Natural Resources Canada | Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8927

A three-dimensional bedrock hydrostratigraphic model of southern Ontario

T.R. Carter, C.E Logan, J.K. Clark, H.A.J. Russell, E.H. Priebe, and S. Sun

2022

Canada

ISSN 2816-7155
ISBN 978-0-660-46068-0
Catalogue No. M183-2/8927E-PDF

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8927

A three-dimensional bedrock hydrostratigraphic model of southern Ontario

T.R. Carter[1], C.E. Logan[2], J.K. Clark[3], H.A.J. Russell[2], E.H. Priebe[4], and S. Sun[5]

[1]Carter Geologic, 35 Parks Edge Crescent, London, Ontario
[2]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario
[3]Oil, Gas and Salt Resources Library, 669 Exeter Road, London, Ontario
[4]Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario
[5]University of Western Ontario, 1151 Richmond Street, London, Ontario

2022

Permanent link: https://doi.org/10.4095/331098

This publication is available for free download through GEOSCAN (https://geoscan.nrcan.gc.ca/).

Recommended citation
Carter, T.R., Logan, C.E., Clark, J.K., Russell, H.A.J., Priebe, E.H., and Sun, S., 2022. A three-dimensional bedrock hydrostratigraphic model of southern Ontario; Geological Survey of Canada, Open File 8927, 1 .zip file. https://doi.org/10.4095/331098

Publications in the GSC OF series have not been edited; they are released as submitted by the author.

Contents

Figures

Tables

Abstract

A hydrostratigraphic framework has been developed for southern Ontario consisting of 15 hydrostratigraphic units and 3 regional hydrochemical regimes. Using this framework, the 54 layer 3-D lithostratigraphic model has been converted into a 15 layer 3-D hydrostratigraphic model. Layers are expressed as either aquifer or aquitard based principally on hydrogeologic characteristics, in particular the permeability and the occurrence/absence of groundwater when intersected by a water well or petroleum well. Hydrostratigraphic aquifer units are sub-divided into up to three distinct hydrochemical regimes: brines (deep), brackish-saline sulphur water (intermediate), and fresh (shallow). The hydrostratigraphic unit assignment provides a standard nomenclature and definition for regional flow modelling of potable water and deeper fluids. Included in the model are: 1) 3-D hydrostratigraphic units, 2) 3-D hydrochemical fluid zones within aquifers, 3) 3-D representations of oil and natural gas reservoirs which form an integral part of the intermediate to deep groundwater regimes, 4) 3-D fluid level surfaces for deep Cambrian brines, for brines and fresh to sulphurous groundwater in the Guelph Aquifer, and the fresh to sulphurous groundwater of the Bass Islands Aquifer and Lucas-Dundee Aquifer, 5) inferred shallow karst, 6) base of fresh water, 7) Lockport Group TDS, and 8) the 3-D lithostratigraphy. The 3-D hydrostratigraphic model is derived from the lithostratigraphic layers of the published 3-D geological model. It is constructed using Leapfrog Works at 400 m grid scale and is distributed in a proprietary format with free viewer software as well as industry standard formats.

This page left blank intentionally

Introduction

In 2019, the Geological Survey of Canada (GSC), Ontario Geological Survey (OGS), and the Oil, Gas and Salt Resources Library (OGRSL) initiated a 3-year project to: i) develop version 2 of the 3-D geological model of southern Ontario, and ii) develop a 3-D hydrostratigraphic model for southern Ontario. The revised 3-D geological model (Carter et al. 2021b) and a hydrogeological framework for the Paleozoic bedrock of southern Ontario (Carter et al. 2021a) were both published in 2021. The project is part of an initiative by the GSC and OGS to advance knowledge of a regional geoscience framework and groundwater systems in southern Ontario. This report describes and discusses development of the 3-D hydrostratigraphic model.

The lithostratigraphic layers of the geological model (hereafter referred to as the lithostratigraphic model) provide the necessary foundation and geological context for the hydrostratigraphic model, such as geological formations, regional structure, bedrock topography, land surface topography, and geographic elements. Within this framework it has been possible to display the wealth of data available in provincial wells databases as discreet occurrences of groundwater and hydrocarbons in the bedrock of southern Ontario which were previously only viewed as 2-D interpolated surfaces. This is the first opportunity to view this data at a regional scale in three dimensions and it is hoped it will result in new insights into hydrochemical zonation of groundwater, potential pathways of fluid movement, interaction of deep, intermediate and shallow groundwater systems, development of the porosity and permeability networks that connect these fluids and help direct future research initiatives.

Bedrock formations are important sources of potable groundwater at shallow depths. At intermediate to deep depths these aquifers are used for disposal of saline oilfield water produced as a by-product of petroleum production operations and have been used in the past for disposal of liquid industrial wastes. Some deep brine aquifers are utilized as a source of brine for winter ice control on provincial highways. There is potential for CO_2 sequestration in some deep brine aquifers within the bedrock (Shafeen et al. 2004; Carter et al. 2007; Waterloo Institute for Sustainable Energy 2021) and hydrogen storage in bedded salt formations (Lemieux et al. 2019; Muhammed et al. 2022). Hydrochemical and isotopic zonation of groundwater also provides data on the origin of the water, its residence time in the subsurface, and history of movement. These factors provide important supporting scientific knowledge to develop a safety case for deep disposal and long-term isolation of industrial wastes, including nuclear wastes.

Three-dimensional models estimate the geometry of buried geological formations, structural features, and hydrogeological features based on interpolation of discreet geological measurements. These data can be surveyed/observed geological contacts and structural measurements at surface, observations of groundwater seeps in quarries or artesian flow from confined aquifers at springs or up unplugged wellbores, and/or subsurface data from boreholes and geophysical surveys. These models provide a powerful visualization tool for improving our understanding of the bedrock geology and hydrogeology which supports and enhances management of groundwater resources for agricultural, industrial, municipal and domestic supply. 3-D models are also excellent tools for illustration of geological and hydrogeological concepts for outreach to the general public, and for training of the next generation of earth scientists and engineers at universities and colleges (e.g., Johnson et al. 2020; Russell et al 2022) as described below.

Model accuracy relies primarily on the accuracy and coverage of the available data in three dimensions, and consistent application of quality assurance standards. Consequently, project resources were focussed on compiling and verifying existing data, identifying data gaps, anomalies, and outliers, and the addition of new data and/or data enhancements created by project contributors. Interpretation of model layers is augmented and enhanced with expert knowledge where primary data are sparse or lacking. The process of constructing the model has also revealed shortcomings in our knowledge and understanding of the bedrock hydrogeology, and related gaps in the data that hinder that understanding.

Project Area

The project area is the same as the 3-D lithostratigraphic model area (Carter et al. 2019, 2021b), encompassing all the contiguous Paleozoic sedimentary rocks underlying southern Ontario west of the Frontenac Arch and south of the Precambrian Canadian Shield. The 109 800 km^2 area extends beneath the waters of the Great Lakes (Huron, Erie, Ontario) to the international boundary with the United States, and to the subcrop map extent of these strata beneath the waters of Georgian Bay (Figure 1).

Stratigraphically, the project encompasses the complete Paleozoic sedimentary succession and includes the interface with the Precambrian crystalline basement rocks of the Canadian Shield (Figure 1). Above the erosional surface of the Paleozoic bedrock, the unconsolidated surficial sediments are included in the model as a single layer. The modelled volume consists of 15 modelled hydrostratigraphic units (HSUs). The basal boundary of the model is set to an arbitrary elevation of -2000 m asl within the Precambrian, identical to the geological models. A 3-D model of the surficial sediments is in development (Logan et al. 2020).

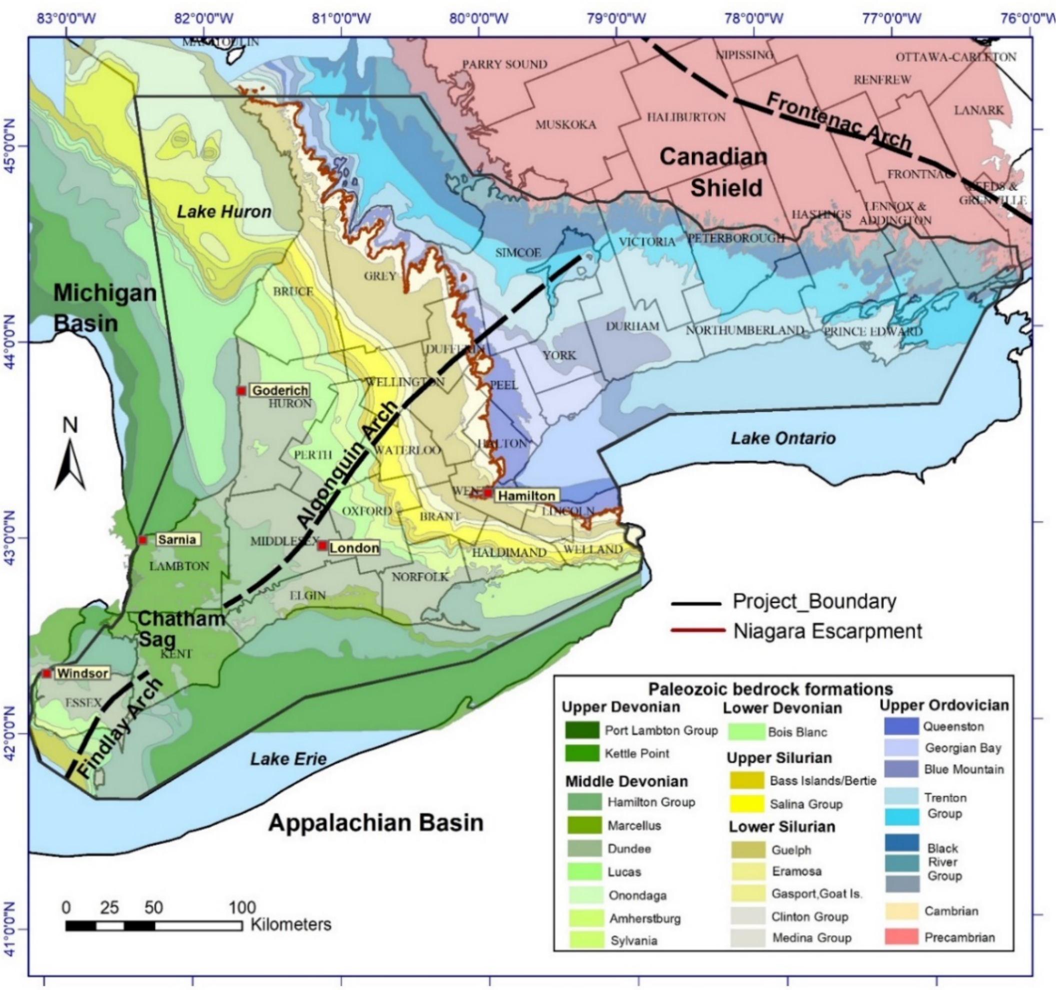


Figure 1. Simplified bedrock geology and project boundary adapted from Carter et al. (2019).

