	Wentworth Till - may contain stratified drift	Stony, sandy till	1500
AFA2	Outwash deposits – mainly Grand River valley outwash	Coarse sand and gravel	1000
ATA3	Fine-grained deposits confined to Grand River valley under AFA2	Sandy silt and silt	500
ATB1	Upper Maryhill Till, Port Stanley Till, Tavistock Till, Mornington Till	Silty to clayey till	1000
AFB1	Upper Waterloo Moraine stratified sediments and equivalents	Mainly fine sand, some gravel	1000
ATB2	Middle Maryhill Till and equivalents	Silty to clayey till, silt, clay	500
AFB2	Middle Waterloo Moraine stratified sediments and equivalents	Mainly fine sand, some gravel	500
ATB3	Lower Maryhill Till and equivalents	Silty to clayey till, silt, clay	2500
AFB3	Lower Waterloo Moraine stratified sediments or Catfish Creek outwash deposits	Sand, some gravel	500
ATC1	Upper/Main Catfish Creek Till	Stony, silty to sandy till	3500
AFC1	Catfish Creek stratified deposits	Sand and gravel	500
ATC2	Lower Catfish Creek Till	Stony, silty to sandy till	500
AFD1	Pre-Catfish coarse-textured glaciofluvial/glaciolacustrine deposits	Sand and gravel	1500
ATE1	Canning drift (till and associated fine-textured glaciolacustrine deposits)	Silty to clayey till, silt, clay	1500
AFF1	Pre-Canning coarse-textured glaciofluvial/glaciolacustrine deposits	Sand and gravel	1500
ATG1	Pre-Canning coarse-textured till	Stony, silty to sandy till	1500
Bedrock	Guelph, Salina, Bass Islands and Bois Blanc formations	Refer to bedrock geology map (Figure 2)	6000

Ten of the most regionally significant geologic units (Figure 9) consist, from oldest to youngest, of:

1. Paleozoic bedrock consisting of dolostone and shale;
2. older tills and stratified deposits;
3. Canning drift, which is a fine-textured package of diamicton and associated glaciolacustrine sediment believed to be either Ontario Subepisode or Illinois Episode in age;
4. Pre-Catfish coarse-textured glaciofluvial/glaciolacustrine deposits which are often closely associated with the overlying Catfish Creek Till and locally act as an important aquifer;
5. Catfish Creek Till, which consists of stony, silty to sandy diamicton and represents the deposit of the main Michigan Subepisode glaciation. This unit acts as an important, relatively continuous regional aquitard;
6. a lower till package, consisting of Stirton and Lower Mayhill tills, which tends to be fine-textured, closely associated with glaciolacustrine sediments and deposited shortly after the initial breakup of Catfish ice by ice lobes originating in the Huron and Erie–Ontario lake basins. This unit acts as a significant regional aquitard with local breaches to underlying deposits;
7. Waterloo Moraine and equivalent aquifers consisting primarily of fine- to medium-textured sand with localized accumulations of gravel and isolated lenses of muddy glaciolacustrine sediments and diamicton. This unit is probably the most significant regional aquifer exploited to date within the RMOW;
8. Upper Tills, consisting of Mornington, Tavistock, Upper Maryhill and Port Stanley tills, which were laid down after the deposition of the Waterloo Moraine as the ice margin retreated back into the Huron and Erie–Ontario lake basins;
9. Grand River outwash deposits, consisting of well bedded sands and gravels restricted to the valleys of the Conestogo, Grand, Nith and Speed rivers. In the southeastern corner of the region, these deposits conceal much of the Waterloo Moraine deposits as well as a series of moraines extending northward from the Lake Erie basin; and
10. Wentworth Till, which represents the deposit of a late stage advance/readjustment of Erie–Ontario lobe ice into the region, its outer limit marked by the Paris Moraine. This till is closely associated with stratified deposits of sand and cobble-boulder gravel and therefore acts regionally, as a poor aquitard and locally, as an aquifer within the region.

The time-transgressive nature of some of these units proved difficult to model in three dimensions. For example, an ice advance/retreat sequence will result in the deposition of a layer of till out to a given ice margin. Beyond the ice margin, there is continuous deposition of glaciofluvial/glaciolacustrine sediment, whereas, inside the ice margin, the stratified deposits are subdivided into an upper and lower sequence separated by the layer of till. It is difficult to subdivide the stratified deposits beyond the ice margin into a similar upper and lower sequence as data quality generally prevents this. Similar bifurcating sequences occur in till units along the eastern edges of the region. In the east, a single layer of Port Stanley Till may correlate and span the same time interval as 3 layers of till in the central parts of the region (e.g., Catfish Creek, Maryhill and Port Stanley tills). Diachronic subdivision of Port Stanley Till along the eastern margin of the region was not attempted. Rather, a lithostratigraphic approach was chosen whereby Port Stanley Till was lumped as a single unit.

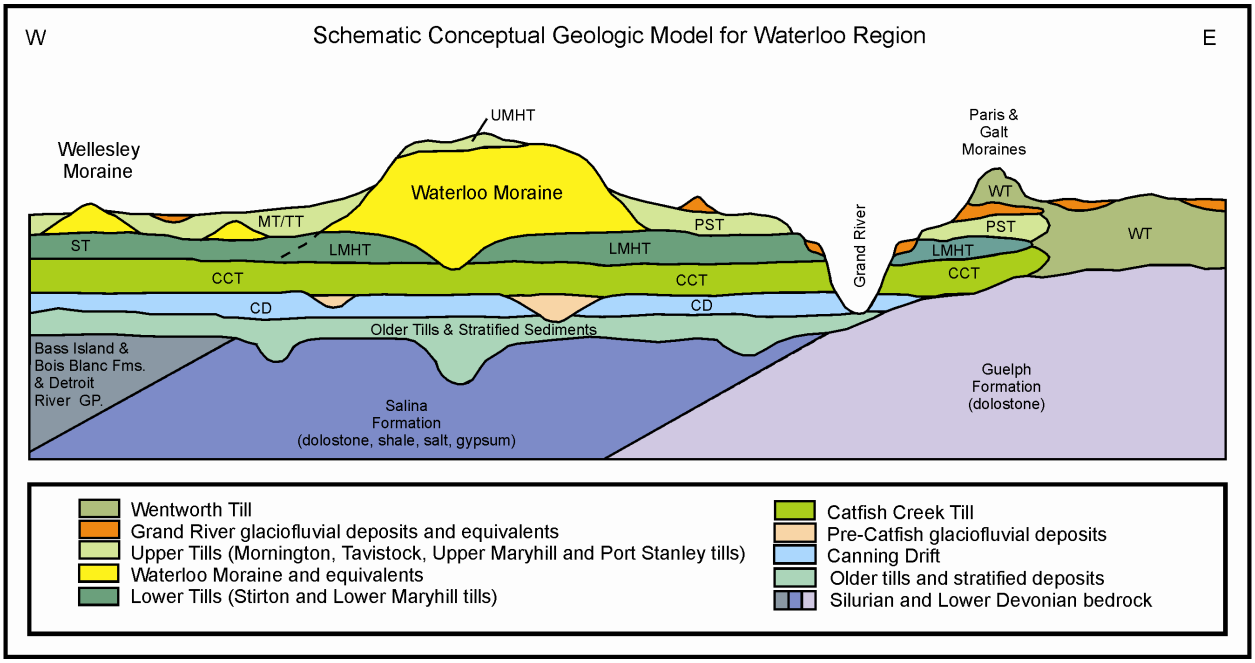


Figure 9. Conceptual geologic model for the Regional Municipality of Waterloo. Ten regionally significant lithostratigraphic units are recognized over the Waterloo Region.

MODEL CREATION

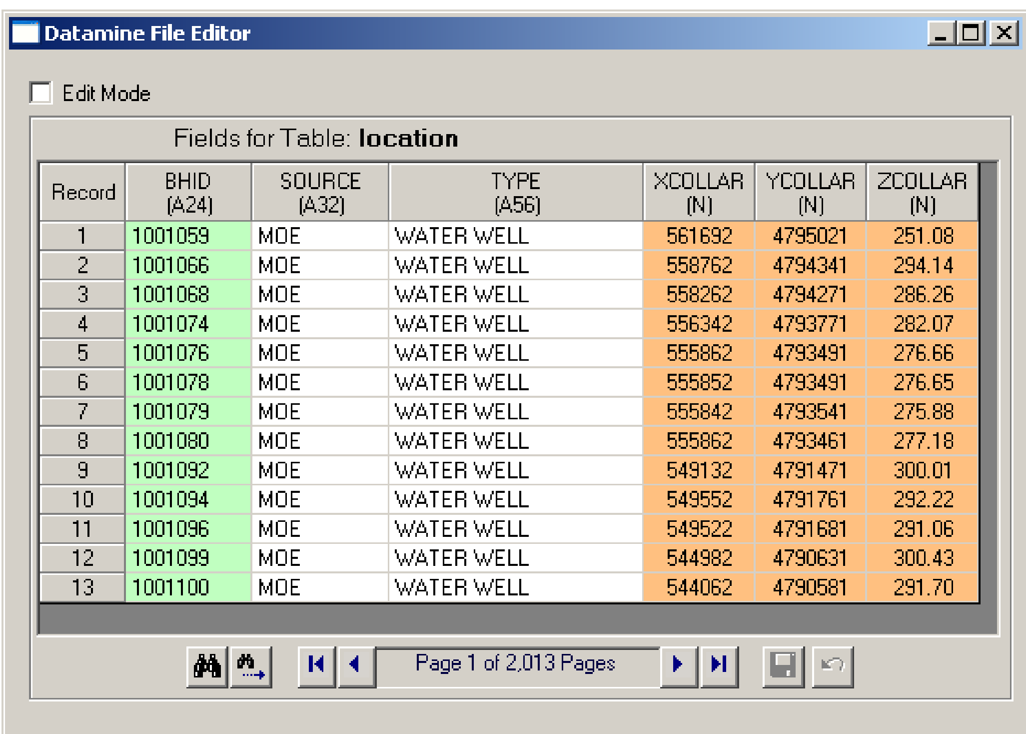
A number of software packages were looked at and evaluated for their ability to meet our specific 3-D mapping needs. The main elements of interest in a software program were:

1. strong 3-D visualization capability for data interpretation;
2. excellent linkage and live update capacity with the working database;
3. ability to interpolate surfaces and apply logical rules that allow for laws of superposition to be honoured;
4. ability to create wireframe surfaces, solid models;
5. ability to calculate volumes of solids;
6. ability to import ESRI® ArcInfo® shape files and drape base information over a 3-D model;
7. ability to import raster images such as seismic sections into the model for added interpretation;
8. ability to create isopach maps of individual strata;
9. ability to create elevation maps of the tops of individual strata;
10. ability to export, in ASCII format, top of formation data at a specified grid spacing;
11. the ability to provide a free viewing software that allows for flexible client interaction with the 3-D model.

Datamine Studio®, a software package used primarily by the mining sector for mine design and orebody modelling, was chosen for this study. This software met all of the criteria listed above and appeared to be suitable for 3-D modelling of complex Quaternary sequences where units frequently pinch out forming lenses. This software has also been successfully used in the coal mining industry to similarly model discontinuous lenses and seams of coal. Another strength of Datamine Studio that was used to great effect on this project is the customizable interface that allows a series of repeatable tasks to be defined and presented to the user through a scripted interface using the same tools that are available for creating web sites. This makes it very easy for the user to carry out complex modelling procedures.

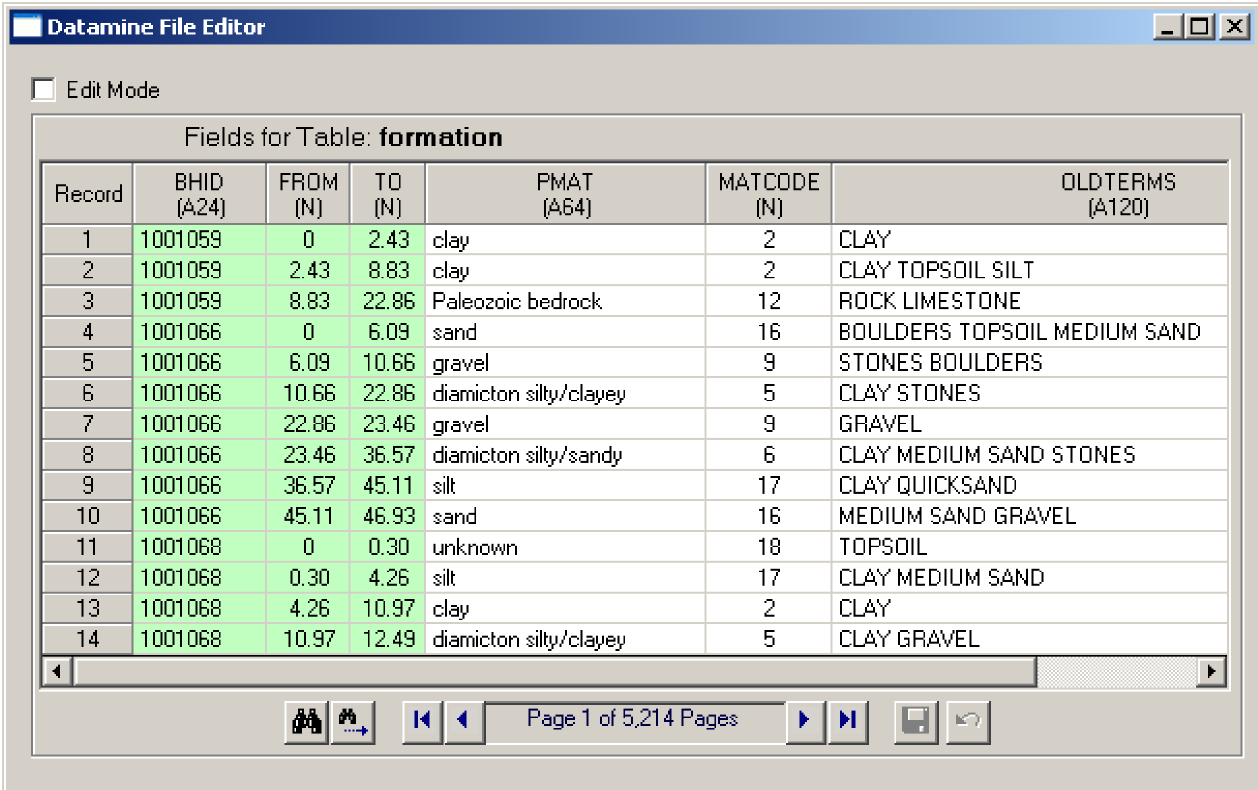
Data Preparation

Three tables were created from the master subsurface database and imported into the Datamine 3-D modelling software package. One of the tables included a "location" table, which contains information about the borehole such as its original identification, source, location (X,Y,Z) and boring type (Figure 10). A "formation" table that contains descriptive and depth information regarding the sediment layers present in each borehole was also extracted from the master database (Figure 11). Included in the "Formation" table of the master subsurface database was an "Interpretation" field where a stratigraphic interpretation of the layer described could be included (e.g., Port Stanley Till, Catfish Creek Till, Canning Till). This interpretation was generally available for cored boreholes as well as from logs of surface exposures described as part of Quaternary mapping programs and other recent field investigations. The tops of units with "Interpretation" identifiers were later translated to the terminology of our aquifer/aquitard scheme and exported to a "definitive" picks table containing "borehole identifier", "X,Y,Z coordinates" and "STRATUM" attributes (Figure 12).



