

Base of Fresh Water, Inferred Bedrock Karst, and the Contact Aquifer in Southern Ontario, as Interpreted from Water Well Records

Ontario Oil, Gas and Salt Resources Library, Open File Data Release 2018-1
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Introduction and Purpose

Water contained in Paleozoic bedrock formations and the overlying unconsolidated sediments (“drift”) in southern Ontario exhibits increasing salinity with depth (Carter et al, 2014). There is a down-dip gradation from fresh water at or near the surface in the drift and shallow bedrock to brackish to saline sulphur water at intermediate depths, to dense brines in the deepest bedrock. Fresh water is confined to glacial sediment and shallow bedrock up to 175 metres below the surface, as determined by this study. Saline and brackish water containing dissolved H₂S occurs at intermediate depths from a few tens of metres to 350 m. below the ground surface. Brine with no dissolved H₂S occurs in bedrock formations at depths >200 to 300 m. (Hobbs et al, 2011, Carter et al, 2014, Carter et al, 2015a, 2015b, Sharpe et al, 2014, Carter and Sullivan, 2018).

The base of the fresh water regime has not previously been mapped at a regional scale in southern Ontario. Base of fresh water maps have many practical uses, including:

- Design of petroleum well drilling and casing programs to protect fresh water aquifers from contamination and prevent migration of subsurface fluids from one horizon to another;
- Technical guidance for regulatory review, by Ministry of Natural Resources and Forestry, of proposed petroleum well drilling and casing programs, in regards to isolation and protection of potable water aquifers;
- Provide guidelines for groundwater resources mapping, exploration and development, including expected limits for drilling depth;
- Constraints on modelling of groundwater flow or contaminant movement;
- More accurate conceptual modelling of groundwater aquifers

In late 2013 a project was initiated by the Ministry of Natural Resources and Forestry (MNRF) and the Oil, Gas and Salt Resources Library to investigate the feasibility of mapping the deepest occurrence of fresh water in southern Ontario using a GIS query of the water well records maintained by the Ontario Ministry of Environment, Conservation and Parks (MECP). The successful results of this project are documented here.

The two resulting maps display: 1. the deepest recorded occurrence of fresh water beneath the top of bedrock and; 2. the deepest recorded occurrence of fresh water beneath the ground surface. The first map produced two additional unanticipated results. It is interpreted by the authors to indicate areas where carbonate or evaporite bedrock has been subjected to karstification, resulting in enhanced porosity and permeability and deeper penetration of fresh meteoric water. Proof of this interpretation requires testing by drilling of new stratigraphic test wells and examination of drill core. This map also shows the regional

distribution of the contact aquifer, a regional fresh water aquifer at the interface between the bedrock and the overlying unconsolidated Quaternary sediments.

The maps are considered by the authors to be accurate representations of the deepest *recorded* occurrence of fresh water in southern Ontario, but only at a regional scale. At the scale of individual counties or townships, further data editing would be required to produce an interpretable result. Time and effort considerations and inherent inaccuracies in the MECP Water Well Information System (WWIS) database create practical limits on the scale at which accurate maps can be constructed. There may be deeper occurrences of fresh water than are indicated on the maps as water well drillers usually stop drilling when sufficient fresh water is encountered to meet the needs of the well owner.

The study illustrates the valuable insights that can be gained, at relatively minor cost in time and resources, from careful GIS analysis of data contained in a provincial well database. This study supplements the detailed investigations by the Ontario Geological Survey directed at mapping groundwater resources in Ontario and 3D modelling of sediments and bedrock (see Easton et al, 2017) and identifies targets for further study.

Open File List

1. **Base_Fresh_Water_report.pdf:** This document contains a brief explanation of the data, the maps, mapping and quality control methods, and a discussion of the results.
2. **Base_Fresh_Water_Below_Ground_Level:** A folder with maps in .jpg format, showing the maximum recorded depth below the ground surface at which fresh water was encountered in water wells in southern Ontario.
3. **Base_Fresh_Water_Below_Top_Bedrock:** A folder with maps in .jpg format, showing the maximum recorded depth, relative to the top of bedrock, at which fresh water was encountered in water wells in southern Ontario.
4. **GIS Maps:** A folder with data used to construct the maps and help simplify usage. The folder contains ESRI Shapefile (.shp), and raster files. Files were created in and compatible with ArcMap 10.1. *This folder is only accessible by members of the Oil, Gas and Salt Resources Library.*

Data Sources

The MECP regulates the drilling of water wells in the province of Ontario and collects and manages data from water wells and their associated groundwater resources. Source records for water wells drilled in Ontario are maintained at the Environmental Monitoring and Reporting Branch of the MECP in Toronto.

Water Well Database

The earliest water well records date back to 1899 (personal communication, Tim Cheng, MECP, July 2014) but organized data collection did not begin until approximately 1935 with the amendment of the Well Drillers Act to include water wells (Revised Statutes of Ontario, 1935). MECP collects and manages data on water wells drilled in Ontario under the authority of the Ontario Water Resources Act and Ontario Regulation 903. Hard copy reports on water wells are submitted by well drillers to the MECP. The reports are scanned and data from the reports is entered into an electronic database known as the Water Well Information System. The WWIS has digital records for nearly 720,000 wells drilled in Ontario (personal communication, Tim Cheng, MECP, July 2014). Geographic coordinates are available for 672,000 of

these wells, with over 400,000 of these in southern Ontario west of Kingston, the area covered by this study.

Water well reporting requires the collection of data concerning well location, sediment or rock type, water quantity and static level, pumping rates, well construction, well depth, depth interval at which water was encountered, water type, and more. The base of the water-bearing interval usually cannot accurately be determined and is rarely reported for individual wells. Most water wells either do not penetrate bedrock or extend only a few metres into bedrock in most parts of southern Ontario and therefore provide very little information about the bedrock geology.