Geological and Hydrogeological Setting of Southern Ontario

The following description of the regional geology and hydrogeology is summarized from Carter et al. (2019) and Carter et al (2021a), with updated citations and an updated version of Figure 2. The reader is referred to Armstrong and Carter (2010) for more detailed descriptions of Paleozoic bedrock formations.

South of the exposed Canadian Shield, southern Ontario bedrock comprises Paleozoic marine sedimentary rocks of the northern Appalachian foreland basin and eastern Michigan structural basin (e.g., Brunton et al. 2012), which straddle a broad northeast-oriented Precambrian basement structural high, referred to as the Algonquin Arch and its southwestern extension, the Findlay Arch. The Paleozoic sedimentary strata unconformably overlie the crystalline metamorphic, igneous and metasedimentary rocks of the Precambrian basement, all of which are largely covered by a veneer (of variable thickness) of unconsolidated and largely glacially derived surficial sediments up to 260 metres thick. Bedrock strata consist of an interlayered succession of carbonates, evaporites, shales, sandstones and siltstones. The bedrock formations dip to the southwest at 3 to 6 m/km along the crest of the Algonquin Arch and northeast along the crest of the Findlay Arch, into a structural low, the Chatham Sag, and at 3 to 12 m/km down the flanks of the arches westward into the Michigan structural basin and southward into the Appalachian foreland basin (Armstrong and Carter 2010; Figure 1).

The Niagara Escarpment is the highest topographic landform in the study area and forms a natural hydrological and hydrogeological divide for surface water and groundwater. Paleozoic strata are much thicker to the west of the Niagara Escarpment, ranging from 540 m to nearly 1400 m in the Chatham Sag, and 1600 m at the international border beneath Lake Huron. Strata range in age from late Cambrian to late Devonian and possibly early Mississippian (Armstrong and Carter 2010; Carter et al. 2017; Figures 1 and 2). To the east of the Niagara Escarpment, Paleozoic strata within the study area are largely late Ordovician in age because of the erosional removal of all younger sedimentary rocks. Maximum thickness of Paleozoic strata to the north and east of the Niagara Escarpment is 650 m at the Niagara River and 250 m on the south shore of Georgian Bay, thinning northeasterly to zero at the erosional edge in eastern Ontario (Armstrong and Carter 2010).

The bedrock surface is a low-relief angular unconformity resulting from chemical and physical erosion of the shallowly dipping Paleozoic strata over a period of subaerial exposure spanning up to 250 million years (Johnson et al. 1992). This surface is an important hydrogeological feature, forming the recharge area where variably karstic and shallowly dipping permeable sedimentary bedrock is exposed to infiltration of meteoric water at surface, as well as the interface with fresh water-dominated unconsolidated surficial sediment. This contact, or interface aquifer zone, is the most widespread potable water aquifer in southern Ontario (Husain et al. 2004; Brunton 2009a, 2009b; Carter 2012; Carter et al 2021a).

Extensive karstic dissolution has occurred prior to and following the Holocene glacial retreat in areas of thin surficial sediments where carbonate rocks form the uppermost bedrock layer (Brunton 2013; Brunton and Dodge 2008; Brunton et al. 2016). These karstic strata form a complex system of enhanced porosity and permeability, which locally to sub-regionally contain potable water up to 250 m below the surface. These karstic strata and the shallow fresh water system are the subject of ongoing investigations by the OGS (Brunton et al. 2016, 2017; Brunton and Brintnell 2020; Priebe et al. 2014, 2017; Priebe and Brunton 2016; Priebe et al. 2019; Priebe et al. 2021).

In areas of thicker surficial sediment and areas of subcropping shale, wells that penetrate the bedrock more than a few metres encounter groundwater that is brackish to saline and locally sulphurous. Mapping and conceptual modelling of deep groundwater using petroleum well data and geochemical and isotopic analyses have documented an intermediate to deep system of thick regional aquitards and thin confined aquifers containing brackish to highly saline water within the bedrock (Figure 2) (Nuclear Waste Management Organization 2011; Hobbs et al. 2011; Carter 2012; Carter and Fortner 2012; Carter et al. 2014, 2016, 2021a; Sharpe et al. 2014; Skuce 2015; Skuce et al. 2015; Skuce, Potter and Longstaffe 2015). Brackish to moderately saline water containing dissolved H_2S and elevated levels of dissolved sulphate occurs at intermediate depths, from as shallow as 30 m to 350 m. Isotopic ratios of oxygen and hydrogen in sulphur water are typical of either modern precipitation or cold-climate signatures typical of an origin as glacial meltwater (Skuce 2014; Skuce et al. 2015a, b; Carter et al 2021a). Downdip from the sulphur water regime is a deep brine regime with no dissolved H_2S and stable isotopic ratios typical of sedimentary basin brines formed by evaporative concentration of seawater (McNutt et al 1987; Dollar 1988; Dollar et al 1991; Skuce 2014; Skuce et al 2015a; Carter et al 2021a).

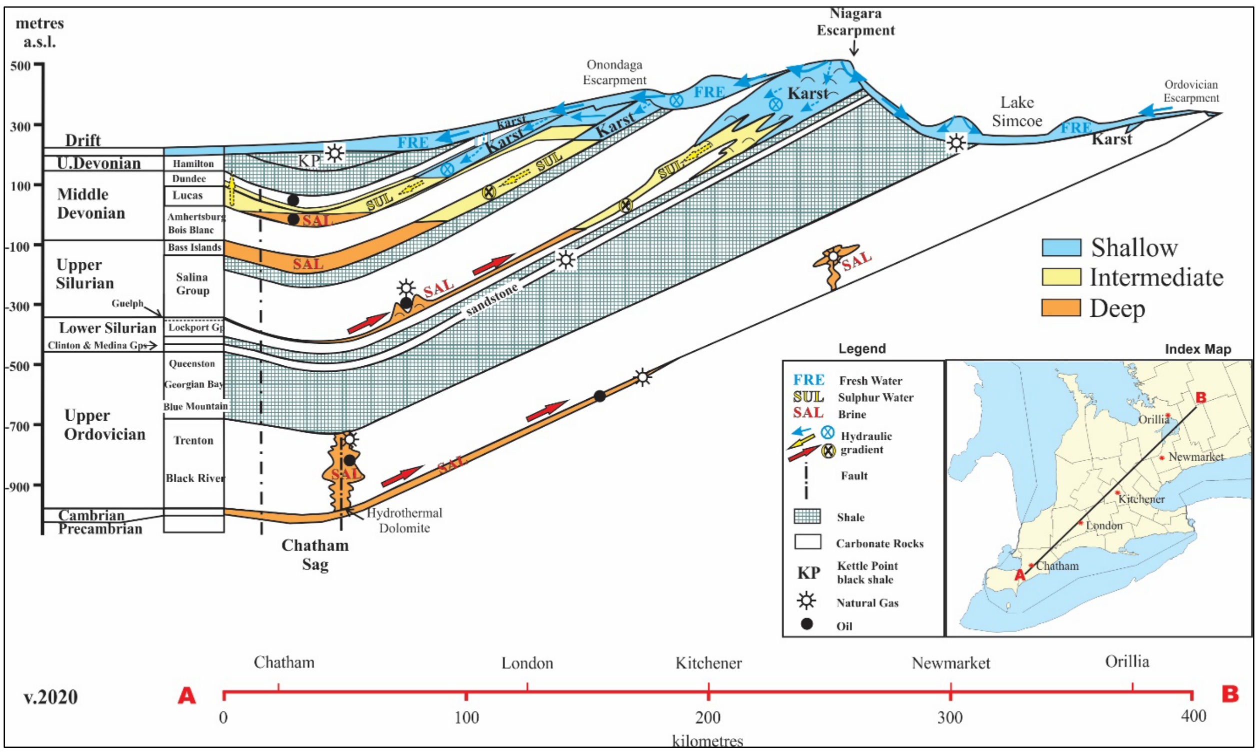


Figure 2. Conceptual model of regional hydrochemical groundwater regimes in the bedrock of southern Ontario. Updated from Carter et al. (2019, 2021a) and Sharpe et al. (2014). In the intermediate to deep subsurface the shales and carbonates both act as aquitards.

Data Sources

Many of the principal data sets are the same as Carter et al. (2021b) (Table 1). Water interval records recorded in the Ontario Petroleum Data System (OPDS) are the primary data source for the intermediate to deep groundwater regimes, and water well records of the Water Well Information System (WWIS) for the shallow regime, supplemented by other data sources and by previous studies. Model bedrock layers from Carter et al. (2021b) were used as the basis of the modelling process.

Table 1. Data sources for hydrostratigraphic modelling.