Record	BHID (A24)	SOURCE (A32)	TYPE (A56)	XCOLLAR (N)	YCOLLAR (N)	ZCOLLAR (N)
1	1001059	MOE	WATER WELL	561692	4795021	251.08
2	1001066	MOE	WATER WELL	558762	4794341	294.14
3	1001068	MOE	WATER WELL	558262	4794271	286.26
4	1001074	MOE	WATER WELL	556342	4793771	282.07
5	1001076	MOE	WATER WELL	555862	4793491	276.66
6	1001078	MOE	WATER WELL	555852	4793491	276.65
7	1001079	MOE	WATER WELL	555842	4793541	275.88
8	1001080	MOE	WATER WELL	555862	4793461	277.18
9	1001092	MOE	WATER WELL	549132	4791471	300.01
10	1001094	MOE	WATER WELL	549552	4791761	292.22
11	1001096	MOE	WATER WELL	549522	4791681	291.06
12	1001099	MOE	WATER WELL	544982	4790631	300.43
13	1001100	MOE	WATER WELL	544062	4790581	291.70

Figure 10. Example of the location table that contains information regarding borehole source, location and elevation.



Datamine File Editor

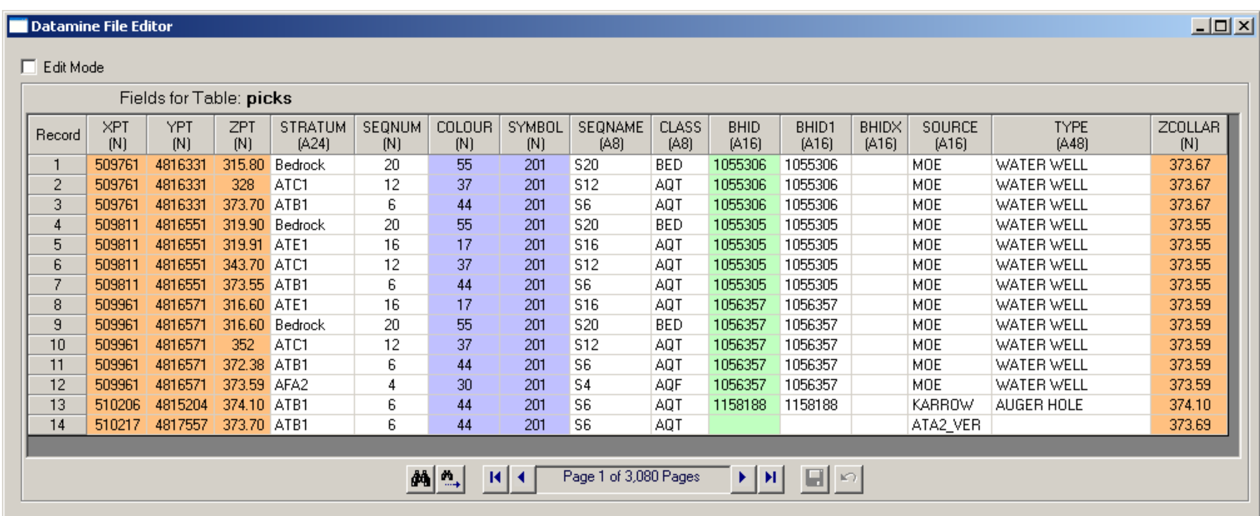
Edit Mode

Fields for Table: **formation**

Record	BHID (A24)	FROM (N)	TO (N)	PMAT (A64)	MATCODE (N)	OLDTERMS (A120)
1	1001059	0	2.43	clay	2	CLAY
2	1001059	2.43	8.83	clay	2	CLAY TOPSOIL SILT
3	1001059	8.83	22.86	Paleozoic bedrock	12	ROCK LIMESTONE
4	1001066	0	6.09	sand	16	BOULDERS TOPSOIL MEDIUM SAND
5	1001066	6.09	10.66	gravel	9	STONES BOULDERS
6	1001066	10.66	22.86	diamicton silty/clayey	5	CLAY STONES
7	1001066	22.86	23.46	gravel	9	GRAVEL
8	1001066	23.46	36.57	diamicton silty/sandy	6	CLAY MEDIUM SAND STONES
9	1001066	36.57	45.11	silt	17	CLAY QUICKSAND
10	1001066	45.11	46.93	sand	16	MEDIUM SAND GRAVEL
11	1001068	0	0.30	unknown	18	TOPSOIL
12	1001068	0.30	4.26	silt	17	CLAY MEDIUM SAND
13	1001068	4.26	10.97	clay	2	CLAY
14	1001068	10.97	12.49	diamicton silty/clayey	5	CLAY GRAVEL

Page 1 of 5,214 Pages

Figure 11. Example of the formation table that contains standardized information regarding the layers of sediment and rock encountered in each borehole. Note that the original description is captured in the "Old Terms" column.



Datamine File Editor

Edit Mode

Fields for Table: **picks**

Record	XPT (N)	YPT (N)	ZPT (N)	STRATUM (A24)	SEQNUM (N)	COLOUR (N)	SYMBOL (N)	SEQNAME (A8)	CLASS (A8)	BHID (A16)	BHID1 (A16)	BHIDX (A16)	SOURCE (A16)	TYPE (A48)	ZCOLLAR (N)
1	509761	4816331	315.80	Bedrock	20	55	201	S20	BED	1055306	1055306		MOE	WATER WELL	373.67
2	509761	4816331	328	ATC1	12	37	201	S12	AQT	1055306	1055306		MOE	WATER WELL	373.67
3	509761	4816331	373.70	ATB1	6	44	201	S6	AQT	1055306	1055306		MOE	WATER WELL	373.67
4	509811	4816551	319.90	Bedrock	20	55	201	S20	BED	1055305	1055305		MOE	WATER WELL	373.55
5	509811	4816551	319.91	ATE1	16	17	201	S16	AQT	1055305	1055305		MOE	WATER WELL	373.55
6	509811	4816551	343.70	ATC1	12	37	201	S12	AQT	1055305	1055305		MOE	WATER WELL	373.55
7	509811	4816551	373.55	ATB1	6	44	201	S6	AQT	1055305	1055305		MOE	WATER WELL	373.55
8	509961	4816571	316.60	ATE1	16	17	201	S16	AQT	1056357	1056357		MOE	WATER WELL	373.59
9	509961	4816571	316.60	Bedrock	20	55	201	S20	BED	1056357	1056357		MOE	WATER WELL	373.59
10	509961	4816571	352	ATC1	12	37	201	S12	AQT	1056357	1056357		MOE	WATER WELL	373.59
11	509961	4816571	372.38	ATB1	6	44	201	S6	AQT	1056357	1056357		MOE	WATER WELL	373.59
12	509961	4816571	373.59	AFA2	4	30	201	S4	AQF	1056357	1056357		MOE	WATER WELL	373.59
13	510206	4815204	374.10	ATB1	6	44	201	S6	AQT	1158188	1158188		KARROW	AUGER HOLE	374.10
14	510217	4817557	373.70	ATB1	6	44	201	S6	AQT				ATA2_VER		373.69

Page 1 of 3,080 Pages

Figure 12. Example of the picks table used for the creation of the 19 hydrostratigraphic units.

"Top of Bedrock" and "DeepOB" picks were also included in this table. "DeepOB" picks were determined by interpolating a "Bedrock" surface in ESRI® ArcInfo® software using "Bedrock" picks only, then searching for deep overburden boreholes that pierced this interpolated bedrock surface. The x,y,z position of the bottom of these boreholes was then added to the "Picks" table and attributed as "DeepOB" picks. By applying this method of "push-down" to the bedrock surface, buried bedrock valleys are better defined and the bedrock surface, in general, better reflects the subsurface information.

To ensure that the three-dimensional model honoured materials mapped at the ground surface, the provincial DEM was sampled on a 200 m grid and attributed with the surficial map unit present at each location (Figure 13). The "Stratum" field of this "Surfs" file was then translated to our aquifer/aquitard scheme for subsequent use with the "definitive" picks information. Together, these data sets were used to create a series of training surfaces to guide the interpretation of the lower quality data sets. These training surfaces were created using Delauney triangulation, where each vertex of the triangles corresponded to a data point. The geometry of each surface was therefore strongly influenced by the location and density of the high quality picks. A similar procedure of utilizing surficial geology information was used by Logan, Russell and Sharpe (2001, 2005) and Logan et al. (2006) in the Oak Ridges Moraine project area. In that case, the polygon perimeters of surficial map units were converted to points spaced at 50 m and the area within the polygons clipped out of the DEM then stamped onto the interpolated surfaces.

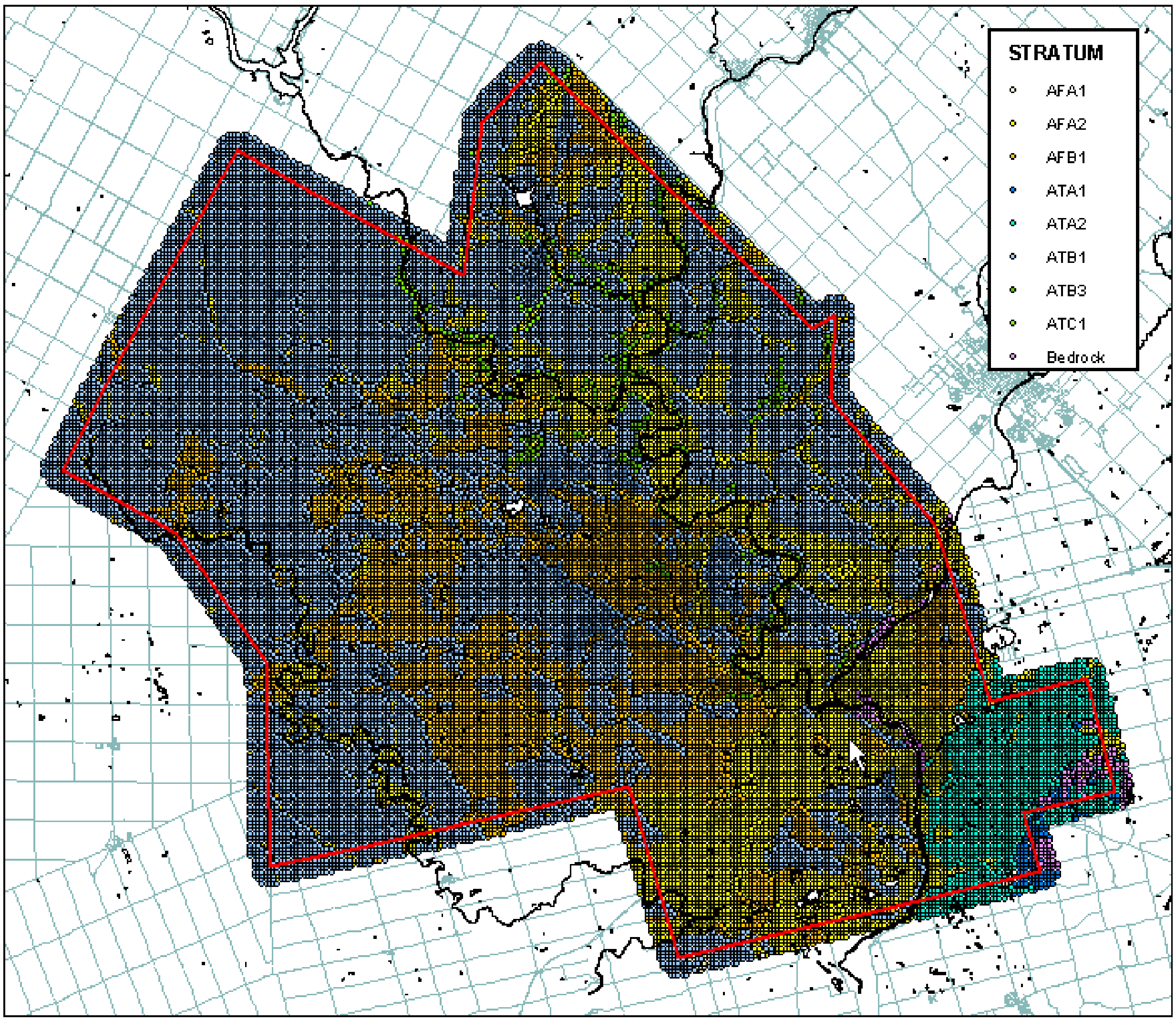


Figure 13. Surface picks sampled on a 200 m grid and attributed with hydrostratigraphic units mapped on the ground surface.

Approach

The approach taken for the interpretation of the subsurface data in Waterloo Region was slightly different than that followed by other jurisdictions doing similar regional three-dimensional modelling. For example, the Geological Survey of Canada opted for an automated approach guided by expert knowledge and a conceptual stratigraphic framework in its regional assessment of the Oak Ridges Moraine (Logan, Russell and Sharpe 2001; and Logan et al. 2006). The Illinois State Geological Survey, in its three-dimensional study of Antioch Quadrangle, chose to evaluate and pre-screen the greater than 4000 drill logs that exist for this area and base their model on the "best" 275 borehole records (Hansel, Stiff and Barnhardt 2004). For the Waterloo study, a decision was made to manually interpret, where possible, the 17 000 borehole records in section guided by the training surfaces previously mentioned and to selectively extract as much information as possible from logs of disparate or lower quality. Interpretations were undertaken along east-west and north-south sections spaced at 100 m with 50 m clipping limits. Although considered to be a poor source of subsurface stratigraphic information, water well records frequently contain valuable elevation information concerning the top of bedrock and important aquifer and aquitard units. For example, the top of Catfish Creek Till is often marked by the term, "hardpan" in driller's logs. Also, seeing that most water wells are screened in the first productive, water-bearing horizon, one can feel fairly confident that the lowest unit in a given water well is an aquifer. The tops of these units form an important component of our picks table.