Drillers record a subjective description of the water type for each of the water-bearing intervals they encounter. These water types are essentially identical to the types reported by petroleum well drillers to the Ministry of Natural Resources and Forestry. Water types provide a subjective judgement of water quality and salinity. Water types recorded in WWIS and their descriptions are:

FR – Fresh
GS – Gas (water containing dissolved methane)
IR – Iron
MN – Mineral
OT - Other
SA – Salty
SU – Sulphur (dissolved H₂S, identified by “rotten egg” smell)
UK – Not stated/unknown
UT - Untested

Only wells that encountered water identified as "fresh" by the driller were utilized in this study.

Water well drillers also report the lithology of the geological strata drilled through. There is no standardization of the terminology employed and there is rarely a geologist in attendance during the drilling of water wells, consequently bedrock geological formations are not identified by name. As a result, it is not practical, and usually not possible, to relate the water intervals to the stratigraphy of the Paleozoic bedrock (Armstrong and Carter, 2010, Armstrong and Dodge, 2007, Johnson et al, 1992). Reliable identification of the top of bedrock is also problematic as the drillers did not use consistent terminology to identify when bedrock was encountered.

Data for water wells in southern Ontario is publicly available for viewing at <http://ontariogroundwater.com/> or at <http://www.ontario.ca/data/well-records>. The data used in this study was downloaded by the Oil, Gas and Salt Resources Library in late November, 2013 from a copy of WWIS2 published under an open data licence.

Water Records Quality Assurance

Water interval data were collected by water well drillers with a wide range of skills and experience, under field conditions, and with no standardized data collection protocol. As a result, there are numerous possible sources of error in the WWIS well records. The accuracy of individual records cannot be guaranteed and should be used with caution. Nonetheless, when used as a dataset at a regional mapping scale, the water well records provide valuable information about the occurrence of water in the drift and shallow bedrock of southern Ontario.

A number of quality assurance issues were identified during review of the data. Corrective edits were applied to several thousand records where it was possible to reliably identify a resolution. If a corrective edit could not be determined, the unreliable records were omitted from the mapping process.

An iterative process of quality assurance edits was performed. After completion of each round of edits, preliminary versions of the maps were interpolated. All *anomalies* represented by single wells on these maps were reviewed and corrective edits applied. The maps were then regenerated for a further round of anomaly checks and corrective edits.

Data quality issues are listed below.

1. Incomplete reporting. There is no corrective fix for this issue.
2. Inaccurate well location.
3. Typographic data entry errors. These were identified by comparison with source records and corrected during the anomaly editing exercise.
4. Incorrect or misleading use of bedrock lithology descriptions by drillers, resulting in incorrect interpolations of top of bedrock. All anomalous values were checked by review and verification of individual water well records in original documents.
5. Null values in the numerical data in shapefile .dbf files are represented as zeroes. Users should exercise caution in utilizing the .dbf files where data values are zero when the actual value should be null.
6. The most significant source of error, for the purpose of this study, was incorrect units of measure recorded for data values in individual water well records. In addition, many water well records were identified to have different units of measure recorded for different attributes of the same well. If original measurements were in feet but were erroneously recorded as metres in the database, the resulting depths would be approximately 3.28x greater than the actual value.
7. Errors in the Gao et al (2006) drift thickness map used to extract raster drift thickness values in the data editing process for this study.

Mapping Methods

Creating a geologically reasonable map from the WWIS is dependent on the design of GIS data filters to derive a subset of wells with the required data attributes, and a laborious process of quality assurance editing of this new dataset. For this mapping exercise, the data editing procedure was designed to focus on the deepest reported occurrences of fresh water. The largest single source of error in this regard was erroneous entry of data values in the WWIS database with respect to unit of measure (feet vs. metres).

Inaccurate well locations are a significant source of error in WWIS. In this study, wells that plotted in offshore locations within the Great Lakes and other waterbodies were assumed to be incorrect and the well records were deleted. A number of records had plotted locations outside the boundaries of Ontario due to transposition of the latitude and longitude values, ie. the latitude was recorded as longitude or vice versa. These locations were fixed by switching the values. All remaining wells plotting outside the boundaries of Ontario were removed. Matching of well locations to the township, lot and concession recorded in WWIS was found to be problematic due to inconsistencies in the survey fabric of the digital base map compared to the values recorded in WWIS. Remaining well location errors were identified indirectly during the mapping and data editing process described below. Correction of erroneous/inaccurate well locations was considered to be impractical.

Many wells encountered water at several different depth intervals. Drillers report the type of water encountered and the depth interval below ground level. For each well record, the deepest interval for which the driller recorded "fresh" as the water type was selected for mapping.

Several trial contour maps were prepared after the initial filtering exercises. Anomalous data were identified by visually reviewing the maps and editing or deleting the individual records contributing to contouring anomalies. The data quality was judged to be acceptable when the resulting maps produced geologically reasonable results, corresponding to known geological features, at the regional scale of interest in this study. The data set would require additional editing for use at local scales.

The occurrence of fresh water in the bedrock is the primary focus of the study. Two subsets of the water well data were created: one with data for wells drilled into bedrock; and one for wells that did not penetrate bedrock. The data sets were queried and edited separately. The data for the bedrock wells was utilized to produce a map showing the deepest recorded occurrence of fresh water below the top of the bedrock. The two edited data sets were then combined to produce a map showing the deepest occurrence of fresh water relative to the ground surface.