Data Set	Description/Source	Application
Water interval data	OPDS - 16 000 petroleum well records with 35 000 reported water intervals including water type and static level	Primary data for model layer assignments, static level interpolated surfaces, hydrochemical zonation by depth
Oil interval data	OPDS – 6000 records	Fluid zonation, porous strata
Gas interval data	OPDS – 26 000 records	Fluid zonation, porous strata
Isotopic and geochemical analyses	130 analyses (Skuce et al., 2015; Skuce, Potter and Longstaffe, 2015; Skuce, 2015)	Hydrochemical zonation, groundwater flow, isotopic fingerprinting,
Petroleum industry water analyses	1024 standard water analyses	Hydrochemical depth zonation, salinity gradients, numeric modelling, Lockport TDS
Petroleum reservoir maps, well completion records	OPDS, OGSRL	Geographic boundaries of oil and gas reservoirs and producing formations and depth intervals
Hydrostratigraphic framework	Carter et al (2021a)	Geological/hydrogeologic/hydrochemical protocol for amalgamation of 3-D lithostratigraphic units into hydrostratigraphic units (HSUs)
Water well data	WWIS	Deepest fresh water, inferred shallow karst
3-D regional faults	Carter et al. (2021b)	Possible correlation with water/oil/gas intervals
Oil, Gas and Salt Resources Library	Drill cuttings from 11 000 wells, well files, drill core from 1100 wells, >20 000 geophysical logs	Quality Assurance and Quality Control
3-D lithostratigraphic model	Carter et al. (2021b)	Modelled geologic formations constrain hydrostratigraphic unit (HSU) boundaries
Breathing well zone	Freckelton 2012	Shallow karst aquifers
Inferred, known, potential karst	Brunton and Dodge 2008	Shallow karst aquifers
Water type maps	89 maps of bedrock saline aquifers, Carter et al. (2015a)	Hydrochemical zonation
Static level maps	17 maps of bedrock saline aquifers, Carter et al. (2015b)	uncorrected hydraulic heads, fluid levels in hydrostratigraphic units.
Base of sulphur water map	Carter and Sutherland (2018)	Hydrochemical zonation, hydrostratigraphic modelling
OGS groundwater mapping	Brunton and Brintnell (2020), Priebe et al (2014, 2016, 2017, 2019, 2021)	Water well drilling, modelling of shallow potable water aquifers
Petroleum industry core analyses	Data digitized late 2018	Porosity and permeability, groundwater flow, hydrostratigraphic modelling
Hydrostratigraphy Bruce nuclear site	Intera Engineering Ltd. (2011)	Comparative local analogy for classification of regional hydrostratigraphic units
Bedrock topographic Digital Elevation Model (DEM)	Carter et al. (2021b), Gao et al. (2006)	Bedrock upper erosional surface
Land surface topographic DEM with bathymetry	https://data.ontario.ca/dataset/provincial-digital-elevation-model, Carter et al 2021b	3-D model upper erosional surface
Geographic/cultural data	LIO, NRCan	Geographic context, towns, counties, townships, highways, Great Lakes

Abbreviations: *MECP – Ministry of the Environment, Conservation and Park, LIO – Land Information Ontario; NRCan – Natural Resources Canada; OGSRL – Oil, Gas and Salt Resources Library*

Petroleum Well Records: Water Intervals

The hydrostratigraphic model is constrained by data recorded in the petroleum well records of the OPDS. OPDS is a relational database of the drilling and completion results for petroleum wells drilled in Ontario, including formation tops and oil/gas/water intervals, derived from data reported to the Ministry of Northern Development, Mines, Natural Resources and Forestry (NDMNRF) and managed by the Oil, Gas and Salt Resources Library (OGSRL). The OPDS has digital records for approximately 26 950 wells, of which 15,600 wells have at least one reported water interval (Fig.3). Most of these wells were drilled by the cable tool method with no hydraulic pressure, which allows groundwater to flow freely into the wellbore. Drillers record the depth at which groundwater is encountered and enters the wellbore. For each water interval the well operator/driller is asked to record the top and bottom depth of the water interval, provide a subjective assessment of the hydrochemistry, or water type, (i.e. fresh, sulphur, salt), and the static level for the water. Salinity of the water is determined by taste and sulphur water is identified by the rotten egg odour of hydrogen sulfide. This is the principal source of data for identification of water-bearing intervals and mapping geographic and depth variations in the hydrochemistry of the groundwater in the bedrock formations. This is opportunistic data for which there is no formal data collection standard. Nonetheless, although accuracy of individual measurements is suspect the large number of measurements, their wide geographic distribution, availability in a publicly accessible database, and no affordable alternative make this data invaluable for regional mapping and modelling of bedrock aquifers and their hydrogeologic properties.

From the 15,600 wells with reported water there are 34,633 water interval records, of which a total of 33,086 have a recorded water type and 21,989 have a recorded static level (Appendix 1). The depth to the top of the water interval is reported for all the water intervals but the bottom depth is recorded for only 3,135. Consequently it is not possible to accurately ascertain the true thickness of water-bearing intervals which contribute water to the wellbore. For modelling purposes it has been assumed that the water-bearing intervals comprise the full thickness of the formation within which the top depth is recorded. This is a reasonable assumption for thin formations (<10 m) such as the interpinnacle Guelph Formation but for thicker formations such as the Bass Islands Formation or Lucas Formation it is likely that the aquifer thickness is overestimated based on field observations in quarries (e.g., Carter et al. 2021a).

Most petroleum wells drilled in southern Ontario have been drilled by the cable tool method, with no hydraulic control on entry of oil, gas or water into the well bore. Groundwater in porous and permeable intervals intersected by these wells enters the well and rises up the wellbore. In rocks with high permeability, the top of the water column stabilizes rapidly at a depth corresponding to the hydrostatic level in the aquifer at that location. Well drillers report the observed depth of the top of the water column as its ‘static level’ in drilling reports. Where the TDS is homogeneous within a HSU, the data can be used to interpolate an approximation of the potentiometric surface for the aquifer, after filtering and anomaly editing as discussed below. Although homogeneity in total dissolved solids (TDS) is not assessed here, the static level maps provided remain useful for identifying areas where the water level in a formation may occur above land surface. This is of particular significance in areas where sulphur water is capable of artesian flow to the surface. Quality and consistency of static level data is unknown, and likely variable due to the usually short periods of time allowed for stabilization of the water level in the wellbore, in combination with variable permeability in the bedrock aquifers.

Statistical analysis of the water type data to determine the depth interface between water types has been completed by Carter and Sullivan (2018, 2020). Localities where artesian flow occurs or is modelled to potentially occur can be ascertained using the digital model (see below). Distribution of water type by depth is illustrated in the Results section.

Data distribution is very heterogeneous (Fig. 3), varying from sparse to clustered, resulting in significant local variability on model reliability. The number of petroleum wells and water interval records declines with depth, with a consequent reduction in resolution and reliability of model layers with depth.

Petroleum Well Records: Oil and Gas Intervals

There are 25,900 gas-bearing intervals ('shows') recorded in 14,028 boreholes, of which 10,565 (~40%) record the bottom depth. There are 5,930 oil shows recorded in 4,256 boreholes, of which 3,214 (~55%) record the bottom depth (see Fig. 4). Approximately 60% of gas depths and 40% of oil depths with recorded bottom depth are minor shows (< 2m thickness). Most oil and gas shows occur within oil and gas reservoirs but ~18% of gas shows and ~36% of oil shows occur outside the boundaries of known oil and gas pools. These comprise small volumes of oil and/or natural gas, trapped in porous bedrock, of insufficient size to support commercial production, but with sufficient permeability to flow into a wellbore. They are often used by the petroleum industry as guides to exploration for undiscovered pools. These porous and permeable intervals also contain associated groundwater, usually basinal brines.

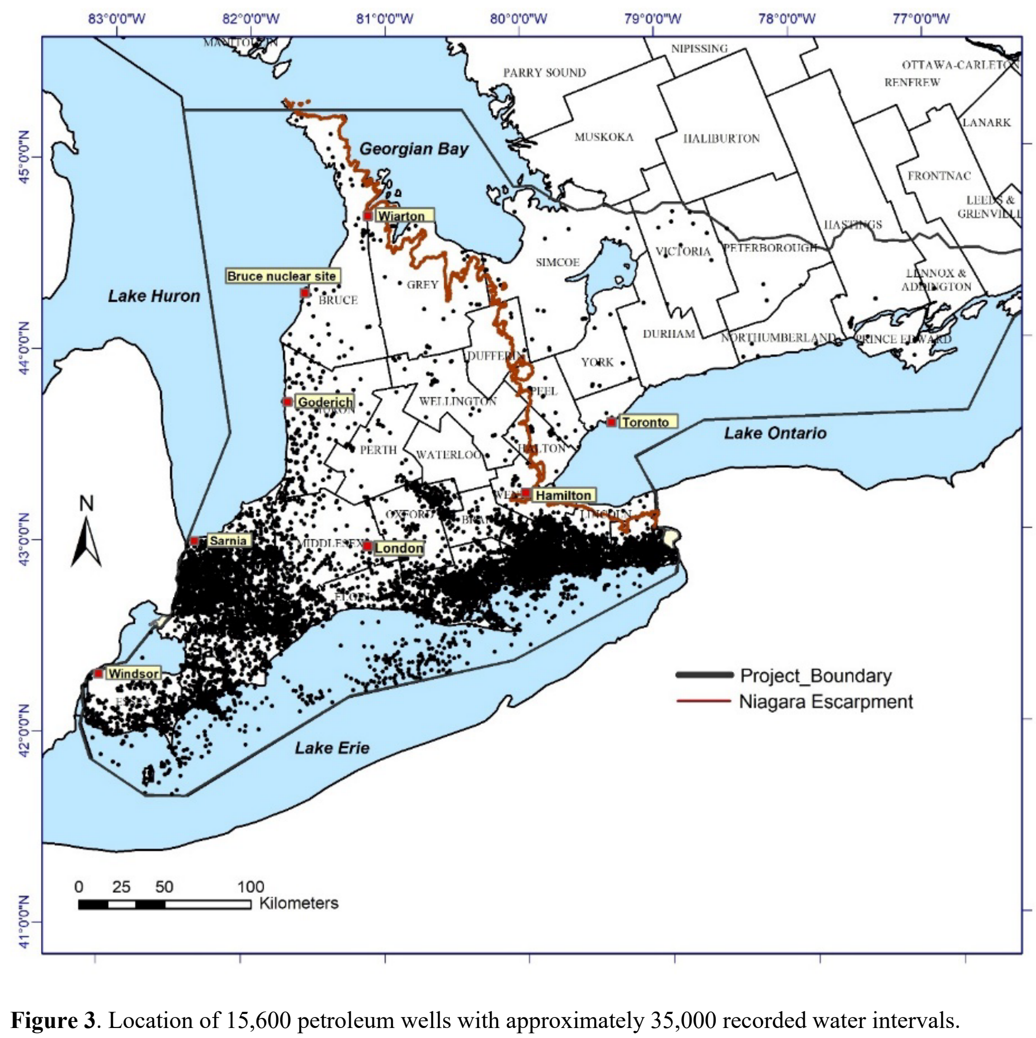


Figure 3. Location of 15,600 petroleum wells with approximately 35,000 recorded water intervals.