As previously mentioned, the lower quality water well data were further examined in Datamine Studio® along east-west and north-south sections. A set of scripts was created to assist with the display and manipulation of the drillhole and picks data. In most cases, the upper surface of a given stratum was identified by digitizing a 3-D point on the drillhole trace. Alternatively, 3-D points were digitized between or off drillhole traces to assist with the refinement of stratum geometry. Over 43 000 picks have been created in this manner. We also have greater than 39 000 surface picks sampled from the surficial geology map on a 200 m square grid that can optionally be used in conjunction with the manually picked data.

If all 19 strata could be identified in all boreholes then modelling would be a straight forward process. However, because of data quality and varying borehole depth, there are on average only 2.2 strata identified per hole suggesting a fair amount of missing information. In addition, not all strata exist over the entire area (i.e., there are either natural limits to strata or strata have been eroded away) so there are holes in, and limits to, the surfaces. The simplest method would be to create a Digital Terrain Model (DTM) wireframe surface for each stratum from the known picks. However, because of the scarcity of the data for some layers, this leads to a large number of overlaps between the surfaces which are difficult to adjust. An alternative approach would be to interpolate the elevations for each stratum onto a regular grid using inverse power of distance or normal kriging and then apply a suite of rules to sort out the overlaps. In this instance, the rules would be complex as they would need to take into account both the sequence of strata at every model column and also the elevations of the strata in adjacent columns of cells in order to avoid large steps in elevation between the cells.

To avoid this problem, the method selected was to interpolate the stratum elevations onto spatially filtered boreholes, apply a set of rules to resolve any overlaps within the holes and then to create a DTM wireframe surface for each stratum. This method ensured that the wireframes do not overlap. The spaces between each successive pair of wireframes are then filled with model cells in order to create a block model of the aquifers and aquitards.

The process for creating the models is very much an iterative one. The models are created using the initial data and then they are checked visually in the 2-D and 3-D graphics windows. Data problems are identified and fixed, and extra data are added to control the position of the strata. A new set of models are then generated and validated and the process repeated. In order to facilitate the procedure, the total area can be divided into user-defined sub-areas and models generated for each.

The system that has been implemented allows the option of whether to use just the digitized picks or both the digitized picks plus the surface picks. Where digitized picks correspond to positions down a borehole, the borehole collar elevation is retrieved from the COLLARS file. Where digitized picks do not correspond to a borehole, the points are projected onto the topography wireframe in order to find the topography elevation. Although the description in the previous section refers to interpolation onto the borehole, in practice a 2-D block model is generated with cell centres at each X,Y location in the picks file. Therefore, some of the cells include several picks, whereas, others will include just a single pick as is the case with the surface pick points. All cells will also include the topography elevation.

The data are initially validated to ensure that the elevations for all picks are in the correct sequence. If any inconsistencies are found then the data for that cell are copied to an errors file, and are removed from the current run. The problem picks can then be edited before any subsequent runs of the system occur.

Interpolating Elevations

The model cells are reformatted into a 2-D point data file which is then used to estimate elevations. A geostatistical approach was taken for the spatial analysis of the stratum picks and the creation of the surfaces. Surfaces were modelled only where the data picks indicated, with some confidence, that they were present. Search radii were drawn around all “real” borehole collars as well as around “virtual” borehole collars defined by the location of surface picks extracted from the surficial geology map (i.e., 200 m regular grid spacing) and any picks digitized in section off borehole traces (Figure 14). The maximum distance between either “real” or “virtual” borehole collars was therefore limited to just over 280 m. The search radius was determined by creating a DTM from the actual picks and varying the maximum length of the edge of any triangle until a suitable value was achieved (i.e., the modelled extent of a given stratum appeared to closely reflect its perceived extent). Larger search radii were used for strata that were considered to be more continuous such as bedrock and Catfish Creek Till. In addition, aquitards were generally assigned larger search radii since they are assumed to be more continuous than aquifers.

A minimum of 3 picks for a particular horizon was required within the user-defined search radius of real and virtual boreholes prior to interpolating an elevation for that stratum onto the borehole trace. If there was insufficient data found (i.e., fewer than 3 picks for that stratum) within the search radius, then an “absent” data elevation was assigned to the borehole trace. Real picks meeting the search radius requirements were used in favour of their corresponding interpolated values. The estimation process allows for the full range of interpolation methods to be selected. This includes polygonal, inverse power of distance and various types of kriging. Currently, isotropic inverse power of distance cubed is used because it honours the stratum picks quite well.

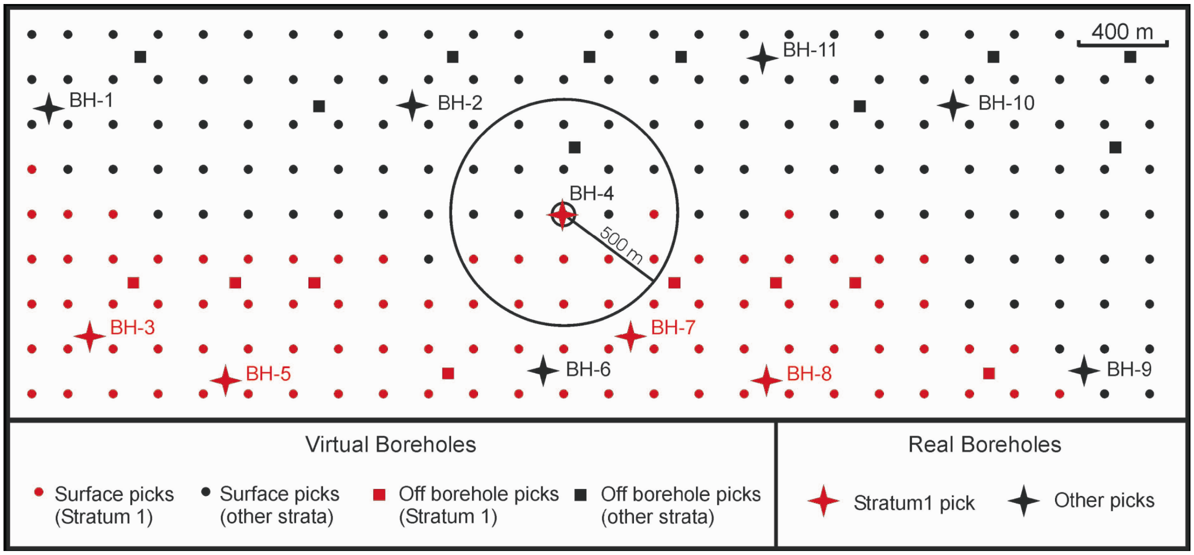


Figure 14. Schematic plan view depicting the spatial distribution of real and virtual boreholes and the corresponding picks for Stratum 1. Note that the surface picks, which are derived from the surficial geology map, are on a regular 200 m grid. A search radius of 500 m is applied to Stratum 1 from real borehole BH-4. Since 10 picks are found for Stratum 1 within the 500 m search radius, the pick for Stratum 1 on BH-4 is accepted. This procedure continues at every real and virtual borehole location for all 19 strata within the modelled area.

Creating the DTMs

At the end of the interpolation stage, every stratum in every cell will have one of the following elevation values: 1) an actual value defined by a pick; 2) an estimated value defined by interpolation; or 3) absent data indicating insufficient data exists within the search area. However, because of the sparsity of the data and the large number of estimated values, elevations are frequently out of sequence. To correct this, the following rules were applied where Z(n) is the elevation of stratum "n" with 1 being the youngest (top elevation) and 19 being the oldest (lowest elevation). The rules are applied to each stratum in turn starting from bedrock (n=19) and working up to ATA1 (n=1). Lower and upper strata refer to the stratum immediately below or above the current stratum, respectively.

If Z(19) = absent then exit.
(i.e., make sure bedrock Z(19) is estimated into all cells. Otherwise exit.)

If Z(n) is an actual pick then no adjustment will be made. The following adjustments therefore only apply to estimated or absent values.

If Z(n) < Z(n+1) then Z(n) = Z(n+1)
(i.e., if the elevation of the current stratum is estimated below the lower stratum then set it equal to the elevation of the lower stratum. This means the thickness is estimated as zero.)

If Z(n) = absent then Z(n) = (Zn+1)
(i.e., if the elevation of the current stratum is absent then set it equal to the elevation of the lower stratum. This means the stratum is being pinched out on the lower stratum.)

If Z(n-1) is "actual" and Z(n) > Z(n-1) then Z(n) = Z(n-1)
(i.e., if the upper stratum is an actual value and the elevation of the current stratum is estimated to be above the upper stratum then reset it equal to the upper stratum. In this case, the current stratum should actually be reset to the base of the upper stratum. This is difficult to achieve in an automated fashion since the base of the upper stratum may not be defined. These picks are flagged for manual adjustment.)

Using the above rules it is still possible to have strata out of sequence and so a second set of rules is applied. Starting at the top (n=1) and working downwards:

If $Z(n)$ is estimated and $Z(n) > Z(n+1)$ then $Z(n) = Z(n+1)$
(i.e., if the current elevation is estimated and is above the elevation of the upper stratum then reset it equal to the elevation of the upper stratum.)

The logic also includes one final check working from the bottom upwards to ensure that there are no remaining overlaps. The logical rules applied to the picks and interpolated surfaces are displayed in Figure 15.

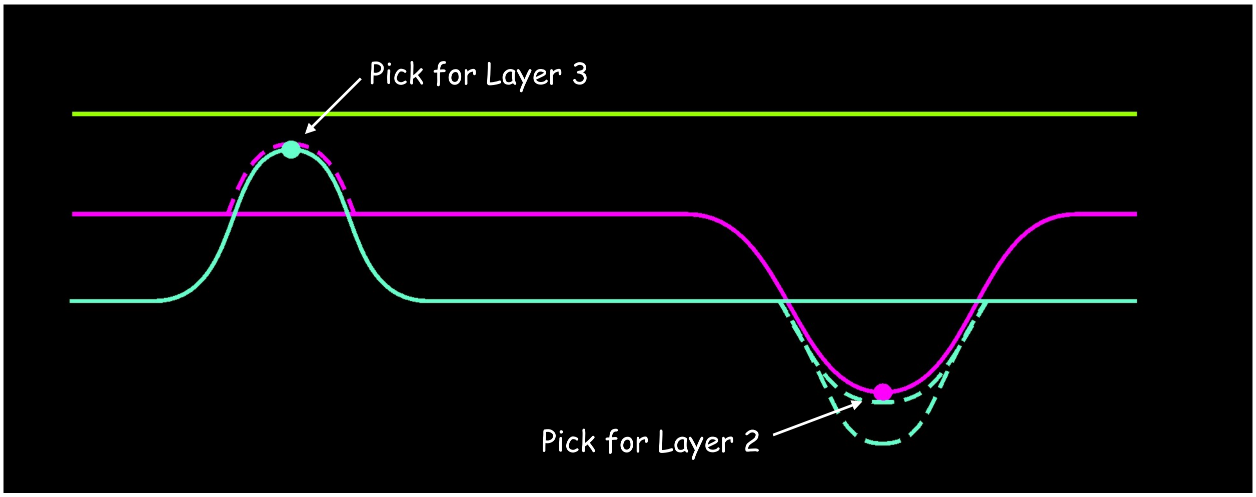


Figure 15. Schematic representation of rules applied to picks and interpolated surfaces to prevent crossovers. In this example, if Layer 2 < Layer 3, then Layer 2 = Layer 3 when a real pick exists for Layer 3, and Layer 3 = Layer 2 when a real pick exists for Layer 2. In practice, Layer 3 should be assigned an elevation at some distance below Layer 2 defined by the thickness of Layer 2.

The method for estimating strata elevations described above ensures that all 19 strata have elevations for each cell. The DTMs for each stratum are created from these elevations and so all DTMs extend over the full extent of the data (Figure 16). This set of DTMs is referred to as DTM1 (Figure 17).

When DTM1 is created, the average Z coordinate for each triangle is calculated. This means that by comparing successive strata, it is possible to identify where the thickness of a stratum is zero and then to remove that triangle. This will introduce holes into the DTMs where there is no data and where the thickness is zero. This new set of DTMs is referred to as DTM2 (Figure 17).

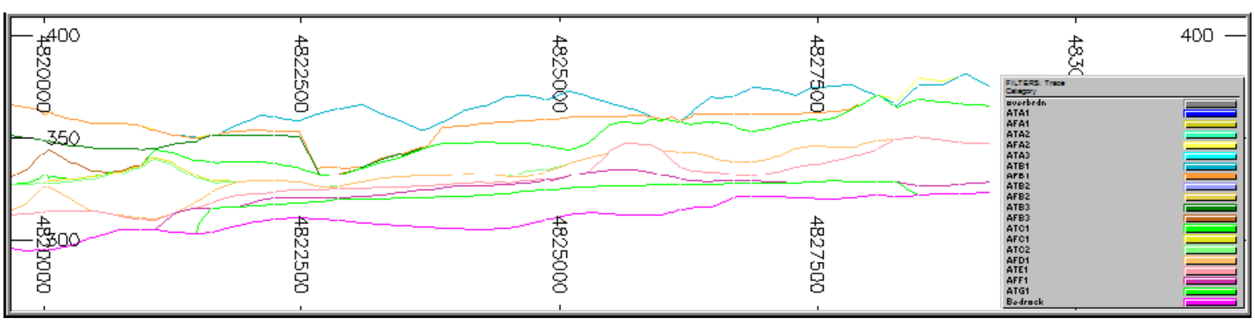


Figure 16. Section view of DTMs (wireframes) for a portion of the study area (vertical exaggeration 20X).