Three data interpolation algorithms are supplied with the 3D Analyst extension of ArcMap 10.1; inverse distance weighted, kriging and natural neighbours. After trial and error, it was determined that the natural neighbours algorithm produced the most geologically meaningful results and was therefore used to create interpolated surface and contour maps of both sets of edited data.

Base of Fresh Water Below Top of Bedrock

In order to construct this map, it was first necessary to identify wells that were drilled deep enough to encounter bedrock. To do this, the lithology descriptions used by the driller and the lithology codes recorded in WWIS were interpreted to correctly identify when the well had encountered bedrock. Numerous wells had non-bedrock codes recorded at depths below bedrock codes. These records were inferred to be unreliable and were deleted. Reiterative generation and review of trial maps eventually resulted in a dataset with only the wells which were drilled into and below the inferred top of bedrock. From this exercise, it was determined that 160,393 water wells penetrate the bedrock in southern Ontario.

A simple algorithm to select the maximum depth of the reported fresh water interval below the top of bedrock for each well was executed, and the result was saved in the project database.

Gao et al (2006) created a raster drift thickness map for all of southern Ontario using a GIS query and an iterative data editing process. ArcMap Spatial Analyst was used in the present study to extract raster drift thickness values from the Gao et al map at the locations of the 160,393 water wells which penetrate bedrock. The resulting values were saved as attributes in a new shapefile data table. These drift thickness values were then compared to the depth-to-bedrock values recorded in WWIS for the same wells and a ratio of WWIS bedrock top depth/raster drift thickness was calculated. For statistical purposes only, well records with ratios >10 or with null raster values (due to gaps in the raster surface), were deleted, leaving 135,484 records. The frequency distribution of these records has a mean value of 1.19 with a standard deviation of 0.99, and a weak secondary peak of 3.27. This secondary peak exceeds the mean by greater than twice the standard deviation and is almost exactly the value expected for a unit of measure error caused by recording depth measurements reported in feet as measurements in metres.

A statistical plot of the data distribution for the deepest recorded fresh water interval in the full corrected dataset had a mean value of 30.9 metres with a standard deviation of 21.3 metres. 1751 records had values more than 3x the standard deviation (95 metres). 198 of these records had a ratio of bedrock top depth/raster drift thickness >2.18 (one standard deviation $>$ mean). These data values were considered to be suspect and were removed from the database.

A trial interpolated surface and contour map created from this dataset had a large number of anomalies defined by either a single data point or a very small number (<5) of clustered data points. Over a period of several weeks, all of the WWIS well records corresponding to the most significant anomalies were reviewed by comparison to the WWIS source records to verify the accuracy of the data. Several hundred records were edited or not utilized, resulting in a dataset containing 131,353 records of *acceptable* data quality. This data was used to create the final interpolated raster map included in this report (Fig.1). The deepest fresh water intervals are up to 130 metres below the top of bedrock.