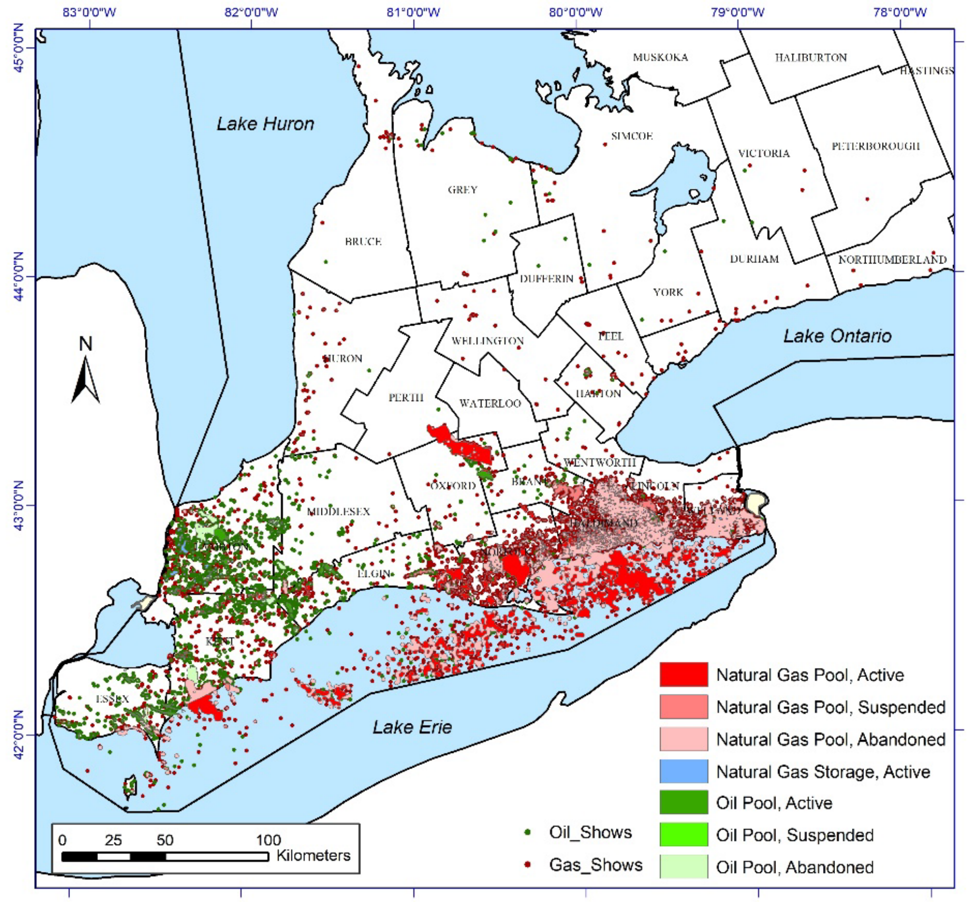


Figure 4. Location of oil and natural gas pools and petroleum wells with oil and gas shows in southern Ontario.

Water Well Records

Water well records in the WWIS managed by the Ontario Ministry of Environment, Conservation and Parks (OMECP) is the principal source of data on shallow fresh water in southern Ontario (e.g., Singer et al. 2003). There are records for approximately 400,000 wells in southern Ontario, of which 160,000 penetrate bedrock (Carter and Clark 2018). The vast majority of the "bedrock wells" penetrate only a few metres into bedrock and provide very little information about confined bedrock aquifers. Their principal use in the model was to identify the deepest penetration of fresh water into the bedrock from which the presence of buried shallow karst was inferred, and the extent of the "contact aquifer" at the interface between the bedrock and surficial sediments.

Petroleum Reservoirs

Hydrocarbons are produced from reservoirs ("pools") formed by a subsurface accumulation of oil and/or natural gas in a body of porous and permeable rock trapped beneath an overlying or updip impermeable seal or trap rock. Oil and natural gas are buoyant in the groundwater that saturates the bedrock in the subsurface and is prevented from migrating to the surface by the trap rock. This is analogous to the confinement of groundwater within aquifers by overlying and underlying aquitards, except that oil and gas reservoirs are much smaller with discrete boundaries and are isolated laterally from other reservoirs in the same geological formation. Also implicit in the definition of a pool is that the accumulation of hydrocarbons is large enough, and the reservoir rocks have sufficient permeability, to support the cost of drilling and completing wells to produce the hydrocarbons.

There is recorded production from 330 discrete reservoirs in 5 principal hydrocarbon “plays” in southern Ontario (Fig. 4). A play is a group of petroleum reservoirs or prospective reservoirs in the same region that have common geological features (Doust, 2010). Conventional petroleum plays in southern Ontario are described by Carter et al. (2016a, b) and Dorland et al. (2016). Principal plays in southern Ontario are:

- Structural and stratigraphic traps in Cambrian and Shadow Lake sandstones and sandy dolomites.
- fault-related hydrothermal dolomite reservoirs in Trenton and Black River Group limestones.
- stratigraphic traps in sandstones and associated carbonates of the Lower Silurian Clinton and Medina groups.
- reefs and structural traps in Silurian carbonates (A-1 Carbonate, Guelph Formation), and
- structural traps in Middle Devonian fractured, dolomitized carbonates and sandstones.

Unconventional hydrocarbons are regionally extensive oil or gas-bearing formations, generally organic-rich shales, where the permeability is very low and the hydrocarbons cannot be economically recovered using conventional vertical wells. These resources require drilling of horizontal wellbores followed by multistage hydraulic fracturing to achieve economic production. Over the past 10–20 years in North America oil and gas exploration and development has become dominated by exploration for and production of unconventional resources of shale oil and shale gas. There are prospective unconventional resources in organic-rich shales in southern Ontario but, except for some early oil production from oil shale mining, there has been no production and very limited exploration (Phillips et al. 2016). Shale units that host potential unconventional oil and gas resources are included in the model as aquitards but not modelled as oil and gas resources due to the lack of commercial production.

Petroleum well records maintained by the OGSRL include reports by well operators on the depth interval over which the well has been completed for production of oil and/or natural gas and identify the producing formation(s). Producing intervals may be only several metres thick within a single formation or may be several tens of metres and include two or more (rarely) formations. OGSRL has compiled a data table accompanying the Oil & Gas Pools & Pipelines Map of Southern Ontario (Oil Gas and Salt Resources Library 2019) which documents the producing formations for each active or past-producing oil and gas pool. The map also illustrates the boundaries of all pools and is available in digital format as shapefile (.shp) or portable document format (.pdf) files.

The boundaries of oil and gas reservoirs are determined principally by the results of drilling of petroleum wells, with the boundary defined by the limit of successful wells in combination with geophysical (seismic) and geochemical surveys and isopach and structural mapping. A comprehensive assessment of Ontario’s oil and gas resources was completed in the 1980’s (Bailey and Cochrane 1984a, b, 1985, 1986, 1990) which included compiling maps of oil and gas pool boundaries and data on depth intervals, producing formations, cumulative production, reservoir geology, exploration history, etc. This data has been subsequently maintained and updated by the NDMNRF and the OGRSL and is the principal source of data for modelling of 3-D reservoir volumes incorporated in the current model.

Land Surface and Bedrock Topographic DEMs

A land surface topographic DEM, including bathymetry of the Great Lakes, was used to form the upper boundary surface of the unconsolidated sediments. A digital bedrock topography surface forms the upper boundary of the bedrock. These surfaces are 400 meter resolution and were adopted without change from the 3-D lithostratigraphic model of the bedrock (Carter et al. 2021b).

Cultural and Geographic Data

Cultural and geographic layers provide locational context for the 3-D model. Data sources for this model are largely unchanged from those utilized for the 3-D lithostratigraphic models (Carter et al. 2019, 2021b).

Cultural and geographic data include major roads, towns, geographic township boundaries, county/municipal boundaries, shorelines. The Great Lakes and a selection of other major lakes, including Lake Simcoe, are represented as two dimensional polygons displayed at their mean elevation relative to sea level. The boundaries for geographic townships (Townships Improved), highways (Transportation), and streams and shorelines (Shorelines 100K, Water Bodies 10-50 K) were obtained from geospatial databases maintained by Land Information Ontario (https://geohub.lio.gov.on.ca). The boundaries for counties were obtained from the PetroGIS application maintained by the Petroleum Operations section of MNRF. Great Lakes polygons were downloaded as shapefiles from Open Government (NRCan) (https://open.canada.ca/en/open-government-licence -canada). Except for the Great Lakes polygons, the polylines representing the other cultural and geographic features are draped on the surface topographic Digital Elevation Model (DEM), (https://data.ontario.ca/dataset/provincial-digital-elevation-model) slightly above the surface for display clarity.

Lithostratigraphic Layers

Lithostratigraphic layers utilized in the model are derived from Carter et al. (2021b) and are incorporated in this model with no modification.