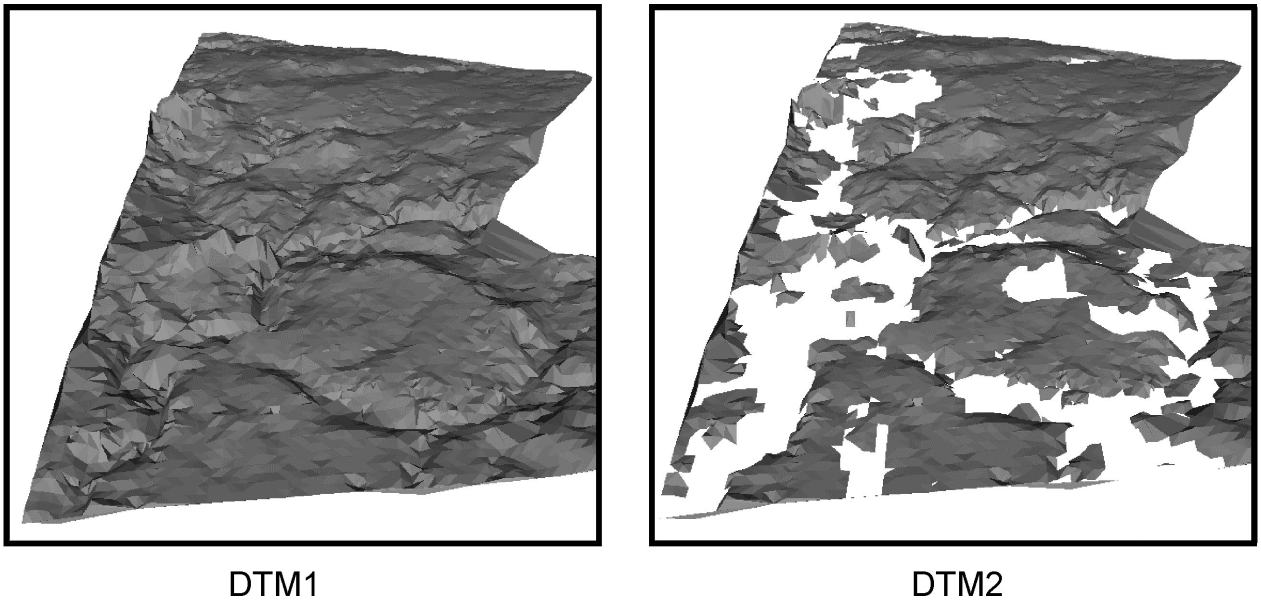


Figure 17. Perspective view of DTMs for aquitard surface ATB1. The left DTM shows the unit as a continuous surface with no holes whereas the one on the right has holes cut out where the unit is not present (vertical exaggeration 20X).

Creating 3-D Block Models

The block modelling techniques described so far have been used to interpolate elevations onto a 2-D grid of irregular points corresponding to the X,Y coordinates of one or more picks. These points are at the centres of the model cells but the actual dimensions of the cells are not used.

A 3-D block model representing all strata is created by filling the space between each stratum in DTM1 with subcells (Figure 18). The planar dimensions of a subcell are user defineable, but it was decided that either 100 or 200 m cell sizes provided a good resolution without creating too many cells; as a result, there are approximately 560 000 cells in the full 100 by 100 m block model. The dimension of each subcell in the vertical direction is calculated automatically so that it fits exactly between the strata (i.e., the block thickness is variable). The model created using this method is referred to as model 1.

A second model, model 2, is created in which all subcells are split along the horizontal planes corresponding to 10 m benches. Thus the thicker strata will contain several full 10 m subcells plus both an upper and lower subcell of less than 10 m. The number of cells in this model is approximately 4 times that of model 1. The advantage of model 2 is that the subcells for an individual stratum can be displayed and coloured according to the elevation of each subcell.

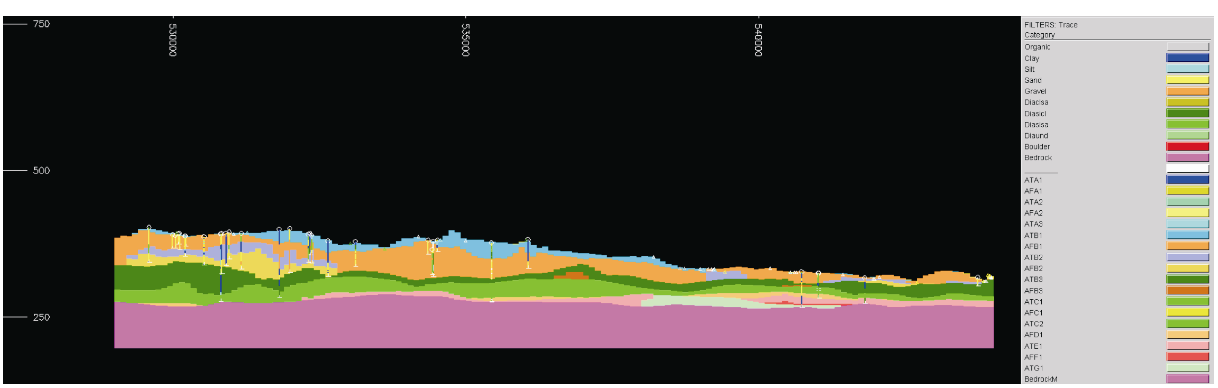
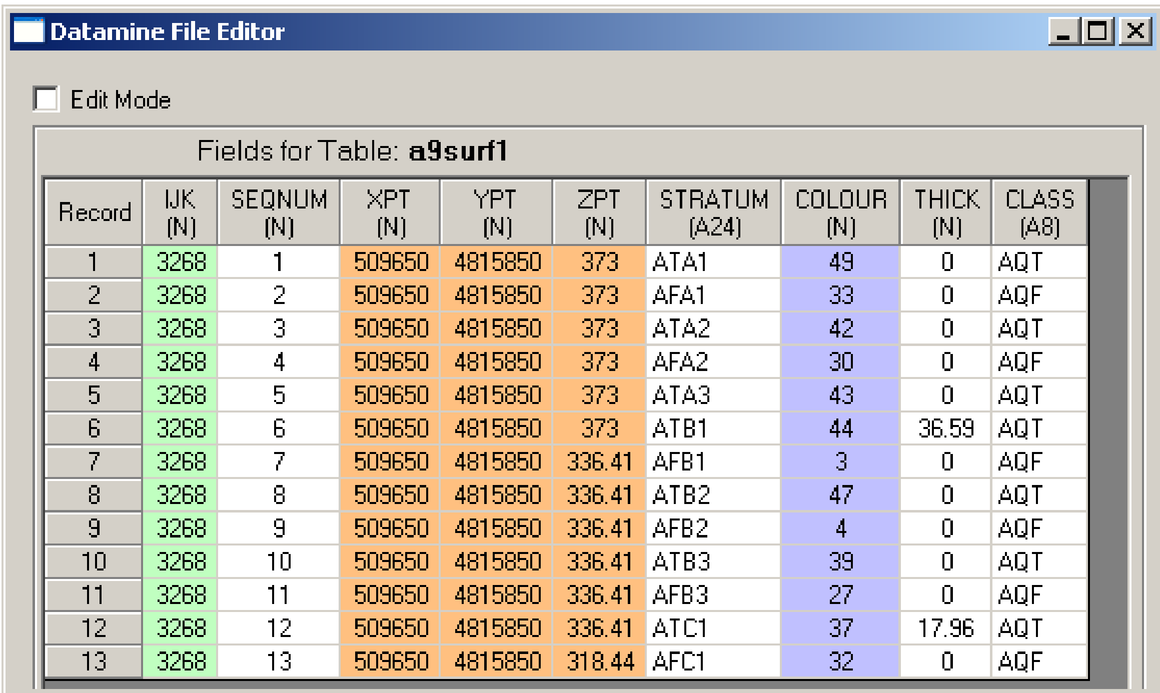


Figure 18. Section view of block model 1 created for a portion of the study area (vertical exaggeration 20X).

Calculating Volumes and Grids

The volume of each stratum over the whole area or over a subset of the area can be calculated from either DTM1 or either model. The results are classified both by stratum and by aquifer/aquitard. Model 1 includes the coordinates of each subcell centre and the thickness of each subcell on a regular XY grid. Hence, the elevation of the top and the thickness of each stratum is easily calculated and exported to a text file which can be used as input to other software packages for hydrogeological modelling or visualization (Figure 19).



Record	IJK (N)	SEQNUM (N)	XPT (N)	YPT (N)	ZPT (N)	STRATUM (A24)	COLOUR (N)	THICK (N)	CLASS (A8)
1	3268	1	509650	4815850	373	ATA1	49	0	AQT
2	3268	2	509650	4815850	373	AFA1	33	0	AQF
3	3268	3	509650	4815850	373	ATA2	42	0	AQT
4	3268	4	509650	4815850	373	AFA2	30	0	AQF
5	3268	5	509650	4815850	373	ATA3	43	0	AQT
6	3268	6	509650	4815850	373	ATB1	44	36.59	AQT
7	3268	7	509650	4815850	336.41	AFB1	3	0	AQF
8	3268	8	509650	4815850	336.41	ATB2	47	0	AQT
9	3268	9	509650	4815850	336.41	AFB2	4	0	AQF
10	3268	10	509650	4815850	336.41	ATB3	39	0	AQT
11	3268	11	509650	4815850	336.41	AFB3	27	0	AQF
12	3268	12	509650	4815850	336.41	ATC1	37	17.96	AQT
13	3268	13	509650	4815850	318.44	AFC1	32	0	AQF

Figure 19. Example of a text file containing X,Y,Z information for the top of each stratum on a regular grid.

Synthesis and Interpretation

A number of derivative products were generated following the creation of the block model for Waterloo region. These include a series of structural contour and isopach maps that depict surface topography and thickness of individual units, respectively (Plates 1 and 2). A series of east-west and north-south cross sections spaced at 5 km intervals were also created (Plates 3 and 4). These can be used as a quick reference guide for subsurface stratigraphy. The structural contour and isopach maps are also viewable in Google Earth™ mapping service as transparent overlays in 3-D space. This allows for interactive viewing by the user.

BEDROCK SURFACE

The elevation of the bedrock surface in Waterloo Region is fairly well constrained with data points (Figure 20). It ranges between 220 and 368 m asl and slopes gently from its highest point in the north towards the south end of the region. A large bedrock basin, open to the south, occurs centrally within the region and likely influenced depositional processes as glacier lobes advanced into and retreated out of the region.

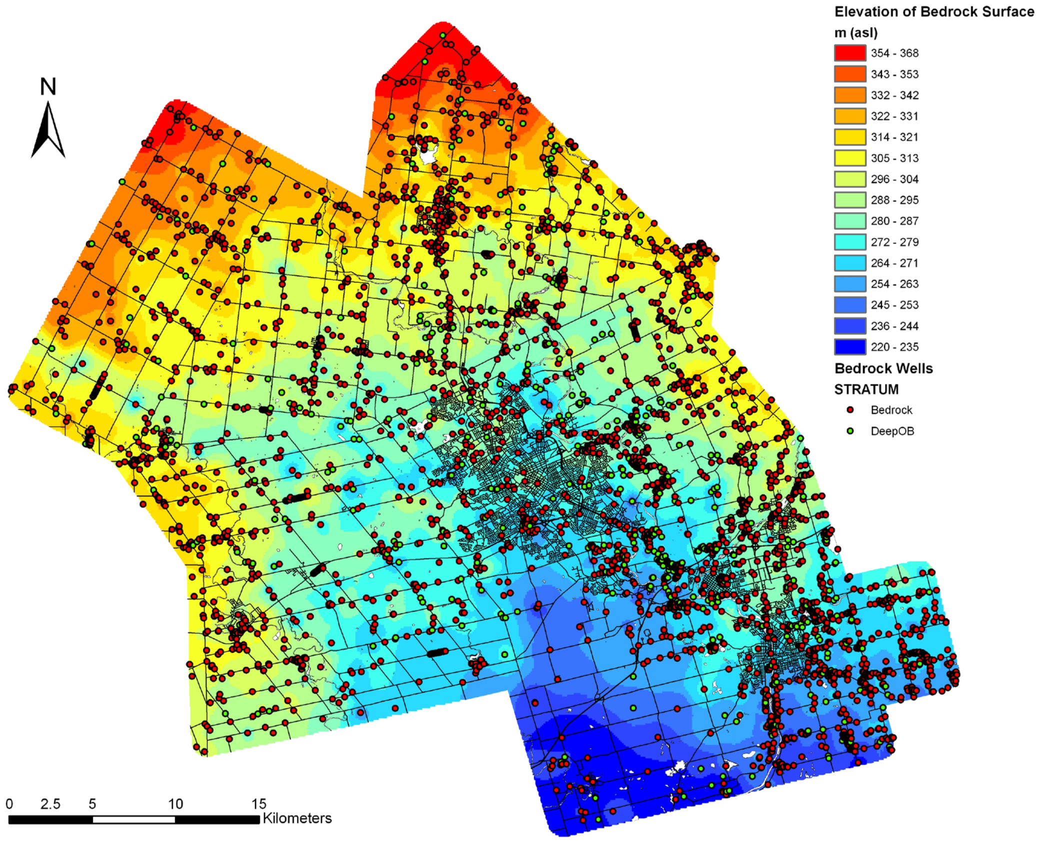


Figure 20. Structural contour of bedrock surface highlighting the location of bedrock wells and deep overburden (DeepOB) holes that push down the bedrock surface.

A number of buried bedrock valleys have been identified within the Region of Waterloo as well. These valleys are important in that they have great potential for hosting significant aquifers and, where laterally continuous, may transmit large volumes of groundwater. Of greatest significance is a southeast-trending buried valley which enters the region at its west-central edge in Wellesley Township and extends eastward through northern Wilmot Township, where its exact position becomes less well defined due to thick Quaternary cover. The valley may bifurcate east of the town of Wellesley, the northern limb extending eastward into the City of Waterloo and the southern limb extending south-southeast towards the hamlet of New Dundee. The northern limb of the valley appears to re-emerge at the south end of Kitchener where its trend shifts to a southerly direction following Westmount and Fischer-Hallman roads towards the hamlet of Roseville. Beyond this point, the course of the buried valley becomes less well defined due to a lack of deep borings. The valley appears to continue either towards the south or southeast out of the region and likely connects up to the Dundas buried valley which cuts through the Niagara Escarpment 35 km to the east. The valley can also be traced for well over 50 km northwest of the region through the town of Wingham. In Wellesley Township, the valley is approximately 50 m deep and 2 km wide. To the east and south, where the valley is eroded into softer shales, evaporites and dolostones of the Salina Formation, the valley appears to be much wider and less well defined. Widths of up to 5 km and depths in the range of 10 to 25 m are commonly observed in this area.