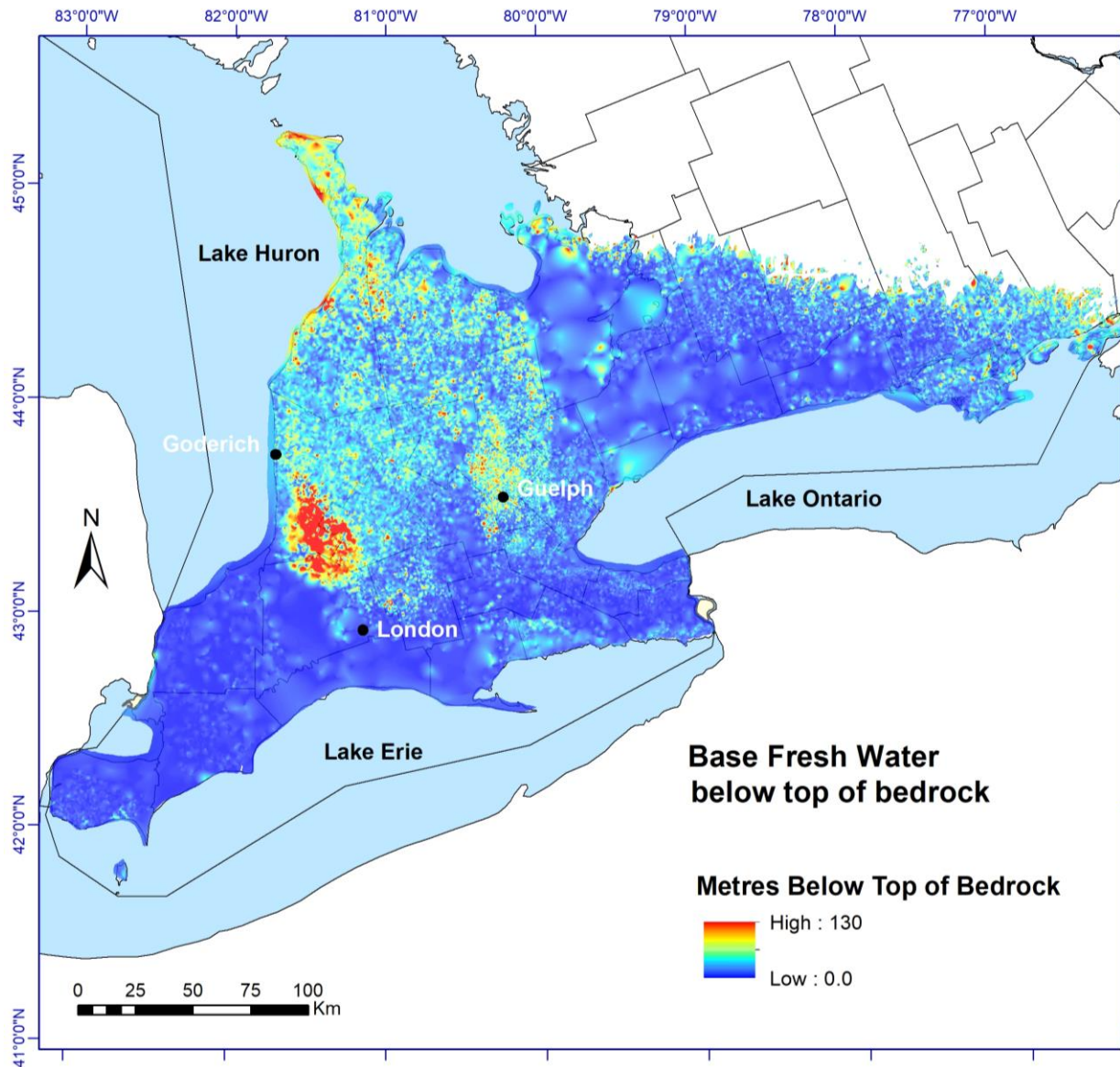


Figure 1. Base of fresh water in southern Ontario, measured as depth below the bedrock surface. Areas where no fresh water is recorded below the top of the bedrock (dark blue) correspond to the contact aquifer. Areas in red and yellow are interpreted to indicate the presence of shallow karst zones in carbonate bedrock. The large area of anomalously deep fresh water between London and Goderich correlates with the breathing well karst aquifer documented by Brunton and Dodge (2008), Hurley et al (2008), and Freckelton (2013).

Base of Fresh Water Below Ground Level

The water well records for wells that do not penetrate the bedrock were edited separately from the bedrock wells. Similarly to the bedrock wells, a drift thickness raster value at the location of each well was extracted from the Gao et al (2006) drift thickness map. The resulting values were saved in a new shapefile data table. These drift thickness values were then compared to the deepest occurrence of fresh water recorded in WWIS for the corresponding well. If the depth of the deepest recorded fresh water interval > raster drift thickness, the well record was deleted from the data set.

The resulting data set was combined with the 131,353 verified and corrected well records used to create the *Base of Fresh Water Below the Top of Bedrock* map. An interpolated raster surface was created from the combined dataset using the natural neighbours algorithm in ArcGIS® 3D Analyst extension. A further review of anomalies and final edits to the well records was subsequently completed resulting in removal of some records and more accurate results. Figure 2 displays the final map of the depth below the ground surface, in metres, at which fresh water is reported in water wells in southern Ontario. The deepest reported occurrence of fresh water is approximately 175 metres below ground level. This is similar to values determined by Sharpe et al (2014) using petroleum well records.

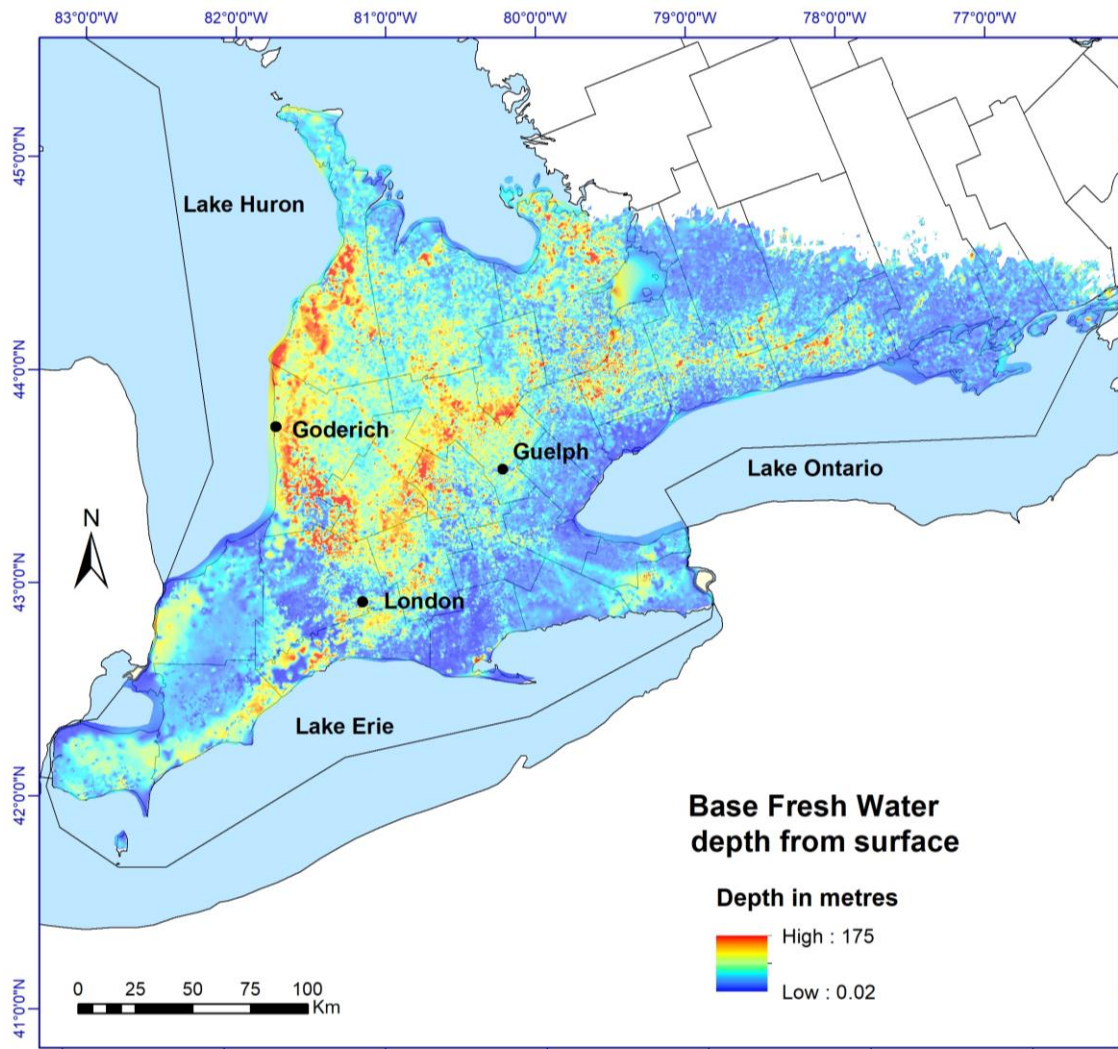


Figure 2. Base of fresh water in southern Ontario measured as metres below the ground surface.