TDS Lockport

The OGSRL has compiled standard petroleum industry chemical analyses for 1023 water samples collected by the operators of licence d petroleum wells and analyzed at commercial laboratories. The laboratory analyses were completed by several different commercial laboratories between 1948 and 2001 with one sample collected and analyzed in 1907. These data are supplemented by chemical analyses of 109 water samples from selected subsurface bedrock formations acquired by the MNRF in 2011–2013 in partnership with the University of Western Ontario (Carter and Sutherland 2018, 2020).

Carter and Sullivan (2018, 2020) completed a Quality Assurance and Quality Control (QA/QC) review of the water analysis data available for the Lockport Group, including identification of well location, sample depth, formation assignment, and data entry errors. After QA/QC filtering to verify well location, and removal of single well anomalies in interim data interpolations, water analysis results were available for 139 samples, of which 2 are classified as fresh water, 21 as brackish to saline sulphur water, and 116 as brine. Interpolation of the data delineates a regional downdip increase in salinity from approximately 200 mg/l TDS in the subcrop belt to a maximum reported value of over 600,000 mg/l in the deep subsurface. A frequency histogram of the data has a median value of 314,000 mg/L (Carter and Sullivan 2020). The interface between brackish and saline water of the intermediate sulphur water regime and deep brine occurs approximately 35 to 65 km downdip from the subcrop exposure of these formations which corresponds to a depth of approximately 250 to 300 m below the top of bedrock. This pattern of hydrochemical zonation and the depth and distance variations correlate very closely with observations and interpretations based solely on water type data for these same formations (Carter et al. 2015a). The stratigraphic and geographic variation of TDS is represented as a 3-D interpolant in the Results section.

Breathing Well Zone

A shallow fresh water karstic aquifer known as the "breathing well zone" underlies an area of approximately 1400 km^2 in southern Huron County (Brunton and Dodge 2008; Freckelton 2012). The wells emit or draw in large volumes of air in response to changes in atmospheric pressure due to the presence of a large volume of unsaturated pore space in the Lucas Formation.

The principal aquifer is comprised of a karstic zone in the Lucas Formation which likely formed due to dissolution of evaporite minerals (anhydrite, halite). The aquifer is recharged by surface water infiltration into sinkholes over solution-widened joints in the overlying, semi-confining Dundee Formation and by lateral regional flow from east to west within the Lucas Formation (Freckelton 2012). Water well logs record the presence of fresh water up to 140 m below the bedrock surface within the zone, some of the deepest occurrences of potable water in bedrock anywhere in southern Ontario (Carter and Clark 2018).

The mapped boundary of the breathing well zone is incorporated as a layer in the model.

Procedures and Data QA/QC

Project Co-ordination and Communication

Team members for this project comprised a multidisciplinary team of expert and experienced professionals, including a sedimentologist and Quaternary geologist (Hazen Russell), subsurface bedrock geologist and deep groundwater geologist (Terry Carter), QA/QC geologists (Alexandre Cachunjua, Candace Freckelton, Hanna Rzyszczak, Shuo Sun), hydrogeologist (Elizabeth Priebe), GIS and data management specialists (Jordan Clark, Maryrose D'Arienzo), and a 3-D modeller (Charles Logan). Project coordination was provided by Terry Carter and the team lead was Hazen Russell.

Project direction and co-ordination included bimonthly online team meetings with written agendas, task assignments and recorded minutes. Five model iterations were reviewed and critiqued by team members. Team members attended and made presentations on model progress at annual one to two-day groundwater workshops hosted by the OGS, GSC and Conservation Ontario in 2021 and 2022. Progress reports were also presented at GSA Montreal 2020 (Carter et al. 2020b), GAC London 2021, Geologic Mapping Forum of the Minnesota Geological Survey in February 2021, monthly meeting of Michigan Basin Geological Society in April 2022, and the 2022 Geoscience Seminar of the Nuclear Waste Management Organization (NWMO).

The hydrostratigraphic framework proposed by Carter et al. (2021a) was developed in the early part of the development and review process of the 3-D modelling project.

Hydrostratigraphy and Conceptual Model Development

A regional hydrostratigraphic framework for the bedrock of southern Ontario (Carter et al. 2021a; open access at: http://www.geosciencecanada.ca/geocan_issue_mar2021.htm) was developed for and has been adopted by this project. It was utilized to guide model development for the five principal iterations of the model. The process of developing each HSU for the model is described, including descriptions of the lithology, sedimentology, hydrogeologic properties, hydrochemistry/water type and the rationale for designation as aquifers and/or aquitards. Hydrostratigraphic units are defined as per the protocols of Maxey (1964) and Seaber (1988).

The 15 HSUs represented in the model, and the lithostratigraphic units of which they are comprised, are illustrated in the hydrostratigraphic chart (Fig. 5). Erosional stratigraphic breaks in the chart represent periods of subaerial exposure and erosion in the geologic past, and karstification of exposed carbonate rocks. These paleokarst intervals are the most significant control on the occurrence of regional aquifers in the subsurface bedrock formations of southern Ontario (Brunton et al. 2007; Brunton 2009a, 2009b; Brunton et al. 2012; Carter et al. 2014, 2021a; Banks and Brunton 2017; Brunton and Brintnell 2020).

The five columns of the chart represent different geographic areas in southern Ontario arranged updip from thickest to thinnest, from west (left) to east (right). All stratigraphic units are colour-coded to indicate their predominant hydrogeologic character as aquifers, aquitards and/or aquicludes. Aquifers are further colour-coded to indicate the predominant water type that occupies the aquifer in the five geographic regions. The erosional profile of the Paleozoic strata, and the carbonate-capped cuestas and associated escarpment cliffs that form the subcrop edges of the stratigraphy (*see* Hewitt 1971; Brunton 2009a; Brunton et al. 2017) are also shown, as these are significant hydrologic divides for potable groundwater in the shallow and subcropping bedrock, in particular the Niagara Escarpment (Brunton et al. 2007; Brunton 2009a, 2009b; Brunton and Brintnell 2011; Brunton et al. 2012; Brunton et al. 2017; Carter and Clark 2018), and are sites for infiltration of meteoric water into the subsurface.

QA/QC of Formation Assignments of Petroleum Well Water Intervals

Extensive edits to formation tops recorded in OPDS were made in 3-D modelling of the bedrock geology (Carter et al. 2019, 2020, 2021b; Clark et al. 2020), with a focus on review of formation tops for the Lockport Group formations. In the present project there was a QA/QC review of formation tops assigned to the Dundee Formation, with a focus on wells for which a water interval is reported within the Dundee Formation, and for the Lockport Group. QA/QC edits and updates to formation assignments of water intervals resulting from these and previous edits of formation tops are detailed in Appendix 2. Revised formation assignments of water intervals and static level data are summarized in Appendix 1

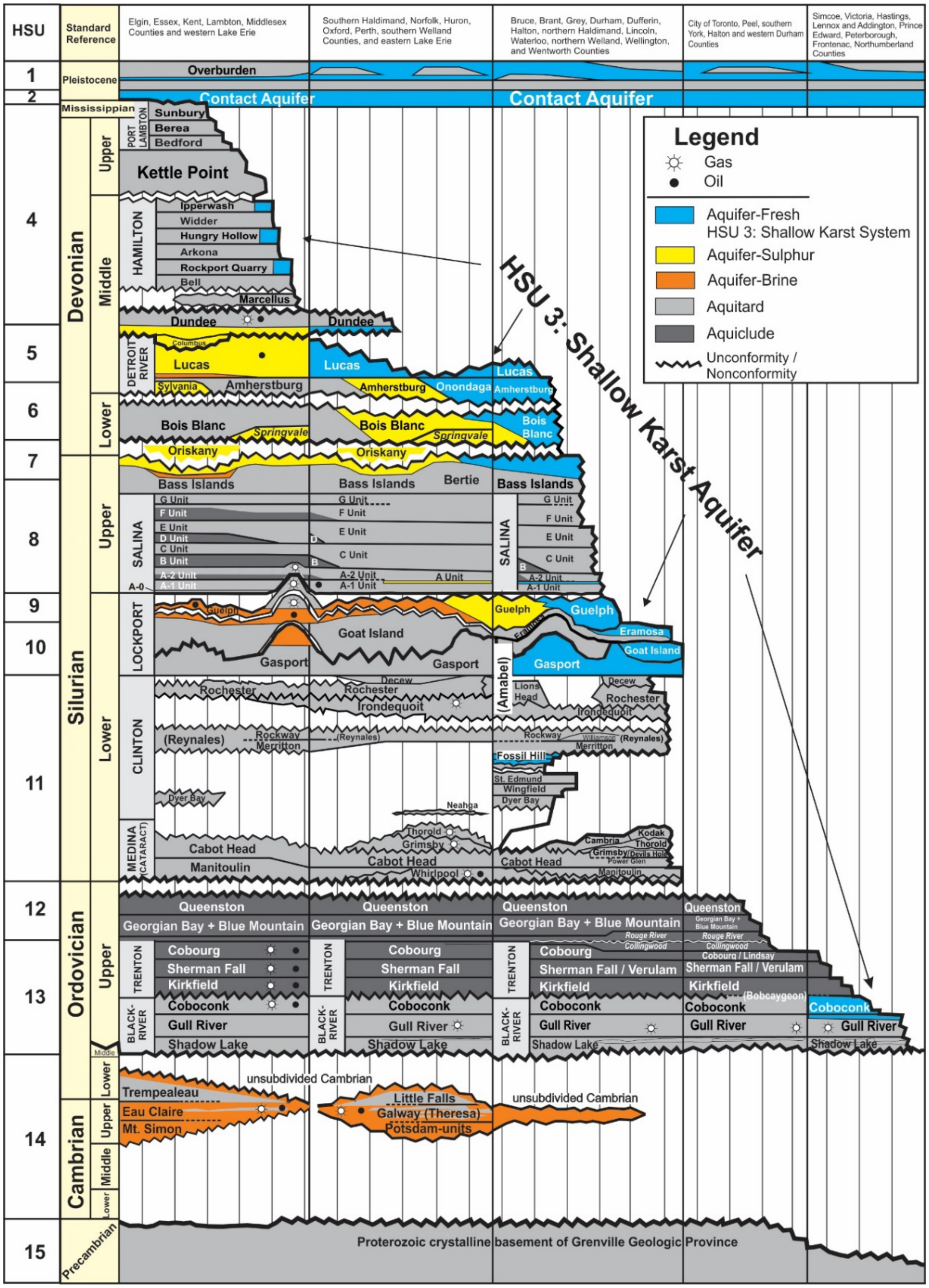


Figure 5. Hydrostratigraphic chart for southern Ontario showing HSU designations and assignment of bedrock lithostratigraphic units as regional aquitards, aquicludes and aquifers, from Carter et al.(2021a). Paleokarst horizons related to regional unconformities are closely associated with aquifer development.