A number of other buried bedrock valleys occur within the Region of Waterloo, the most notable of which are:

1. a south-trending valley in north Woolwich Township that extends for approximately 10 km from the northern tip of the township, under the Woolwich reservoir towards the town of Elmira;
2. a southeast-trending valley in Wellesley Township that extends approximately 15 km from the northern tip of the township to the town of St. Clements;
3. a 10 km long tributary of the Wellesley buried valley that extends from the town of Wellesley up towards the hamlet of Crosshill and off to the northwest;
4. a poorly defined valley following the general course of the Grand River from the town of Elmira through the City of Cambridge to the south end of the region. The Elora buried valley, which originates north of Fergus, may connect up with this valley near the town of Conestogo;
5. the Rockwood buried valley, which originates north of Rockwood and extends through the City of Guelph and south towards Cambridge, is clearly seen in the vicinity of Shade Mills Conservation Area, where a number of deep overburden wells are documented; and
6. a west-trending buried valley extending between Glenchristie and Kossuth south then southwest towards Freeport along the Grand River.

The exact position of these valleys will only be improved by performing additional deep drilling initiatives and geophysical surveys. The valleys should be investigated for their potential to host important aquifers, and hydrogeological surveys should be conducted to determine the lateral extent and connectivity of them.

DRIFT THICKNESS

Drift thickness in the Regional Municipality of Waterloo ranges between 0 and 144 m with a mean value of 54 m (Figure 21). The greatest accumulations of Quaternary deposits are located within the area defined by the Waterloo Moraine (*see* Figure 5) as well as along the thalwegs of buried bedrock valleys. The Philipsburg, Crosshill and Hawkesville–Elmira spurs of the Waterloo Moraine are clearly delineated as areas of thick drift accumulations. Geometrically, it would appear that the area of thick drift west of the Grand River in North Dumfries Township is genetically related to the Waterloo Moraine and simply represents an area of morainic deposits modified by subsequent fluvial activity along the Grand River valley. A large esker complex in the vicinity of the Dryden Tract along Alps Road may represent an important feeder for the Waterloo Moraine. Similarly, the Philipsburg, Crosshill and Hawkesville–Elmira spurs may have contributed significant volumes of sediment to the west and northern parts of the moraine.

Accumulations of Quaternary sediments diminish drastically along the eastern third of the region as well as along the valleys of the Nith, Conestogo, Grand and Speed rivers. Bedrock outcrops occur along the lower reaches of the Speed and Grand rivers as well as along the southeast corner of the region. Localized accumulations of drift do, however, occur along the trend of the Paris, Galt and Breslau moraines.

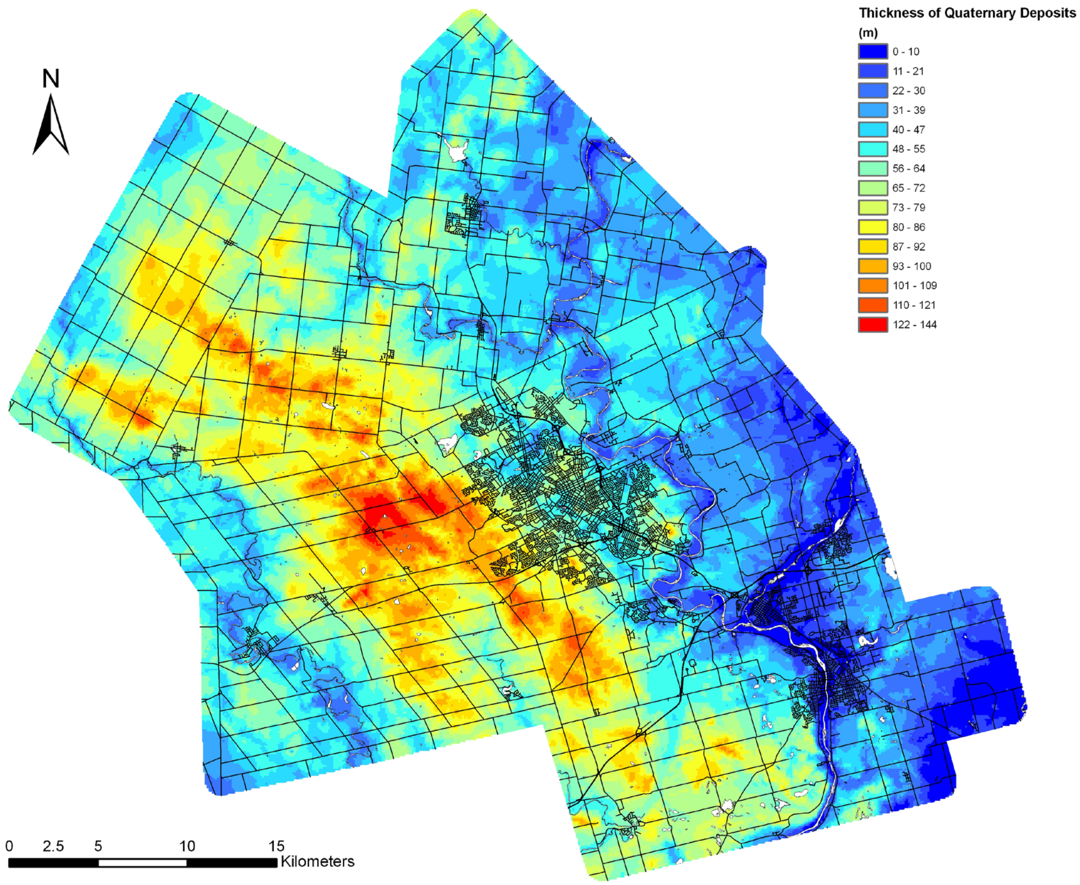


Figure 21. Thickness of Quaternary sediments within the Regional Municipality of Waterloo.

OLDER AQUIFERS AND AQUITARDS (ATG1 AND AFF1)

Aquifers and aquitards predating Canning drift are generally discontinuous and sporadic in their distribution. The absolute ages of these deposits are not known at this time. They do, however, predate the Elgin Subepisode (previously referred to as the Middle Wisconsinan). Notable occurrences of these deposits are found within the buried Wellesley bedrock valley along the western edge of Wellesley Township. Here, greater than 30 m of Aquifer AFF1 underlies Canning drift and infills the buried bedrock valley. Many of the rural land owners in this region have their wells screened into the top of this aquifer.

Extensive deposits of aquifer AFF1 and aquitard ATG1 are preserved within the Elmira area. The aquifer was host to a significant proportion of the city's water supply prior to the discovery of carcinogenic contaminants in 1989 and the decommisioning of several well fields. A cored borehole drilled by Conestoga Rovers Associates in 2004 at the south end of the city (OW161) helped to clarify the stratigraphic sequence preserved in Elmira and placed the producing aquifers into stratigraphic context. Catfish Creek Till typically occurs at shallow depths within the Elmira area and was encountered between 5.8 and 9.1 m below ground surface (bgs) in this borehole. An alluvial sequence containing possible organic remains underlies Catfish Creek Till and occurs between 9.1 and 19.8 m bgs. This unit is in turn underlain by 5.6 m of fine-textured glaciolacustrine sediment and mauve-grey silty to clayey till interpreted to be Canning drift. The main producing aquifer underlies this unit and extends between 25.4 and 50.0 m bgs. This unit is interrupted by a 1 m thick layer of till at 28.0 m bgs. Approximately 3 m of a stoney silt till underlies the aquifer and rests directly on the bedrock surface, which here consists of interbedded dolostones and shales belonging to the Salina Formation. The main aquifer underlying Canning drift in this borehole is assigned to aquifer AFF1 and the basal till is assigned to aquitard ATG1. These older aquifers and aquitards correlate with Baxter's (1996) lower hydrostratigraphic sequence although are placed at a lower stratigraphic position than his interpretation suggests. Aquifer AFF1 is largely confined by Canning drift; however, local windows are present. Thicknesses in excess of 30 m have been documented for this aquifer in the Elmira area. The aquifer appears to be confined to the buried bedrock valley north of the city and fans out to the south with the thickest accumulations occurring within the valley.

Another area where aquifer AFF1 occurs as a significant unit is along the Grand River valley between Breslau and Highway 401. Here, up to 14 m of coarse-grained glaciofluvial deposits underlie a discontinuous confining layer of Canning Till and associated glaciolacustrine deposits. These hydraulic windows have been documented as part of hydrogeologic testing, as well (Regional Municipality of Waterloo Internal Report 2000). The best exposures of this aquifer occur in the Forwell pits (currently operated by Dufferin Aggregates) south of Breslau where coarse-grained, cobble to small boulder gravels are being mined below river level. Once again, this unit appears to be confined to a bedrock valley following a similar course to that of the modern Grand River. Both the Forwell and Pompeii well fields are screened within this aquifer. It would appear that a significant amount of recharge of river water occurs within the aquifer as well.

CANNING DRIFT (ATE1)

Canning drift (also referred to as Aquitard 4 by the RMOW) is defined as a complex of fine-textured glaciolacustrine sediments and till that pre-date the deposition of Catfish Creek Till in southwestern Ontario. Canning Till is often stone-poor, silty to clayey, although silty to sandy facies have been observed, and often displays a red to grey-mauve colouration. The glaciolacustrine deposits are well laminated, occasionally display rhythmic cycles (varves) and are commonly overconsolidated. Canning drift occurs across approximately 50% of the Regional Municipality of Waterloo and as such is considered a regional aquitard. Nonglacial, occasionally organic-rich deposits are intermittently encountered between Canning drift and Catfish Creek Till. A weathering profile developed on the top of Canning Till in OGS borehole OGS-04-02 further supports this nonglacial episode. Erosive processes during this interval and the subsequent time period during which Catfish Creek Till was deposited undoubtedly resulted in the development of a regional unconformity. As a result, it is not uncommon to observe windows in this hydrostratigraphic unit that hydraulically link upper and lower aquifers.

Canning drift occurs primarily within the central, northern and northwestern parts of the region as well as along the course of the Nith River in the west and southwest. The upper surface of this unit slopes gradually from a high in the north and northwest of 390 m asl to a low in the south of 228 m asl. The maximum observed thickness of this unit approaches 45 m although 10 m or less is more representative. A belt of thicker deposits of Canning drift extends from the southwest corner of Kitchener near Doon Pinnacle up towards the northeast corner of Wellesley Township near the town of Hawkesville. The significance of this trend is not known at this time. Numerous small windows in ATE1 exposing aquifer AFF1 occur throughout the region as well. Some of these windows measure up to 1 to 2 km in diameter. Canning drift has not been observed east of the Grand River valley and occurs as an isolated patch along the Nith River at the south end of North Dumfries Township.

PRE-CATFISH AQUIFERS (AFD1)

Aquifers underlying Catfish Creek Till are widespread across the Regional Municipality of Waterloo. They occur primarily within bedrock depressions and valleys where glaciofluvial sediments associated with the advance of Catfish ice would have been concentrated. The aquifers are also collectively referred to as the "Parkway aquifer" or "Aquifer 3" in various reports and publications. The Parkway and Strasburg well fields obtain their water from this aquifer. This unit is exposed at a few locations within the region. The gravel pits along the Grand River south of Breslau (Preston Sand and Gravel and Dufferin Aggregates) expose 5 to 10 m of pebble to cobble gravel between Catfish Creek Till and Canning drift. Canning drift occurs as discontinuous lenses in this area making it difficult to distinguish the Parkway aquifer from older aquifers (AFF1). This aquifer occurs at or slightly above river level and is easily recharged by river water. The decommissioned well fields at Forwell, Pompeii and Woolner Flats all obtained their water from this aquifer. A couple of gravel pits within the Nith River valley at Haysville in Wilmot Township (Figure 22) also expose 5 to 10 m of sand and gravel directly beneath Catfish Creek Till. An OGS borehole (OGS-04-03), which was drilled approximately 1 km to the southeast of these gravel pits, also contained approximately 15 m of stratified sand and gravel beneath Catfish Creek Till.

Visual inspection of the isopach map for the Parkway aquifer shows a remarkable coincidence between thick deposits of this unit and the location of buried bedrock valleys. For example, thicknesses of 10 to 45 m occur within the Wellesley buried bedrock valley along much of its inferred length. Thick accumulations also occur in the buried bedrock valleys of northern Wellesley and Woolwich townships as well as along the trends of the Nith, Conestogo and Grand river valleys.

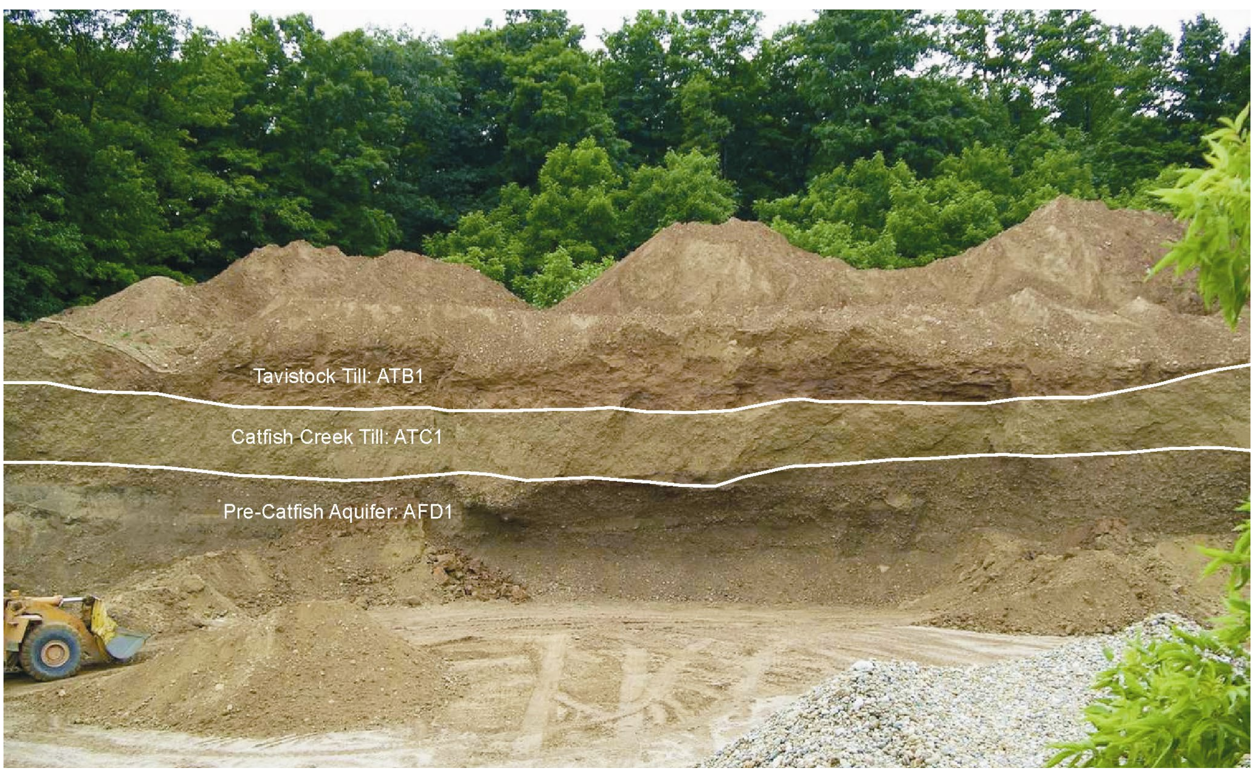


Figure 22. Stratified sand and gravel deposits (Parkway aquifer) underlying Catfish Creek Till and younger deposits at the Ross Roth sand and gravel pit, Haysville, Ontario.