Discussion and Interpretation

It is well known in the Ontario water well drilling industry that usable quantities of fresh water are generally encountered at relatively shallow depths (< 100 metres) in the subsurface of southern Ontario, and if wells are drilled too deep they encounter sulphurous and salty water (Singer et al, 2003, Sharp et al, 2014). Water well drillers usually stop drilling when sufficient fresh water is encountered to meet the needs of the well owner. This avoids the risk of encountering salty and sulphurous water and reduces the cost of the well. Consequently, there may be deeper occurrences of fresh water than are indicated in water well records and in this study.

The two maps in this report provide fundamental information on the *reported* stratigraphic and geographic extent of fresh water in the shallow groundwater regime of southern Ontario, as recorded by water wells. The depth to the base of fresh water varies considerably.

The unconsolidated Quaternary and Recent sediments (drift) that overlie bedrock in southern Ontario are variably porous and permeable and water-saturated and are utilized as a source of potable water by most of the water wells drilled in southwestern Ontario (Singer et al, 2003; Sharpe et al, 2014). Sediment types include sand, clay, till and gravel. Aquifers are complex and discontinuous.

The contact with the underlying bedrock is a low-relief angular unconformity resulting from subaerial exposure and erosion of the slightly inclined Paleozoic strata over an extended period of geologic time. The uppermost few metres of bedrock is often porous due to a combination of weathering and the ubiquitous occurrence of joints. The fresh water-dominated drift is generally much more porous and permeable than the underlying sedimentary bedrock, although exceptions occur where the underlying bedrock is karstic or where the basal drift is comprised of dense clay-rich till. The uppermost few metres of bedrock together with the overlying few metres of sediment form an aquifer of regional extent. This “contact aquifer” is the most widespread potable water aquifer in southern Ontario (Husain et al, 1998, 2004; Brunton 2009a, 2009b; Carter, 2012; Sharpe et al, 2014) (see Fig.4).

Figure 1 indicates large parts of southern Ontario with no fresh water below the top of bedrock. This area is interpreted to represent the extent of the contact aquifer. East of the Niagara Escarpment the contact aquifer is nearly continuous, east from the escarpment to the contact with the Precambrian rocks of the Canadian Shield. This area is underlain by thick impermeable shales of the Queenston, Georgian Bay and Blue Mountain formations, and by dense limestones of the Trenton and Black River groups. West of the Niagara Escarpment the contact aquifer occurs in areas underlain by the shale-dominated Kettle Point Formation and the Hamilton Group, and in areas underlain by the Dundee Formation south and southwest of London. The contact aquifer is also generally continuous in areas underlain by the Salina Group beneath the counties of Brant, Haldimand and Welland (see Fig.3).

Recent and continuing studies by the Ontario Geological Survey clearly indicate the importance of karst in controlling the occurrence and flow of groundwater in the bedrock. Extensive karstic dissolution has occurred in areas where carbonate bedrock is exposed at the surface or is covered with thin overburden (Brunton and Dodge 2008; Brunton 2009a, 2009b; Brunton and Brintnell, 2011; Brunton, Priebe and Yeung 2016; Golder Associates and Ontario Geological Survey, 2008) resulting in greatly enhanced porosity and permeability. Where the karst is well-developed it can form localized aquifers of potable water that extend below the drift/bedrock contact. In this study, fresh water occurs up to 130 metres below the top of the bedrock within areas of inferred karst (see Figure 1).