QA/QC of Oil, Gas and Water Analysis Data

The OGSRL has completed a QA/QC review to improve the accuracy of oil, gas and water analytical data recorded for petroleum wells in OPDS. A total of 1,759 records for oil, gas and water analyses from 967 wells have been reviewed to verify and update the recorded depth interval and formation assignment for 245 oil analyses, 491 gas analyses and 1,023 water analyses by comparison to hard copy source records. Details of the project are described in Appendix 2.

3-D Modelling Methodology

As in development of the 3-D bedrock lithostratigraphic model of southern Ontario (Carter et al. 2019, 2021b) there were several iterative rounds of model development to allow for model corrections and adjustments based on expert feedback, resulting in five QA/QC cycles of a full model. Model resolution is 400 m. Leapfrog® Works (Seequent Limited) implicit 3-D modelling software was used to develop both the lithostratigraphic model and the hydrostratigraphic model.

The 15 HSUs comprise the principal model layers and are based directly on the published lithostratigraphic model of southern Ontario (Carter et al. 2021b) and the hydrostratigraphic framework established by Carter et al. (2021a). The lithostratigraphic model was developed primarily from borehole log formation contacts, 2-D bedrock subcrop mapping, the bedrock topographic DEM and the land surface topographic DEM. Carter et al. (2019, 2021b) documents this model development in detail. The HSUs that form the basis of the hydrostratigraphic model were assembled by merging lithostratigraphic model volumes to produce 13 of the 15 HSU layers. Hydrostratigraphic layers are based on grouping similar hydrogeologic properties and geologic ages. HSU02_Contact Aquifer and HSU03_Inferred Shallow Karst Aquifer are produced in part using lithostratigraphic model bedrock and topographic surfaces. These two shallow aquifer layers were developed independently of bedrock lithologic layer volume boundaries and subsequently used to help estimate Fluid Zones within the other lithologic HSUs. HSU02_Contact Aquifer represents the zone of contact between near-surface jointed and weathered bedrock and surficial sediment. HSU03-Karst Aquifer is inferred by deep fresh water occurrences reported in water wells that penetrate bedrock (Carter and Clark 2018).

In addition to providing the main HSU volumes, this 3-D hydrostratigraphic model also sub-divides each of the formation-based HSU volumes into Fluid Zones based on material properties and fluid types determined by hydrochemical analysis or driller observation of water type as recorded in OPDS (e.g., Carter et al. 2015a). HSU02_Contact Aquifer and HSU03_Inferred Shallow Karst Aquifer are developed for the entire model area independently of merged formation boundaries. For the other HSUs, Fluid Zones were developed within a series of sub-models using the overall volume of the corresponding HSU as the 3-D boundary extent. HSUs are broadly classified as aquifer or aquitard. Aside from some areas of exposed bedrock outcrop, aquifer HSUs are fully saturated with varying proportions of brine (TDS > 100,000 mg/L), brackish to saline sulphur water, fresh water in karst, fresh water at bedrock-drift contact, or undifferentiated fresh water. Aquitard HSUs are mostly classified as aquitard, aquiclude or outcrop, aside from varying proportions of fresh water in shallow inferred karst or contact aquifer depending on rock type. The sub-division of Fluid Zones within each HSU is summarized in Fig. 6.

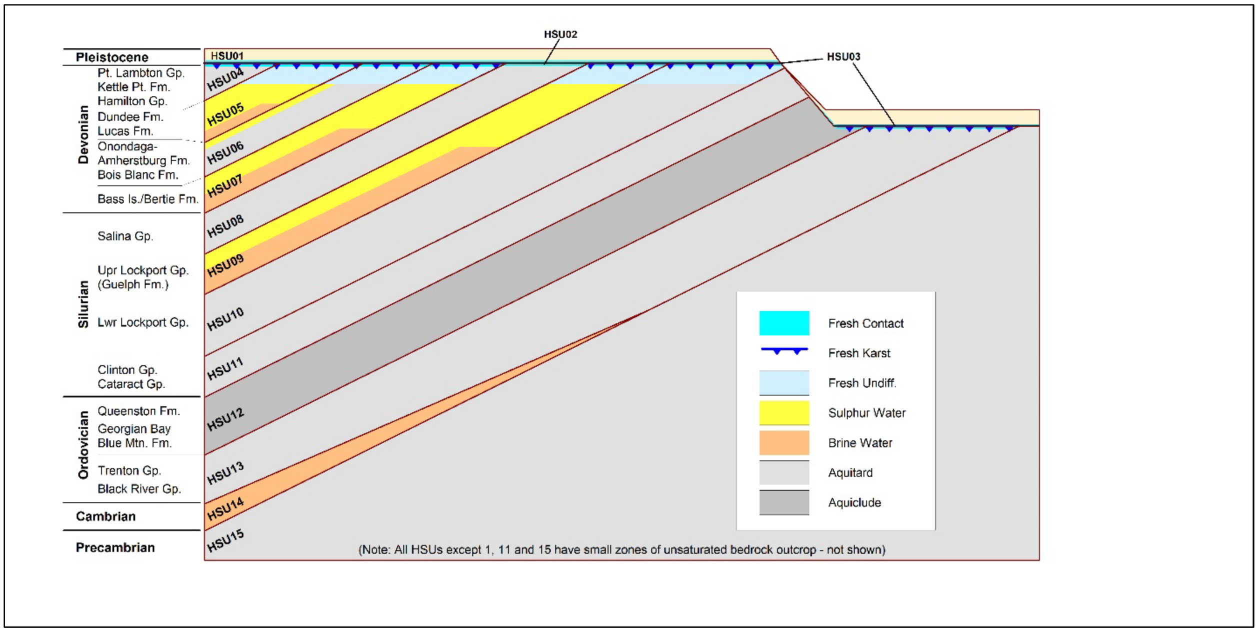


Figure 6. West to east representative cross-section illustrating the sub-division of Fluid Zones within Hydrostratigraphic Units (HSUs). Not to scale.

The modelling software provides several options to govern how interpolated surfaces interact to produce 3-D volumes. Based on corresponding real-world lithology and geologic processes, the primary options in Leapfrog to define contact type are 1-Deposition, 2-Erosion and 3-Intrusion. When identified as one of these options, the contact surface developed from some combination of borehole logs, points, lines, surfaces, structural data etc. will either cause younger layers to drape onto older layers (deposition), remove lower layers (erosion) or cause younger volumes to completely replace older layer volumes (intrusion). Contact types used to develop Fluid Zones do not relate to the strict geological definition, rather they are used as needed to replicate the layered nature of hydrochemical Fluid Zones and aquifer/aquitard geometry based on the hydrogeologic properties of bedrock formations. Generally, groundwater in aquifer HSUs is stratified based on density with fresh water at and near the surface, brackish to saline sulphur water at intermediate depths, and deep brine, however not all water types exist in every HSU. Varying amounts and combinations of the following zones are defined within each aquifer HSU: 1-Unsaturated Bedrock Outcrop, 2-Fresh Water Contact, 3-Fresh Water Karst, 4-Fresh Water Undifferentiated, 5-Sulphur Water and 6-Brine. Of the 75,114 km^3 total volume that the 3-D model covers, Table 2 outlines both the percentage that is occupied by each HSU and the percentage of Fluid Zones with each HSU.

HSU01 Surficial Sediment System – Fluid Zones

The Surficial Sediment System is represented as a single layer. No attempt was made to render the complex aquifer and aquitard systems that exist within the glacial sediment sequences that comprise the bulk of unlithified material that overlies bedrock in the southern Ontario model area (e.g., Sharpe et al. 2014, Logan et al. 2020) as it is beyond the resolution and scope of this model. A companion model of the surficial sediments is underway and will attempt to merge existing OGS and GSC surficial models and related data to produce a regional model of these important groundwater resources (Logan et al. 2020). The portion of the HSU02 Contact Aquifer that extends into the surficial sediment is delineated in this model by subtracting the HSU02 volume from the HSU01 Surficial Sediment System volume. The fluid model boundary is first set to the extents of the HSU01 Surficial Sediment System. The background (default) zone is set to 1-Undifferentiated Surficial Sediment and then the HSU02 volume mesh is used to define an "intrusion' type contact of younger age. This replaces the overlapping portion of HSU01 and HSU02 with a new Fluid Zone: 2-Fresh Water Contact Aquifer.

Table 2. Summary of HSU volumes as a percentage of the total 3-D model and Fluid Zone volumes as a percentage of total HSU volume. Approximately 85% of the volume of Paleozoic bedrock is classified as aquitard or aquiclude, vs 15% as aquifer.