CATFISH CREEK TILL (ATC1, AFC1 and ATC2)

Catfish Creek Till (also referred to as Aquitard 3 in RMOW studies) is widely distributed in southwestern Ontario and is regarded as a regional aquitard. It was deposited during the Michigan Subepisode (formerly Late Wisconsinan) approximately 20 ka BP. The properties of Catfish Creek Till are regionally consistent. It commonly has an olive-grey colour when unoxidized, is often stony and has a silty to sandy matrix and is generally overconsolidated. Clasts of Huronian conglomerates and sandstones, including jasper conglomerate and Gowganda tillite, commonly occur within the till. Water well drillers frequently refer to this unit as "hardpan" in their well logs.

Catfish Creek Till occurs as a nearly continuous lithostratigraphic unit within the Regional Municipality of Waterloo. It does, however, appear to pinch out in the southeast corner of the region where the younger Port Stanley and Wentworth tills are the only tills preserved. As with the bedrock surface, the upper surface of Catfish Creek Till slopes gently from a high in the north and northwest of 416 m asl to a low in the south of 259 m asl. A number of valleys appear to be cut into the upper surface of this till plain, the most notable of which extends from the northeastern tip of Wellesley Township and extends south-southeastward toward the town of New Dundee in Wilmot Township. The valley is 1.5 to 2.0 km wide and up to 35 m deep. In a few places along this valley, windows in the Catfish Creek Till surface exist and measure up to 500 to 1000 m in diameter. The regional significance of this valley is unknown at present but may indicate the occurrence of tunnel channels on the Catfish Creek Till surface not unlike those developed on the Newmarket Till surface below the Niagara Escarpment. East of this valley, a topographic high in the Catfish Creek till surface coincident with the position of the Waterloo Moraine is recognized. This may suggest a possible genetic relationship between Catfish Creek Till and the Waterloo Moraine. This conclusion is contrary to that proposed by Karrow and Paloschi (1996) who saw no relationship between the 2 deposits.

Catfish Creek drift is subdivided into an upper and lower aquitard with an intervening aquifer. The reason for this subdivision is the discovery of significant coarse-grained glaciofluvial deposits between 2 layers of Catfish Creek Till in OGS borehole OGS-03-08. It was felt that similar situations could easily occur elsewhere within the region so an attempt was made to model these deposits if present. As it turns out, very few areas of mappable intervening glaciofluvial deposits were encountered. Small areas of an intervening aquifer occur in Wellesley Township near the town of Wellesley, in central Kitchener by the Greenbrook well field and along the Grand River valley just east of the town of Conestogo.

Catfish Creek Till ranges between 0 and 65 m in thickness with a mean value of 15 m. The thickest deposits occur in central Wellesley Township, eastern Wilmot Township and western North Dumfries Township. Linear accumulations of Catfish Creek Till may represent ice-marginal positions or moraines. For example, in central Wellesley Township, there are 2 linear accumulations of Catfish Creek Till, one aligned northwest-southeast and the other east-west. These deposits are coincident with the Crosshill and Wellesley moraines, respectively, and may therefore suggest a genetic relationship between Catfish Creek Till and these features. As a general observation, Catfish Creek Till also appears to be thicker over the area defined by the Waterloo Moraine. Once again, this may suggest a genetic relationship between the 2 deposits. A similar situation occurs over the Elmira Moraine at the north end of Woolwich Township.

CATFISH CREEK OUTWASH DEPOSITS (AFB3)

Deposits of sand and gravel associated with the retreat of Catfish ice occur as isolated patches throughout the region of Waterloo with no apparent linear trends. This is likely attributable to a general lack of high quality subsurface information. This unit is referred to as the Greenbrook aquifer and is named after the well field in which it occurs. Although thicknesses of up to 42 m have been documented in the subsurface model, values of less than 10 m are much more common.

LOWER MARYHILL TILL AND EQUIVALENTS (ATB3)

A fine-textured complex of till and glaciolacustrine deposits commonly separates Catfish Creek Till from overlying Waterloo Moraine sands and gravels and equivalent-aged deposits throughout the region. This till unit is referred to as Lower Maryhill Till beneath the Waterloo Moraine, Maryhill Till to the east where it lies between Catfish Creek Till and Port Stanley Till, and Stirton Till west of the moraine where it occurs between Catfish Creek Till and Tavistock/Mornington Tills (*see* Figure 9). Stirton Till and Maryhill/Lower Maryhill Till are believed to be contemporaneous and represent the deposits of ice originating from the Huron and Erie–Ontario lake basins, respectively. This unit is referred to as Aquitard 2 in RMOW studies. It occurs as a nearly continuous veneer over Catfish Creek Till throughout the region and pinches out in the extreme southeast corner of the region where drift thickness diminishes. Small windows in aquitard ATB3 occur in the peripheral areas of the region. Some of these windows may simply indicate areas where Waterloo Moraine and equivalent-aged aquifers are absent.

The upper surface of aquitard ATB3 slopes gently from a high in the north and northwest of 413 m asl to a low in the southeast of 228 m asl. This unit also rises coincidently with the Crosshill and Hawkesville–Elmira moraines, implying a possible link. This tight aquitard can attain a thickness of up to 78 m and is therefore important from a hydrogeological perspective. The thickest deposits appear to be coincident with the trend of the valley carved into Catfish Creek Till in eastern Wellesley and Wilmot townships. Thick accumulations also occur in North Dumfries Township between the Grand River and Cedar Creek. Slightly increased thicknesses are also observed along the trend of the Breslau Moraine in the eastern part of the region.

WATERLOO MORAINE AND EQUIVALENTS (AFB1, ATB2 and AFB2)

The Waterloo Moraine, or Mannheim aquifer (Aquifer 1 in RMOW studies), is probably one of the most prolific overburden aquifers in southwestern Ontario. It provides water to 11 well fields within the Regional Municipality of Waterloo and likely contributes water via leakage to a number of others. The Waterloo Moraine is thought to have been deposited in a large lake during the early stages of deglaciation. It was surrounded on all sides by glacial ice allowing for the accumulation of glaciolacustrine sediments at very high elevations. Rivers flowing to the ice margins in large subglacial conduits carried enormous volumes of sediment into the lake from the southeast (Dryden Tract esker complex), east (Sportsworld Complex esker), north (Hawkesville/Elmira esker), northwest (Crosshill esker) and possibly the west (Baden Hills esker). Thicknesses in excess of 45 m are commonly observed within the moraine and locally may reach 70 m or more (Figure 23).

Both conduit and subaquatic fan facies have been observed within the moraine. Sedimentological studies of these deposits suggest that they were deposited in a series of high-magnitude meltwater discharge events (Russell, Sharpe and Bajc, in press). Lenses of diamicton and glaciolacustrine mud, some of which have dimensions exceeding 3 to 4 km in length or width, occur within or between the subaquatic fan deposits. These units, which were deposited either in slack water areas by suspension settling or in unstable areas adjacent to melting ice as debris flows and resedimented glaciolacustrine deposits, are significant from a hydrogeological perspective as they can locally impede groundwater flow to lower aquifers.

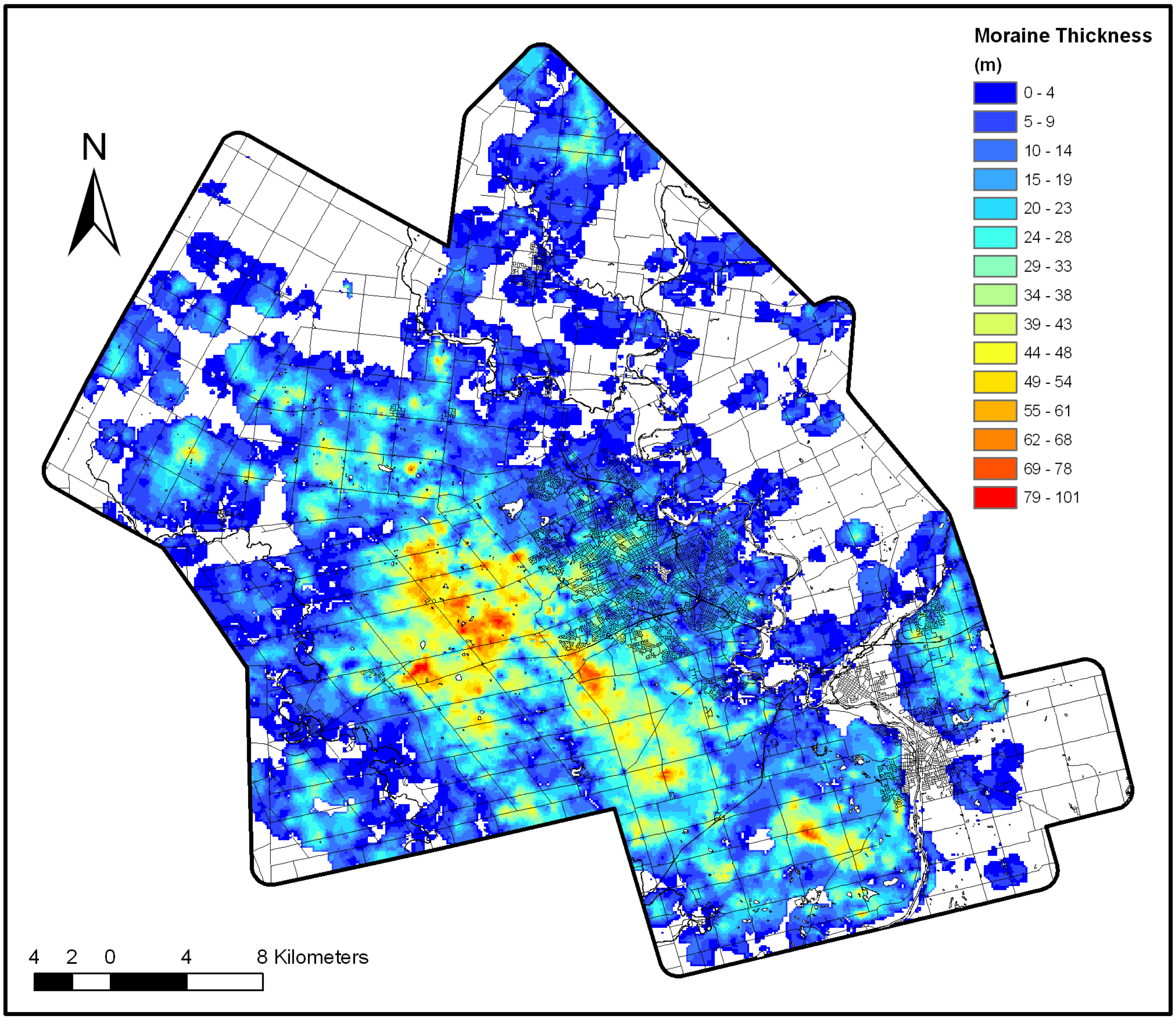


Figure 23. Isopach map of Waterloo Moraine and equivalent aquifers in the Regional Municipality of Waterloo.

At Mannheim, the site of an aquifer storage and recovery system (ASR), an extensive layer of glaciolacustrine silt (modelled up to 10 m thick) occurs within the Mannheim aquifer at a depth of about 15 m. This aquitard played a role in the decision to construct a series of injection wells at the site rather than using infiltration ponds for the replenishment of the aquifer during low demand periods. The rate of infiltration to the lower, coarse-grained part of the Mannheim aquifer would have been too low for effective recharge. An attempt has been made to map out these impervious zones within the Waterloo Moraine using the available subsurface information. The model allows for a single layer of aquitard material within the moraine at any given site. These units are defined as aquitard ATB2 and where present have aquifer AFB2 beneath them.

Aquifer AFB1 is widely distributed across the RMOW. The greatest accumulations occur within the Waterloo Moraine and its feeding spurs. Modelled thicknesses range between 15 and 100 m with values of 15 to 40 m being more common. Linear northwest-trending strings of thicker deposits occur within the core of the Waterloo Moraine and may indicate the location of subglacial conduits or feeding eskers. An abrupt decline in the thickness of aquifer AFB1 occurs along the west edge of the cities of Kitchener and Waterloo. This may represent an important ice-marginal position along which coarse aquifer material would have accumulated. A number of important well fields, including the Waterloo North, Strange Street, Greenbrook, Parkway and Strasburg, coincidently lie along this trend.

The Elmira Moraine, which is exposed at surface at the north end of Woolwich Township, appears to extend in the subsurface beneath Tavistock Till to the south where it links to the Hawkesville "esker". Similarly, the Crosshill glaciofluvial system appears to extend to the southeast in the subsurface beneath Mornington Till, connecting to the main mass of the Waterloo Moraine in the vicinity of Bamberg. The Wellesley Moraine may also extend in the subsurface through the town of Wellesley and eastward to the Waterloo Moraine south of Bamberg. The Dryden Tract esker complex appears to be truncated along the Cedar Creek valley then reappears to the northwest in the Waterloo Moraine proper in the vicinity of Roseville. Significant accumulations of aquifer AFB1 also occur southeast of the Speed River and west of Puslinch Lake. These deposits may be genetically related to a series of moraines (St. Thomas, Norwich and Tillsonburg moraines) that converge from the south into the Grand River valley where they are obscured (modified and buried) by younger outwash deposits.