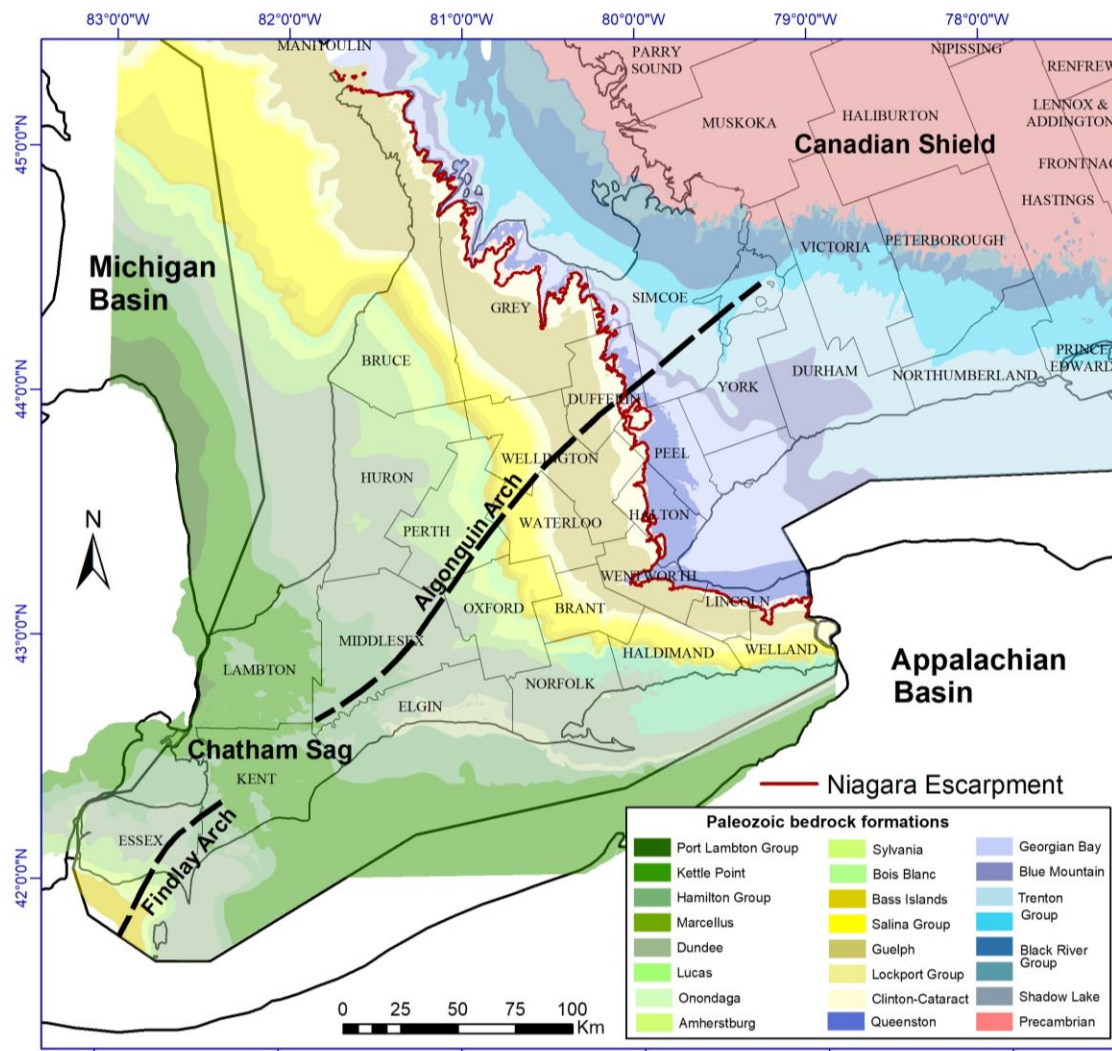


Figure 3. Paleozoic bedrock geology of southern Ontario, from Somers and Fortner (2017), shown relative to the administrative boundaries of regional municipalities and/or counties.

The most prominent and deepest known occurrence of fresh water in karstic bedrock occurs between London and Goderich and is known as the “breathing well zone” (Brunton and Dodge, 2008; Freckelton, 2013). The breathing well zone is a karstic aquifer in the limestone and dolostone bedrock of the Dundee and Lucas formations (Fig.5). Karrow (1977) was the first to document sinkholes in the thin drift overlying limestones of the lower Dundee Formation in this area. Subsequent studies have provided a better understanding of the extent and geological relationships of this large karst feature (Merry et al, 2004; Brunton and Dodge, 2008; Hurley et al, 2008; Freckelton, 2013)

A second prominent zone of deep fresh water in the bedrock is centred on the city of Guelph. It represents an area of karstic dolostone in the Lockport Group which forms the principal source of fresh water for the city (Brunton et al, 2007; Perrin et al, 2011). Exposed dolostone bedrock of the Lockport Group in the Bruce Peninsula also exhibits karstification at the surface with deep penetration of fresh water. The intervening area between Guelph and the Bruce Peninsula, underlain by the Lockport Group, is the subject of on-going long-term groundwater studies by the Ontario Geological Survey (e.g. Brunton and Brintnell, in progress; Priebe et al, 2017).

Recent work by Hamilton et al (2017) utilized dissolved O₂ and CO₂ in groundwater to infer the presence of buried karst in the shallow bedrock of southern Ontario. The present study has identified known areas of karst not identified in that study but noted by Brunton and Dodge (2008). The two methods are complementary, and a combination of the two methods may provide the best regional-scale mapping of buried karst in southern Ontario to supplement field mapping of karst in outcropping bedrock.

The maximum recorded depth to the base of fresh water in southern Ontario relative to the surface, as determined in this study, is 175 metres (Fig.2). Petroleum well records record the occurrence of fresh water at a maximum depth of 250 metres below ground level, but depths of greater than 200 metres are very rare (Sharpe et al, 2014). The deepest occurrences of fresh water in Figure 2 are in unconsolidated sediments, corresponding to areas with the greatest thickness of sediments (Fig.6). Sediment thickness ranges from zero to more than 200 metres in southern Ontario, averaging a few tens of metres (Gao et al, 2006). The areas of thickest drift correspond to glacial landforms such as kames and moraines or to the location of buried valleys eroded into the bedrock surface.

The fresh water regime in the shallow bedrock is the subject of ongoing investigations by the Ontario Geological Survey (OGS) as part of its groundwater mapping program (Brunton, 2009a, 2009b; Brunton, Priebe and Yeung 2016; Brunton and Brintnell, 2017; Priebe and Brunton, 2016; Priebe et al, 2017). Improved understanding of karstic flow systems in shallow bedrock has recently been utilized to identify a new, deeper supply of potable water for the Town of Shelburne (Banks and Brunton, 2017). The Ontario Geological Survey also has an on-going program of groundwater studies in the unconsolidated sediments involving a number of geoscientists (e.g. Bajc and Shirota, 2007).

The present study is a supplement to the ongoing work of the Ontario Geological Survey, and others, to map the groundwater resources of Ontario, and has contributed to a better understanding of the occurrence of fresh groundwater in the sediments and bedrock of southern Ontario. The study illustrates the valuable insights that can be gained, at relatively minor cost in time and resources, from careful GIS analysis of data contained in a provincial well database.