	% of 3-D Model	Undiff - erentiated	Fresh Contact	Fresh Karst	Fresh Undiff.	Sulphur Water	Brine	Aquitard / Aquiclude
HSU01	4.7%	91.4%	8.6%					
HSU04*	2.1%		6.3%	0.2%				93.5%
HSU05*	2.8%		1.9%	0.2%	25.5%	65.2%	7.3%	
HSU06*	3.7%		0.9%	<0.1%	2.2%	6.0%		90.9%
HSU07*	2.5%		0.4%	<0.1%	25.9%	51.5%	22.2%	
HSU08*	12.7%		0.5%					99.5%
HSU09*	2.7%		1.4%	0.4%	11.4%	25.3%	61.3%	
HSU10*	3.6%		0.4%	0.3%	2.6%			96.7%
HSU11	4.4%							100.0%
HSU12*	28.8%		0.2%					99.8%
HSU13*	27.5%		0.6%	0.1%				99.4%
HSU14*	4.3%		<0.1%		<0.1%		100.0%	
HSU15	NA							100.0%

(* <0.1% Unsaturated Bedrock Outcrop not shown)

HSU02 Contact Aquifer

The contact aquifer occurs along the sediment/bedrock interface where bedrock subcrops beneath surficial sediments (e.g. Carter et al. 2021a). For this model, it was assumed that the saturated zone of fresh water extends 4m below the modelled bedrock subcrop surface and upward into unlithified sediment for 3m based on water well records and petroleum well records. As shown in Fig. 7, the bedrock surface mesh was extracted from the lithologic model and offset +3m and -4m to define the upper and lower bounding surfaces for the contact aquifer throughout the model area.

Where sediment is thin (i.e., < 3m) and bedrock is very close to ground surface, a correction was applied to ensure that the model doesn't falsely predict surface water or wetland. The land surface DEM was offset -1m in the Z direction and used to enforce an upper elevation maximum on the HSU02 volume (Fig. 7). This ensures that the contact zone only exists into the surficial sediment to the full 3m extent where sediment is greater than 4m thick. Where bedrock outcrops with very little or no sediment (i.e., 0-1 m), the topographic correction depresses the contact aquifer up to 1m below the bedrock outcrop surface. A more intensive study involving identifying wetland / lake areas that are not perched in sediment above bedrock would need to be made to allow more thorough exceptions to this correction, however only the Great Lakes were used in this way for this model.

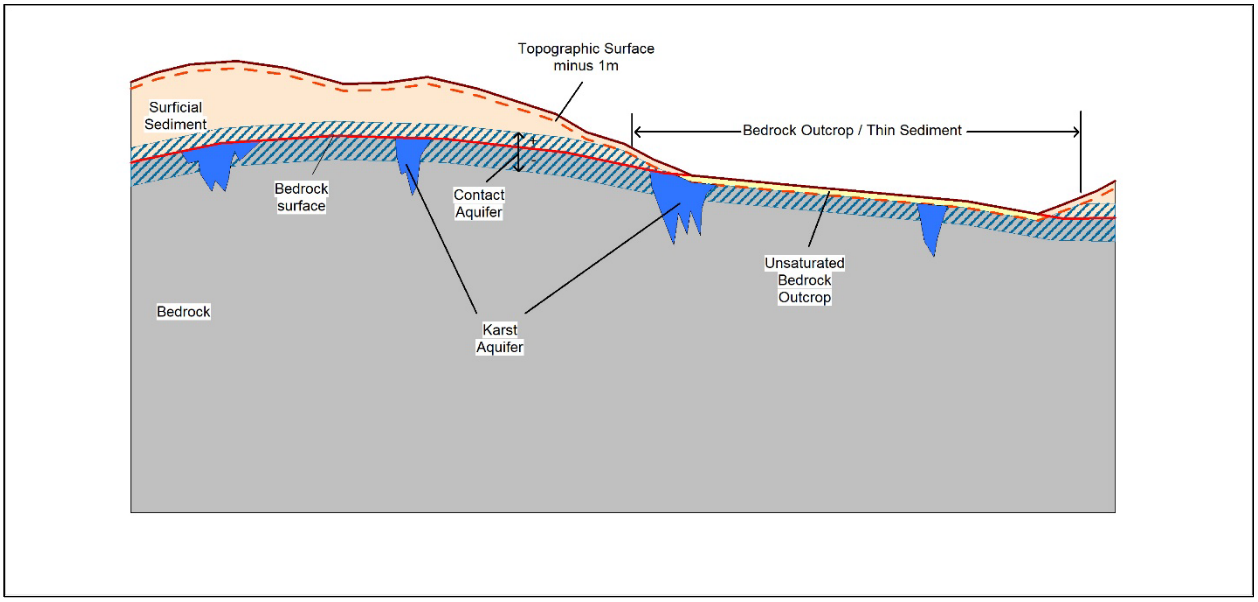


Figure 7. Illustration of Contact Aquifer, Karst Aquifer and Unsaturated Bedrock Outcrop Zones. Contact aquifer upper surface is depressed by up to 1m where bedrock outcrops or surficial sediment is thin (<4m thickness).

HSU03 Inferred Shallow Karst Aquifer

Like HSU02 Contact Aquifer, the Inferred Shallow Karst Aquifer zones were developed for the entire model area. The deepest recorded intervals of fresh water from water well records were used to interpolate the karst volumes (Carter and Clark 2018). Water wells with depth penetration into bedrock greater than 4m, i.e. below the contact aquifer, and not drilled in shale were used to define the extents of the inferred shallow karst. The base of fresh water points are interpolated along with bedrock surface vertices to define the base of karst surface. The bedrock surface vertices force the base of karst surface to coincide with the bedrock surface where no base of fresh water points occur thereby limiting the karst volume to recorded depths. By only snapping the surface interpolation to base of fresh water points and not bedrock surface vertices, the surface is more constrained to the base of fresh water data when they are present (Fig. 8). The resulting conical shape of inferred karst may not be geologically plausible; however, the complex geometry of karsts is well beyond the resolution of this model. The karst volumes are best regarded as inferred karst zones that are influenced by local bedrock fracture patterns. As these fractures often diminish with depth from the bedrock surface, the conical shape of the HSU03 zones may be good schematic representations.

For comparison, also included in the model are 2-D layers of shallow karst identified by Brunton and Dodge (2008): GRS005_Karst_Outline_Inferred, GRS005_Karst_Outline_Known, and GRS005_Karst_Outline_Potential, which are interpreted from field observations in outcrops and quarries and shallow drilling. There is a good correlation to the areas identified in the model as inferred shallow karst.

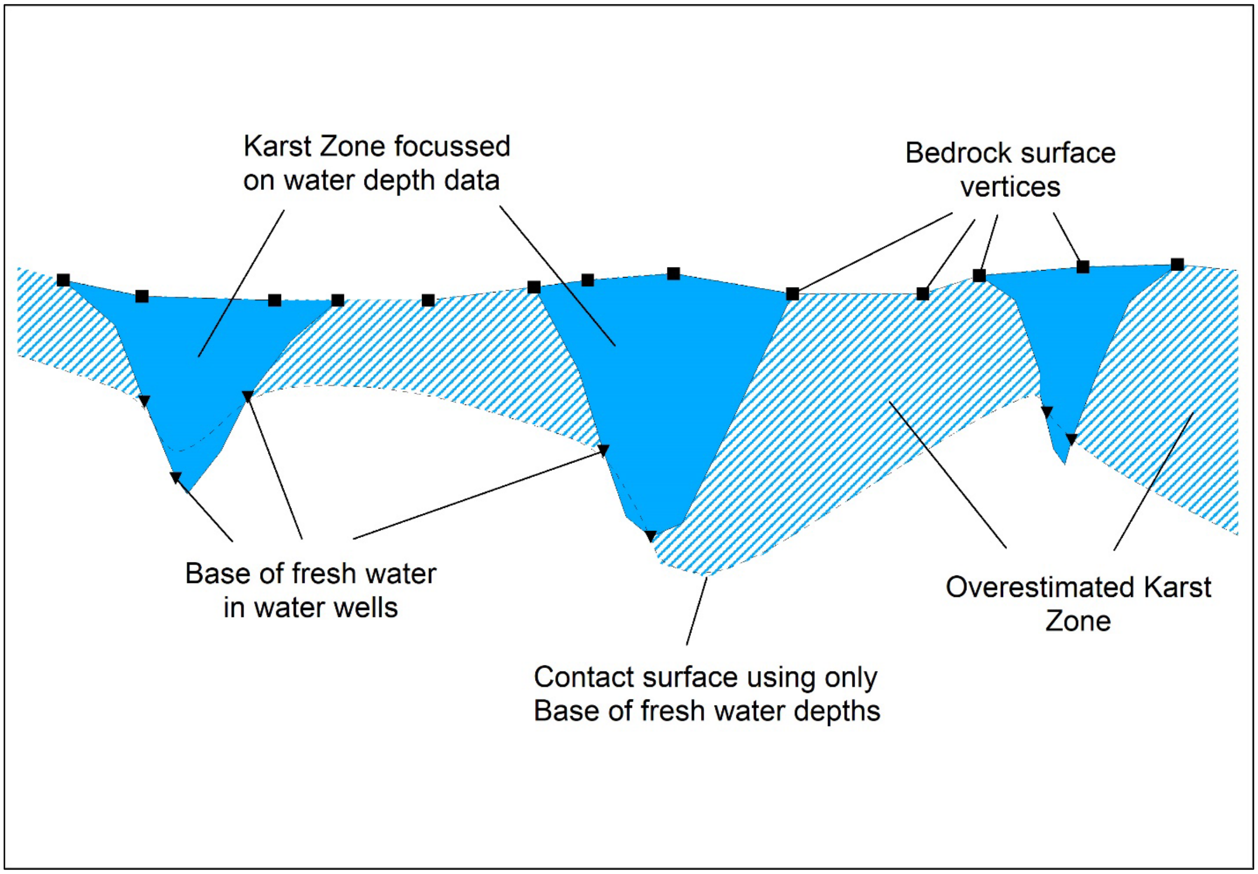


Figure 8. Illustration of the effect of using bedrock surface vertices to draw the interpolated karst contact surface upward where no measured base of fresh water points occurs. Karst volume is restricted to areas of deep fresh water data (solid blue) and not interpolated to avoid an overestimated (hash marked blue) karst extent which is instead modelled as Fresh Water Undifferentiated.