Seams and lenses of aquitard ATB2 are sporadically distributed across the Waterloo Moraine. To the east, over the cities of Kitchener and Waterloo, thicknesses in the range of 1 to 10 m are common. Thicker accumulations occur to the west in Wilmot Township over depressions in the Catfish Creek Till surface. These depressions appear to have been the loci of basinal sedimentation during the formation of the Waterloo Moraine. The distribution of aquifer AFB2 is similar to that of aquitard ATB2, with thicknesses of 1 to 13 m being most common and thicknesses of 20 to 30 m occurring in the depressions of the Catfish Creek Till surface in central Wilmot Township.

UPPER MARYHILL TILL AND EQUIVALENTS (ATB1)

Aquitard ATB1 (also referred to as Aquitard 1 in RMOW reports) consists of the Huron lobe Mornington, Stratford and Tavistock tills and the Erie–Ontario lobe Upper Maryhill and Port Stanley tills. It occurs at ground surface over most of the region with the exception of the Grand River valley and the extreme southeastern corner of the region where younger glaciofluvial deposits and Wentworth Till, respectively, conceal it or have completely eroded it away.

The Tavistock, Mornington and Upper Maryhill tills are fine-textured diamictons (silty to clayey) whereas the Stratford and Port Stanley tills are silty to sandy and slightly more transmissive. Aquitard ATB1 forms a discontinuous cover over the Waterloo Moraine and its radial spurs thus only locally protecting the underlying aquifer from surface contamination. Recharge of the aquifer is greatly diminished within these areas. Aquitard ATB1 is generally between 0 and 20 m thick. Locally, thicknesses of greater than 45 m have been modelled. The thickest deposits are situated in the north and west parts of Wellesley Township, the southwest corner of Wilmot Township and the drumlinized area east of Kitchener–Waterloo (Guelph drumlin field). The Waterloo landfill site is situated over the Waterloo Moraine in an area where aquitard ATB1 is modelled to be between 20 and 50 m thick. The eastern edge of this extensive area of aquitard ATB1 coincides with a probable ice margin trending northwest that controlled the overall thickness of not only the aquitard but the underlying Waterloo Moraine aquifer (AFB1).

GRAND RIVER OUTWASH DEPOSITS AND EQUIVALENTS (AFA2)

Grand River outwash deposits and equivalents are confined to the Grand River, Nith River, Speed River and Conestogo river valleys with isolated patches occurring locally throughout the remaining portions of the region. As with most strata, the elevation of aquifer AFA2 slopes gently from a high in the north of 424 m asl to a low in the southeast of 270 m asl. Thicknesses generally range between 0 and 10 m with local accumulations of up to 45 m being modelled in the extreme southern reaches of the Grand and Nith river valleys. Extensive deposits of Grand River outwash occur beneath Wentworth Till in the Paris and Galt moraines suggesting a possible readvance of the Erie–Ontario ice lobe to this ice position. Outwash deposits in the lower reaches of the Grand River generally display a coarsening upward sequence with silts and very fine-textured sands at depth indicating possible delta progradation into a high level Erie basin lake. An attempt has been made to model these finer-textured deposits (ATA3) although the data distribution did not allow for a good representation of this unit.

WENTWORTH TILL (ATA2)

Wentworth Till occurs in the extreme southeastern corner of the region within the Paris and Galt moraines. It is modelled as an aquitard although its loose, stony, silty to sandy character and close association with stratified deposits of sand and gravel suggest that it should probably be classified as a leaky aquitard or poor aquifer. Abundant closed depressions or kettle holes on the moraine surface, many of which are dry, suggest that precipitation is readily infiltrating through Wentworth Till, recharging the aquifers below. Two distinct ridges of Wentworth Till representing the Paris and Galt moraines to the west and east, respectively, have been modelled. The surface elevation ranges between 322 and 277 m asl within the morainic belt and drops to 242 m asl on the eastern side of the moraines. Wentworth Till ranges between 10 and 30 m thick within the moraines with local accumulations of up to 57 m modelled in places. Till thickness generally declines to the east on the proximal side of the morainic belt where bedrock outcrops occur. Locally, however, thick deposits of Wentworth Till occur in the Westover drumlin field, which contains west-northwest-oriented till ridges that protrude up from a bedrock plain. Thin deposits of Wentworth Till between the drumlin ridges are often capped by either glacial Lake Whittlesey sands (AFA1) or silts and clays (ATA1) within this area.

Aquifer Vulnerability and Recharge Areas

An attempt has been made to model aquifer recharge areas and assess aquifer vulnerability in the Regional Municipality of Waterloo using the 3-D block model and some basic hydrogeologic parameters. For this purpose, an aquifer is defined as a mappable unit of sand and gravel with a total thickness of greater than 3 m. The Grand River Conservation Authority used a similar thickness for its assessment of aquifer vulnerability (Holysh, Pitcher and Boyd 2001). This assessment was also undertaken using a minimum thickness of 5 m with no significant change in the observed patterns. By mapping out the depth to the first significant aquifer of thickness greater than 3 m as well as areas where drift cover over bedrock is less than 1 m (Figure 24 or Plate 5), one obtains a view of areas where aquifers are easily recharged with surface precipitation as well as where they may be more susceptible to surface contamination by agriculturally applied nutrients, livestock wastes, road salt or industrial contaminants. Depth to water table within these areas will dictate the degree to which these aquifers are vulnerable. That is, an unconfined aquifer with a deep water table is far less vulnerable than one with a shallow/high water table. This information is important to the planning community as it helps to identify areas that should be protected from development. It can also help the Ministry of Agriculture, Food and Rural Affairs as it develops nutrient management guidelines for the region.

Areas of red, orange and purple are those where aquifers occur at shallow depths. Note that much of the Waterloo Moraine and its radial spurs occur at depths of less than 1 m. A notable exception includes the large patch of Upper Maryhill Till (ATB1) located immediately west of Kitchener–Waterloo that confines the morainic deposits with greater than 10 m of protective clay. The Waterloo landfill site is situated within this area. Guelph Formation dolostone bedrock occurs at shallow depths along the Speed and Grand river valleys near Cambridge as well as over a large area east of the Paris and Galt moraines in North Dumfries Township. Fractures in the upper bedrock within these areas are conduits for the rapid transmission of surface contaminants into the bedrock groundwater system. Caution should be taken within these areas to minimize the potential impacts of agricultural practices and urban and industrial expansion.

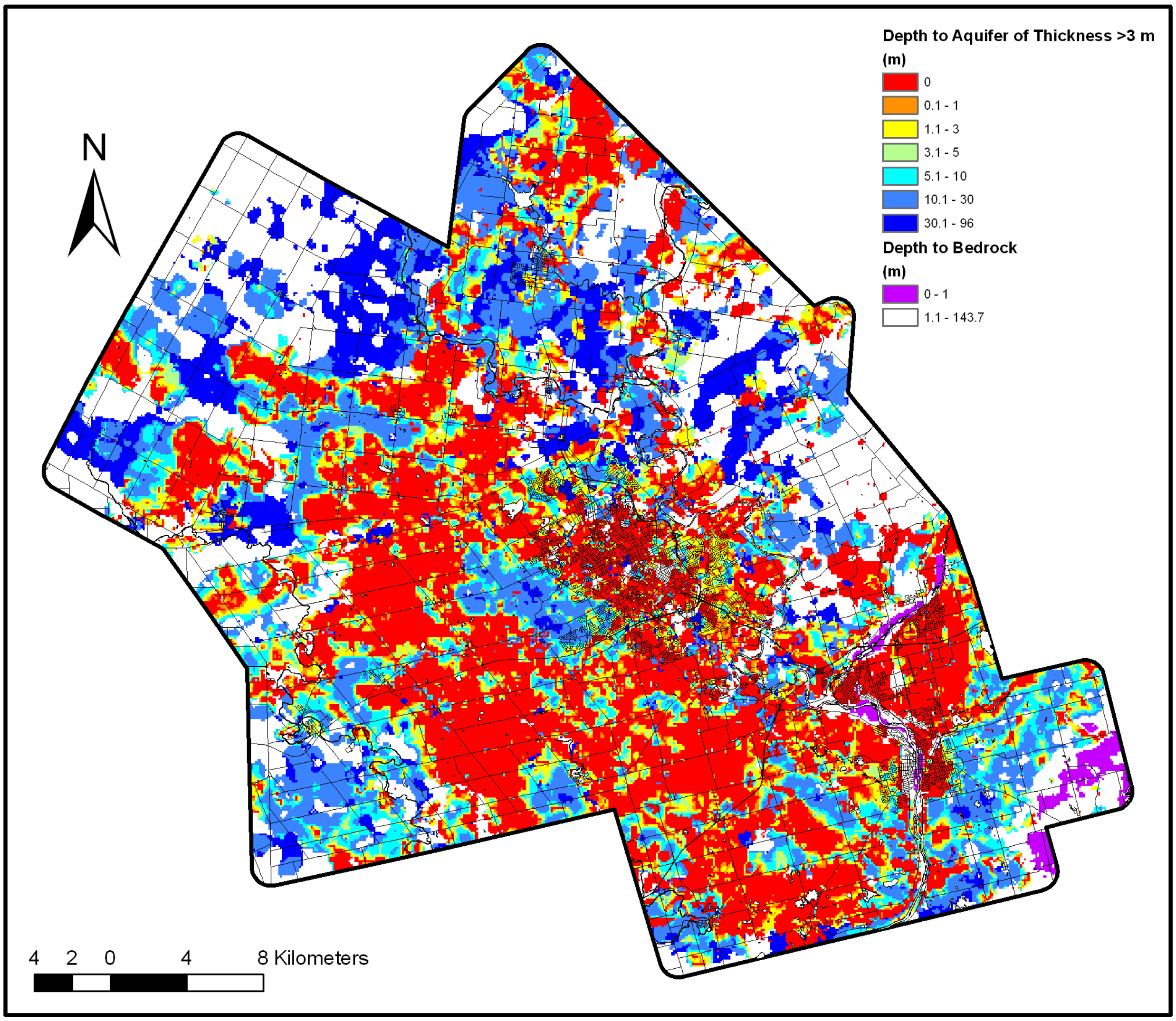


Figure 24. Depth to first aquifer of thickness greater than 3 m in the Regional Municipality of Waterloo. Areas shown as white on this map are those where aquifers of thickness greater than 3 m have not been modelled or where depth to bedrock is greater than 1 m.

Figure 24 also displays a number of similarities to a groundwater recharge layer developed by the Grand River Conservation Authority for the watershed (Bellamy, Boyd and Pitcher 2002). This coverage was produced using the GAWSER (Guelph All-Weather Sequential-Events Runoff) hydrologic model and uses precipitation, temperature, surficial geology and land cover as the main inputs. The model was classified according to 3 main categories; namely, areas that produced 40% of the total recharge which constituted 10% of the total watershed area; areas that produced 30% of the total recharge which constituted 20% of the total watershed area; and areas that produced 30% of the total recharge which constituted 70% of the total watershed area. The results of this classification showed that much of the undeveloped parts of the Waterloo, Orangeville, Paris and Galt moraines accounted for a significant proportion (70%) of the total recharge within the watershed. The undeveloped parts of the Waterloo Moraine in Wilmot and North Dumfries townships display strong downward hydraulic gradients (Holysh, Pitcher and Boyd 2001) and clearly stand out as important areas of recharge that should be protected from future development. Figure 25 highlights the areas of the Waterloo Moraine and equivalent aquifers with a total thickness exceeding 10 m and an aquitard cover of less than 1 m. Once again, the western and southern parts of the Waterloo Moraine stand out as significant areas of possible recharge.

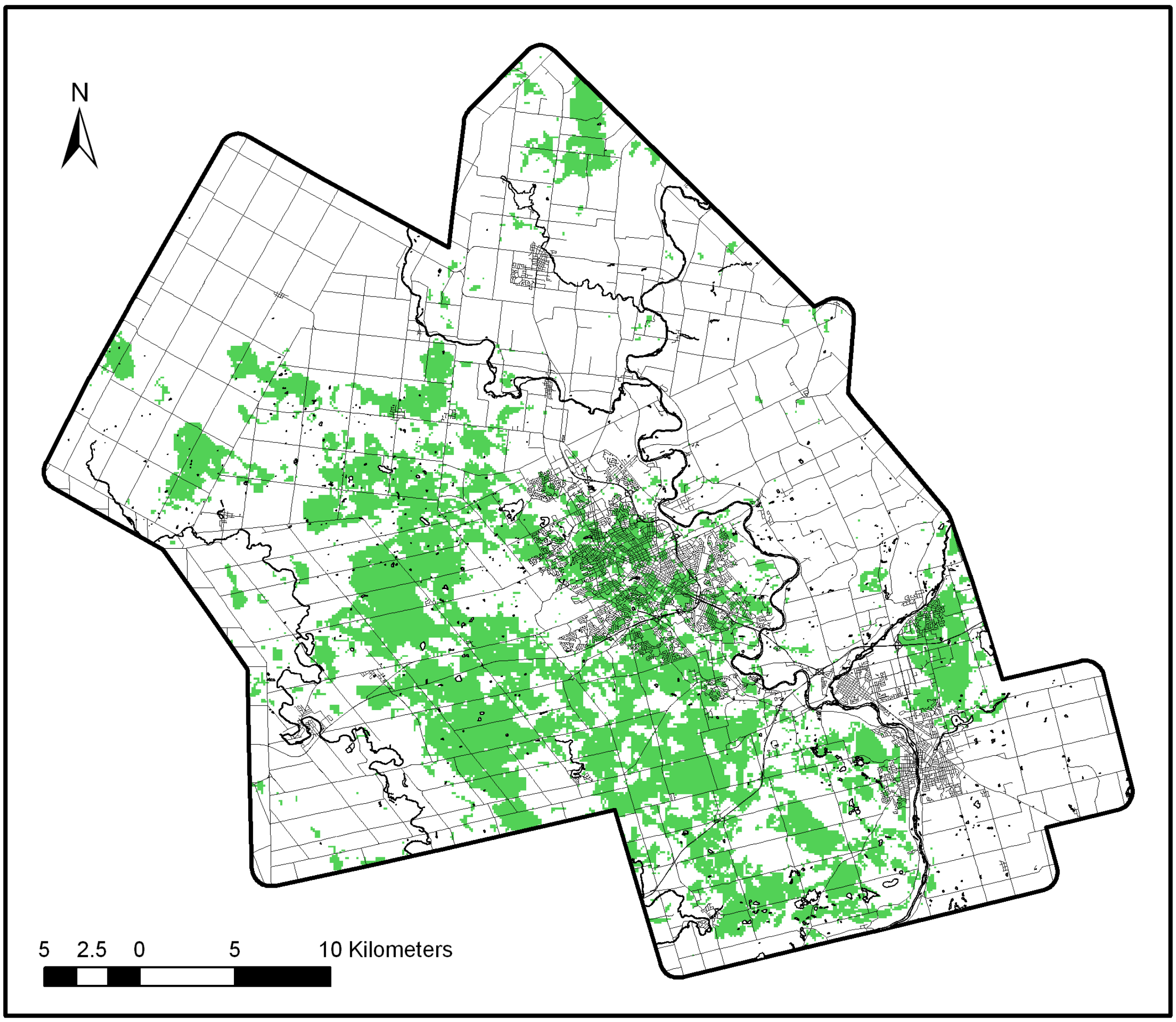


Figure 25. Areas of the Waterloo Moraine and equivalent aquifers with a total thickness greater than 10 m and an aquitard cover of less than 1 m are shown in green. These are areas of significant recharge potential within the moraine.