Acknowledgements

Many past and present staff members of the MECP have contributed to the collection and management of water well data. In addition, the cooperation of water well drillers in this data sharing process has been fundamental to its success.

Most of this work was completed while the principal author was employed as Chief Geologist of the Ministry of Natural Resources and Forestry. This report was reviewed by Lee Fortner and Arthur Castillo of MNRF and Frank Brunton of the Ontario Geological Survey. Their comments and suggestions have been incorporated in the report and are gratefully acknowledged. Lively discussions and ongoing collaboration with Frank Brunton have been particularly useful to the first author in staying up to date on new geological insights and discoveries about the bedrock geology of southern Ontario, the occurrence and extent of karst in the bedrock, and karstic controls on the occurrence of water in the near-surface Paleozoic bedrock formations of southern Ontario.

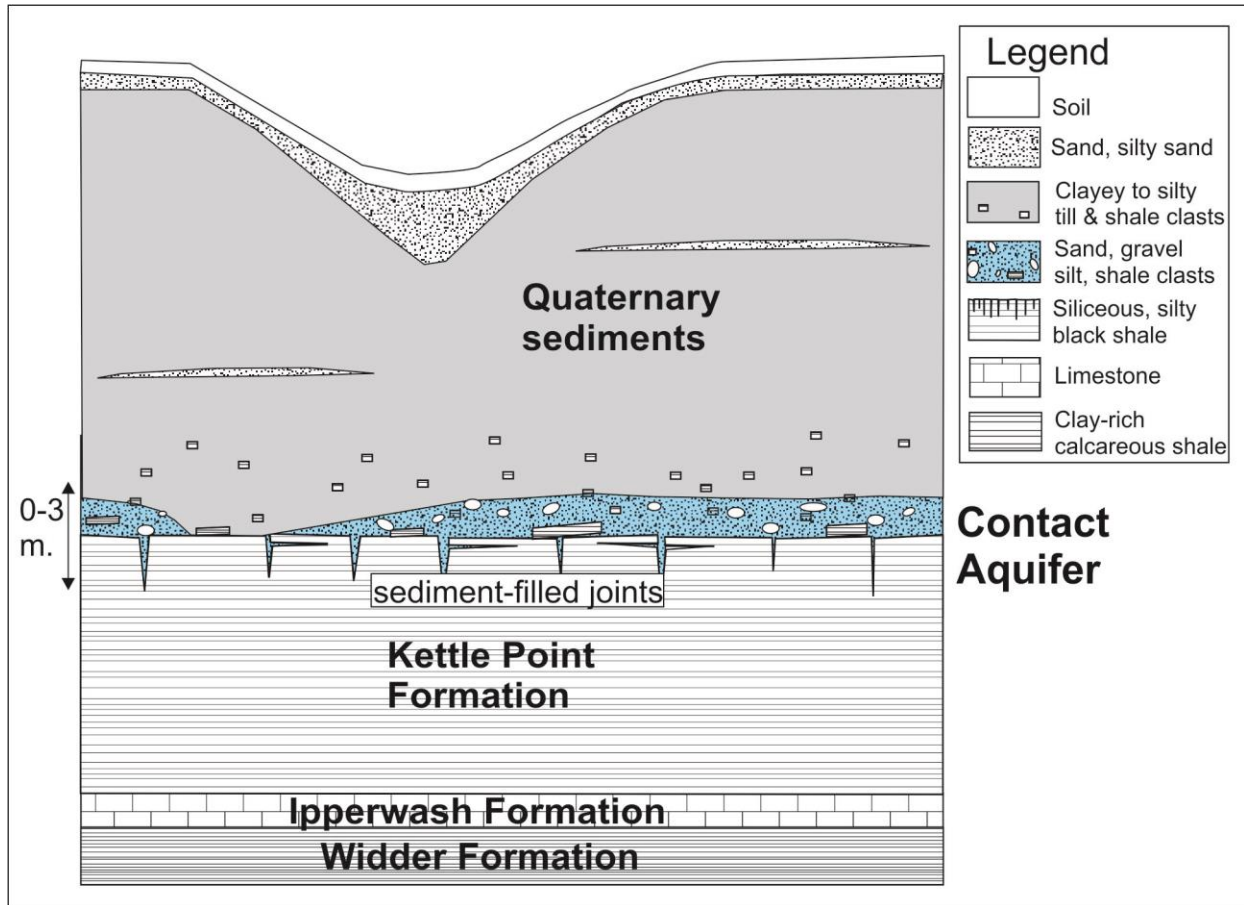
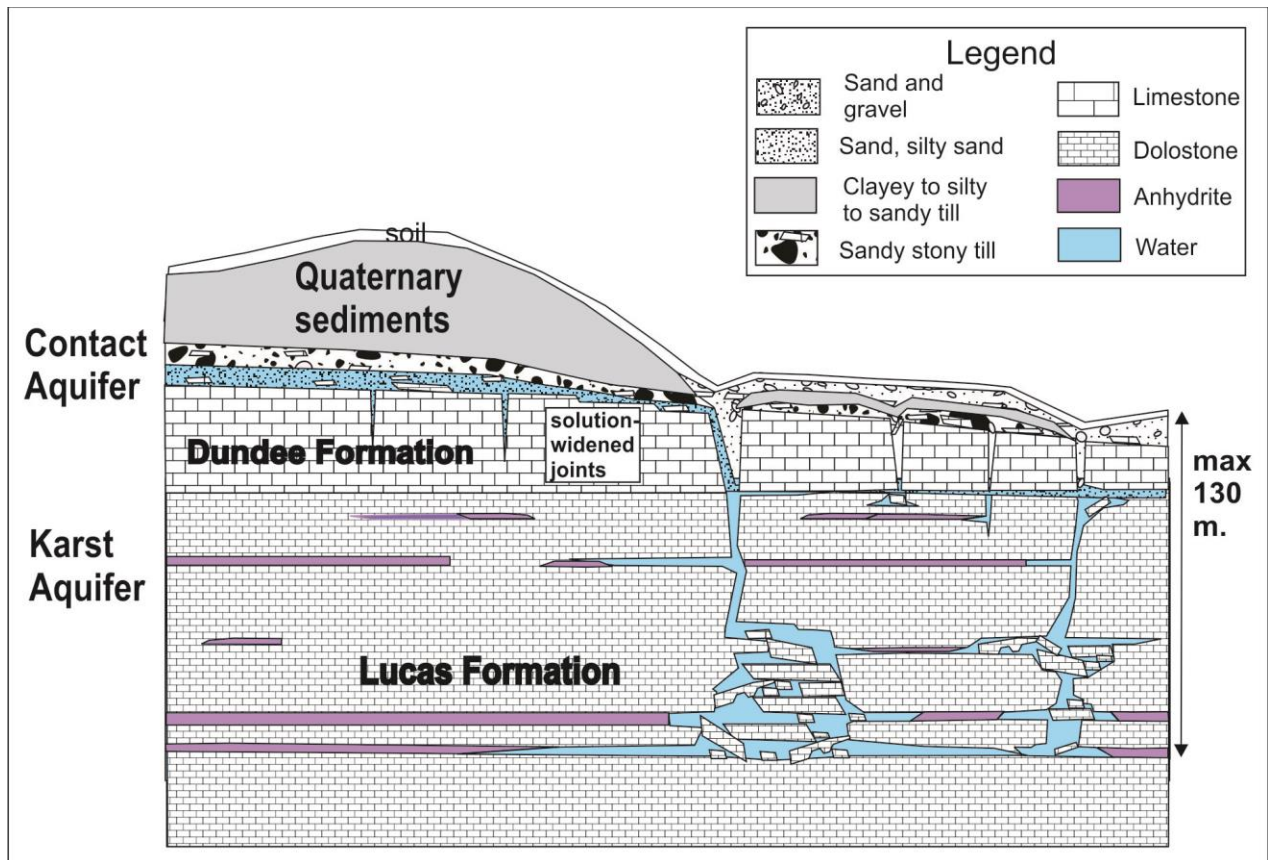


Figure 4. Conceptual model of the contact aquifer in the Lambton County area southwest of London.



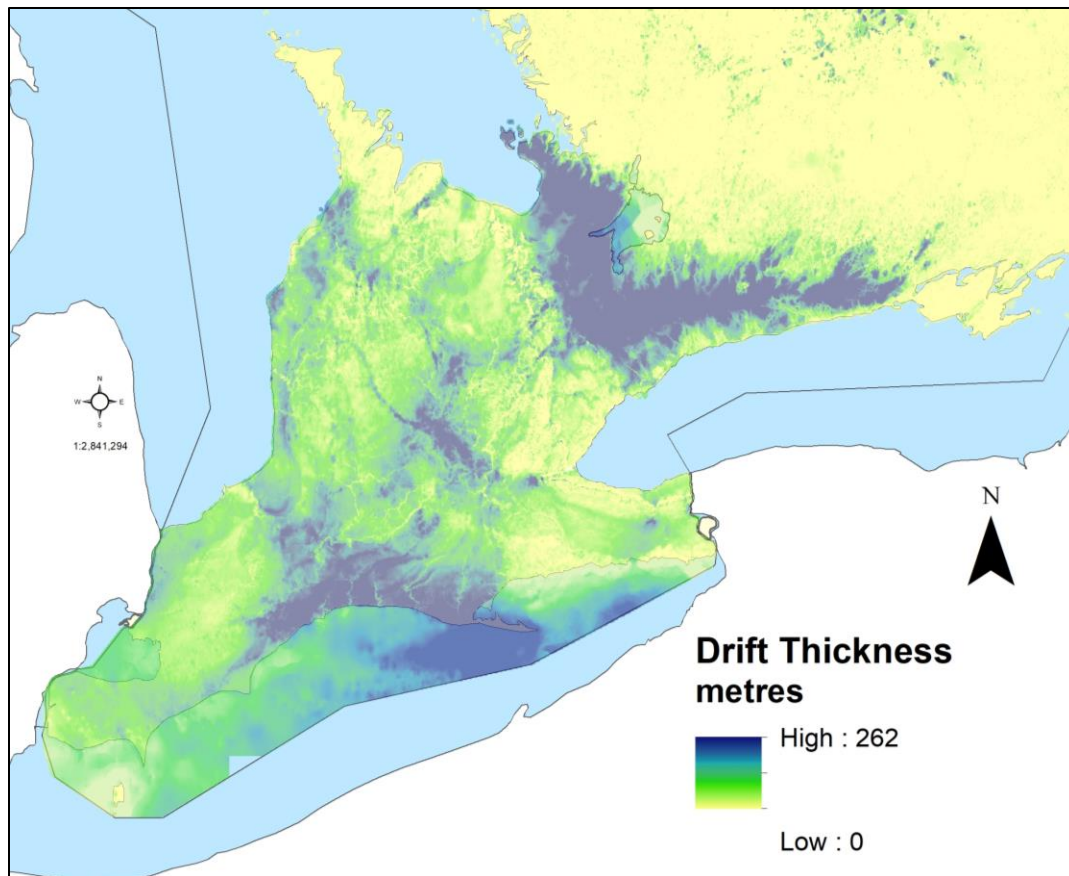


Figure 6. Drift thickness in southern Ontario, adapted from Gao et al (2006.)

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