By plotting the depth to the shallow water table (i.e., <35 m) in areas where significant aquifers (i.e., >3 m thick) and bedrock occur within 5 m of the ground surface, one can more clearly assess aquifer vulnerability (Figure 26 or Plate 6). A number of areas are identified where the shallow water table is projected to occur above the ground surface. These potential discharge areas are important in that they provide cold water habitats for trout species within the region. Minor fluctuations in the water table in response to climatic variation or excessive pumping of municipal wells can have a strong impact on the health and survival of the local fishery. Those areas where the water table occurs fairly close to the ground surface are most vulnerable to agriculturally applied nutrients, road salt and any industrial/commercial/residential sources of contamination. Great care must be taken within these areas to ensure that the groundwater resource is protected.

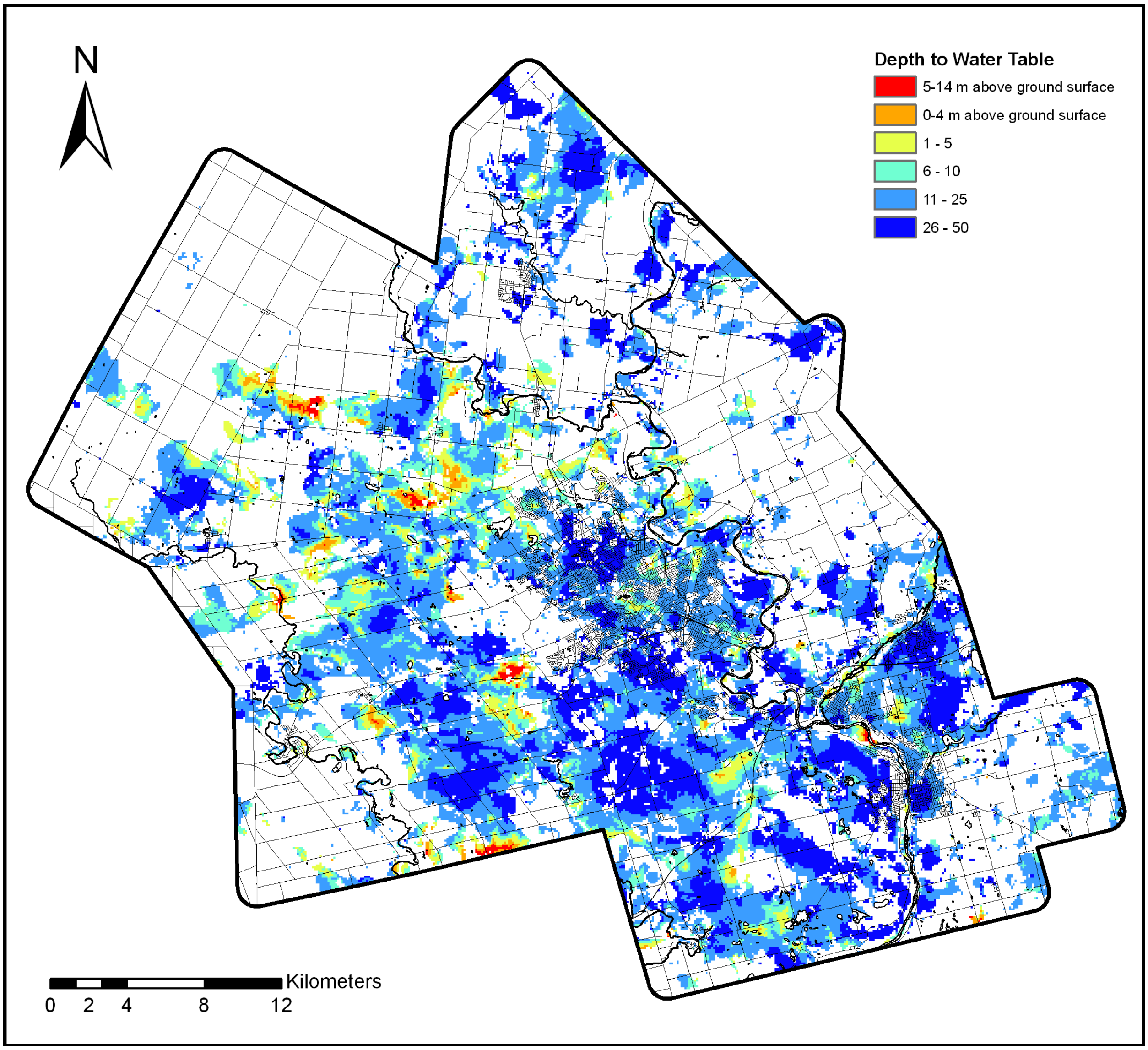


Figure 26. Depth to water table in areas where either a significant overburden aquifer (i.e., >3 m thick) or bedrock occurs within 5 m of the ground surface.

Conclusions

As pressures directed at protecting and preserving the quality and sustainability of the provincial groundwater resource increase, three-dimensional geologic studies such as the one highlighted in this report will become increasingly more important. A good knowledge of the distribution and character of aquifers and aquitards in the subsurface is essential as source water protection plans are developed and implemented for the province. A five-phased approach to three-dimensional mapping has been undertaken as part of this study. This includes 1) data compilation and standardization; 2) acquisition of new geological and geophysical data; 3) development of a conceptual geological model; 4) data interpretation and synthesis; and 5) generation of digital products understandable/useable by a wide range of client groups. Future 3-D mapping studies should employ a similar approach.

The protocols of three-dimensional mapping developed for this project will be used in other areas of the province. Minor modifications to the procedures and software applications are envisioned over time as needs arise. The OGS has opted for an approach to 3-D mapping that blends expert knowledge-based interpretations guided by a conceptual geological model with the powerful capabilities of a true 3-D modelling software package capable of performing complex tasks quickly and repeatedly. As source data sets are generally of disparate quality, it was essential that interpretations be evaluated using spatial geostatistics to establish a degree of confidence regarding the outcome of the interpolations.

Datamine Studio®, a 3-D mapping software developed primarily for the mining sector, was utilized in this study and proved to be a powerful tool for the modelling process. It allowed for the interpretation, in true 3-D space, of the borehole information and the digitization of pick points that represent the tops of formations along boreholes as well as along georeferenced raster images. These points were spatially assessed in terms of their regional significance then filtered to produce a series of surfaces representing the tops of 19 hydrostratigraphic units. Post-processing of these surfaces to correct crossovers was undertaken using Boolean operators. A series of comma-delimited text files representing the tops of each stratigraphic unit on a 100 m grid were exported from the software. These files are easily imported into other applications for hydrogeological modelling, plotting or further assessment.

It is clear that geologic maps and products must be tailored to both technical and nontechnical users for input to source water protection plans. Derivative or value-added products such as aquifer vulnerability maps require a good knowledge of the distribution and character of the overburden materials. Much of this information is easily extracted from the geologic model created as part of this project. Interactive viewing of transparent structural contour and isopach overlays in Google Earth™ mapping service also permits improved communication to a wider audience.

Acknowledgments

The authors would like to thank the Regional Municipality of Waterloo, the Ministry of the Environment, the Department of Environmental Studies at the University of Waterloo and Dr. P.F. Karrow for allowing access to their respective databases of subsurface information. We also acknowledge the numerous aggregate operators and land owners for allowing access to their properties. Supportive research by the Geological Survey of Canada (seismic reflection and borehole geophysics) and the Department of Earth Sciences, University of Waterloo (ground penetrating radar), was instrumental in the development of the conceptual geologic model for the region. Competent field assistance was provided by Lona-Kate Dekeyser and Matt Sooley.

References

Bajc, A.F. and Hunter, J.A. 2006. Results of 2003-2004 overburden drilling programs in the Region of Waterloo, southwestern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 205.

Bajc, A.F. and Karrow, P.F. 2004. 3-dimensional mapping of Quaternary deposits in the Regional Municipality of Waterloo, southwestern Ontario; Geological Association of Canada Fieldtrip Guidebook FT-7, 72p.

Barnett, P.J. 1991. Quaternary geology of Ontario; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.1011-1090.

Baxter, K. 1996. Groundwater contamination in Elmira, Ontario; regional correlation of hydrogeology and the effect of geology on multi-directional plume migration; University of Waterloo, MSc thesis, 206p.

Bellamy, S., Boyd, D. and Pitcher, J. 2002. Production of a groundwater recharge layer; Grand River Conservation Authority, unpublished Internal Report, 8p.

Chapman, L.J. and Dell, C.I. 1963. Revisions in the early history of the retreat of the Wisconsin glacier in Ontario based on the calcite content of sands; Proceedings of the Geological Association of Canada, v.15, p.103-108.

Chapman, L.J. and Putnam, D.F. 1951. The physiography of southern Ontario; Ontario Research Foundation, 284p.

deVries, H. and Dreimanis, A. 1960. Finite radiocarbon dates of the Port Talbot interstadial deposits in southern Ontario; Science, v.131, 1738-1739.

Gautrey, S.J. 1996. The hydrostratigraphy of the Waterloo moraine; unpublished MSc thesis, University of Waterloo, Waterloo, Ontario, 309p.

Hansel, A.K., Stiff, B.J. and Barnhardt, M.L. 2004. Three-dimensional geologic mapping in rapid-growth areas: a case study from Lake County, Northeastern llinois; Illinois State Geological Survey, Open File-Series 2004-8, p.23-27.

Holysh, S., Pitcher, J. and Boyd, D. 2001. Grand River regional groundwater study; Grand River Conservation Authority, Cambridge, Ontario, Technical Report, 271p.

Johnston, M.D., Armstrong, D.K., Sanford, B.V., Telford, P.G. and Rutka, M.A. 1991. Paleozoic and Mesosoic geology of Ontario; *in* Geology of Ontario, Ontario Geological Survey, Special Volume 4, Part 2, p.907-1008.

Karrow, P.F. 1988. Catfish Creek Till: an important glacial deposit in southwestern Ontario; 41st Canadian Geotechnical Conference, Kitchener, Ontario, Preprints, p.186-192.

——— 1993. Quaternary geology of the Stratford - Conestogo area; Ontario Geological Survey, Report 283, 104p.

Karrow, P.F. and Paloschi, G.V.R. 1996. The Waterloo kame moraine revisited: new light on the origin of some Great Lakes region interlobate moraines; Zeitschrift für Geomorphologie, v.40, p.305-315.

Karrow, P.F. and Warner, B.G. 1984. A subsurface Middle Wisconsinan interstadial site at Waterloo, Ontario, Canada; Boreas, v.13, p.67-85.

Logan, C., Russell, H.A.J. and Sharpe, D.R. 2001. Regional 3-D stratigraphic modelling of the Oak Ridges Moraine area, southern Ontario; Current Research 2001-D1, Ottawa, Geological Survey of Canada, p.19.

——— 2005. Regional 3-D structural model of the Oak Ridges Moraine and Greater Toronto Area, southern Ontario: version 2.1; Geological Survey of Canada, Open File 5062, 27p.

Logan, C., Russell, H.A.J., Sharpe, D.R. and Kenny, F.M. 2006. The role of expert knowledge, GIS and geospatial data management in a basin analysis, Oak Ridges Moraine, southern Ontario; *in* Harris, J., ed., GIS Applications in the Earth Sciences, Geological Association of Canada, Special Paper 5, p.523-545.

Ontario Geological Survey 2003. Surficial geology of southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 128.

Paloschi, G.V.R. 1993. Subsurface stratigraphy of the Waterloo moraine; unpublished MSc Project Report, Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, 153p.

Pullan, S.E. and Hunter 1999. Land-based shallow seismic methods; *in* A Handbook of Geophysical Techniques for Geomorphic and Environmental Research; compiled by R. Gilbert, Geological Survey of Canada, Open File 3731, p.31-55.

Rajakaruna, N. 1994. The Waterloo moraine project phase 1: Subsurface stratigraphy of western Kitchener-Waterloo, Ontario; unpublished MSc Project Report, Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, 135p.

Regional Municipality of Waterloo Internal Report 2000. Flow and capture zone modelling of the River Wells, Kitchener, Ontario; unpublished report, Regional Municipality of Waterloo, 147p.

Ross, L.C. 1986. A Quaternary stratigraphic cross-section through Kitchener–Waterloo; MSc Project Report, Department of Earth Sciences, University of waterloo, Waterloo, Ontario, 55p.

Russell, H.A.J., Sharpe, D.R. and Bajc, A.F. in press. Sedimentary signatures of the Waterloo Moraine: Emerging insights; International Association of Sedimentologists, Special Publication.

Taylor, F.B. 1913. The moraine systems of southwestern Ontario; Transactions of the Canadian Institute, v.10, p.57-79.

White, O.L. and Karrow, P.F. 1996. Urban and engineering geology of the Kitchener–Waterloo area, Ontario; *in* Urban Geology of Canadian Cities, Geological Association of Canada, Special Paper 42, p.261-278.

Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
			LENGTH		
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
			AREA		
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
			VOLUME		
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
			CAPACITY		
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
			MASS		
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton(short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 9**	t
			CONCENTRATION		
1 g/t	0.029 166 6	ounce (troy) / ton (short)	1 ounce (troy) / ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights / ton (short)	1 pennyweight / ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors in **bold** type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.