HSU04 Devonian Aquitard – Fluid Zones

The Devonian Aquitard unit is a collection of primarily thick beds of shale with interbeds of limestone and minor sandstone. The entire HSU04 is modelled as an aquitard except along the bedrock surface where HSU02 Contact Aquifer is defined. The limestone beds can be karstified where they subcrop and are not capped by shale. The HSU04 Devonian Aquitard is divided into 1-Unsaturated Bedrock Outcrop, 2-Fresh Water Contact, 3-Fresh Water Karst and 4-Aquitard zones. The HSU04 Fluid Zone model is developed by first establishing Aquitard as the background layer (and oldest chronologically) throughout the HSU04 3-D model volume boundary. The HSU02 Contact Aquifer volume is treated as an 'intrusion' contact type in the software so it will supplant older model layers. In so doing, the HSU02 volume removes overlapping Aquitard volume and replaces it with Contact Aquifer within the HSU04 model boundary. Similarly, the HSU03 Inferred Shallow Karst Aquifer volume is set as a younger 'intrusion' thus supplanting both the overlapping volumes of Contact Aquifer and Aquitard. Lastly, the small portion of contact and karst zones that are within 1m of surface outcrop are classified as Unsaturated Bedrock Outcrop using the land surface DEM minus 1m as an 'erosional' surface contact.

HSU05 Lucas-Dundee Aquifer – Fluid Zones

The Lucas-Dundee Aquifer is composed of primarily limestone and dolostone formations. Porous and fractured bedrock contains groundwater that is sulphurous in most of the subsurface except for some significant fresh water portions toward the upper contact and/or bedrock subcrop surface and shallow karst, and some very limited occurrences of brine in the deepest parts of the aquifer. The HSU05 Lucas-Dundee Aquifer is divided into 1-Unsaturated Bedrock Outcrop, 2-Fresh Water Contact, 3-Fresh Water Karst, 4-Fresh Water Undifferentiated, 5-Sulphur Water and 6-Brine. Based principally on the water types recorded in petroleum wells the extent of the sulphur water zone is modelled to occupy the entire HSU05 volume except where it subcrops and in a region up-dip of the Breathing Well Zone (Freckelton 2012) and a small area of deep brine below the low-permeability Kettle Point Formation. The Breathing Well Zone is provided as a 2-D outline in the model. As above, the HSU05 volume defines the 3-D fluid model extent. The Sulphur Water zone is set as the background; however, its northern extent is limited to a northwest to southeast margin at the breathing well zone via manual surface editing to better agree with observed borehole water chemistry. The Brine zone is established as a 'depositional' type volume at the base of the HSU controlled by recorded brine depths in boreholes and limited horizontally to occur only below Kettle Point Formation with manual edits. Fresh water to the northeast of the Sulphur margin and below contact and karst fresh water is classified as Fresh Water Undifferentiated. Like the HSU04 Fluid Zone, the HSU02 Contact and HSU03 Inferred Karst zones were applied as 'intrusive' layers and the Unsaturated Bedrock Outcrop layer as an 'erosion' contact to define the Fresh Water Contact, Fresh Water Karst Fluid Zones and Unsaturated Bedrock Outcrop zone respectively.

The sulphur water zone in the Lucas-Dundee Aquifer is a known corrosion hazard for unprotected steel and concrete in subsurface infrastructure such as tunnels, mine shafts, petroleum wells and foundations, and knowledge of its presence is important for design of mitigation strategies. In parts of southern Ontario this aquifer is artesian and is a drilling hazard for cable tool drilling operations where it contains high concentrations of H_2S.

HSU06 Amherstburg-Bois Blanc Aquitard – Fluid Zones

The Amherstburg-Bois Blanc Aquitard is primarily limestone and dolostone. Only a small percentage of wells drilled in the deeper parts of these formations encountered any water, so it is classified as a regional aquitard (Carter et al. 2021a). In the shallower parts of these formations near the subcrop belts, in particular in Norfolk and Haldimand counties and to the southwest in Kent and Essex counties, there are numerous reported occurrences of sulphur water which are represented in this HSU model layer. The HSU06 aquitard is divided into 1-Unsaturated Bedrock Outcrop, 2-Fresh Water Contact, 3-Fresh Water Karst, 4-Fresh Water Undifferentiated, 5-Sulphur Water and 6-Aquitard. The aquitard portion occupies the bulk of the unit with subordinate Sulphur Water zones where indicated by water occurrences and fresh water in inferred karst and contact aquifer zones where the formations subcrop. For this HSU, the aquitard is the background (oldest) layer object. Guided by the base of sulphur water shows in boreholes, the sulphur zone is as approximated using an 'erosional' feature governed by depth to the base of sulphur water shows in boreholes. Above this a thin undifferentiated fresh water zone is defined as a similar 'erosional' contact at the base of fresh water karst control points. Next, as above, the contact and karst aquifers are added as 'intrusions', then Unsaturated Bedrock Outcrop as another 'erosion'.

HSU07 Bass Islands Aquifer – Fluid Zones

The Bass Islands/Bertie dolostone underlies an unconformity and is sandwiched between the Amherstburg-Bois Blanc Aquitard above and Salina Aquitard below. There are minor, disconnected volumes of Oriskany sandstone above the unconformity that are hydraulically similar and are included in this HSU. The HSU07 aquifer contains 1-Unsaturated Bedrock Outcrop, 2-Fresh Water Contact, 3-Fresh Water Karst, 4-Fresh Water Undifferentiated, 5-Sulphur Water and 6-Brine. For this HSU, the Brine is established as the oldest (deepest) zone by using the depth to top of brine occurrences in borehole logs to define the top of a 'depositional' layer. The updip extent of the brine is limited to a margin approximated by the updip limit of reported occurrences of "salt water" (brine) in petroleum well records. Beyond this extent and above the brine, sulphur water is established as a younger 'deposition' whose updip extent is also approximated by the transitional boundary from water intervals dominated by sulphur water to water intervals dominated by fresh water, as reported in petroleum well records (Carter et al. 2015a). The remainder of the HSU07 model boundary is zoned by default as Fresh Water Undifferentiated by setting it as the background volume. As above, the contact, karst and unsaturated bedrock outcrop zones are imposed to complete the zonation.

HSU08 Salina Aquitard – Fluid Zones

The Salina Aquitard combines several salt/anhydrite, shale and limestone/dolostone formations. The entire HSU is modelled as an aquitard aside from a contact aquifer zone where it subcrops below surficial sediment. Where salt beds are present, the Salina Group is considered to form an aquiclude. It is divided into 1-Unsaturated Bedrock Outcrop, 2-Fresh Water Contact and 3-Aquitard zones. To produce Fluid Zones, the background is simply set to Aquitard, then contact aquifer added as an intrusion and lastly Unsaturated Bedrock Outcrop as an 'erosion'.

HSU09 Guelph Aquifer – Fluid Zones

The HSU09 Guelph Aquifer is an important regional aquifer in southern Ontario that is composed of the Guelph Formation dolostone and locally the uppermost few metres of the underlying Goat Island Formation. This HSU contains the following zones: 1-Unsaturated Bedrock Outcrop, 2-Fresh Water Contact, 3-Fresh Water Karst, 4-Fresh Water Undifferentiated, 5-Sulphur Water and 6-Brine. For this HSU a TDS analysis dataset was available to help define the transition boundary from brine to sulphur water zone. A numeric model was developed within the HSU09 volume container to produce a 3-D interpolant based on the TDS point values. The 100,000 mg/L isosurface was used to define the brine to sulphur water zone boundary. Since the TDS dataset did not extend to the northern limits of HSU09, the boundary was corrected and extrapolated parallel to the subcrop edge to approximate the location of the zone transition. The sulphur to fresh water transition was established along the subcrop contact edge by manual surface editing based on Carter et al. 2015a. The remaining karst, contact and unsaturated outcrop zones were developed in the same way as described for other HSUs above.

HSU10 Lower Lockport Aquitard – Fluid Zones

The three lower dolostone formations of the Lockport Group are classified as an aquitard due to its very low hydraulic conductivity (Intera 2011; Carter et al. 2021a) and the general lack of water shows at intermediate to deep depths in borehole logs (Carter et al. 2021a, 2015a). The entirety of the 3-D boundary is set to an aquitard background. A Fresh Water Undifferentiated zone was added as an Erosion type surface using the base of fresh water points that were used to make the HSU04 Karst Aquifer. The erosion surface was constrained to the down-dip extent of the karst within the HSU10 boundary using manual edits. The karst aquifer, contact aquifer and unsaturated bedrock outcrop zones were developed in the same way as described for other HSUs above. HSU10 has the most extensive inferred karst aquifer of all the HSU's in southern Ontario, and yet in the intermediate to deep subsurface is an aquitard. It is an excellent illustration of the dramatic effects of subaerial exposure and porosity enhancement by karstification on the hydrogeologic character of carbonate rocks in southern Ontario.

HSU11 Clinton-Medina Aquitard – Fluid Zones

The Clinton-Medina Aquitard consists mainly of shale and dolostone formations with some minor discontinuous sandstones. These formations subcrop on the subvertical faces of the Niagara Escarpment and consequently do not contain substantial karst or contact aquifers. The entirety of the 3-D boundary is set to an aquitard background with no karst, contact or unsaturated bedrock zones.

HSU12 Ordovician Shale Aquiclude – Fluid Zones

The Queenston and Georgian Bay shale formations that comprise this HSU are thick and regionally extensive. Their volume occupies over 30% of the entire modelled volume of sedimentary bedrock (see Table 3). Due to its extent, thickness, shale composition and extremely low permeability, it has been classified as a regional aquiclude by Intera (2011) as adopted by Carter et al. (2021a). The weathered and fractured subcrop surface forms a well-developed and extensive contact aquifer, however there is no shallow karst. The entirety of the 3-D boundary is set to an aquiclude background with contact and unsaturated bedrock zones developed as described above.

HSU13 Trenton-Black River Aquitard – Fluid Zones

This regionally extensive HSU covers the entire model area to the Canadian Shield Precambrian margin to the northeast. It consists mainly of low porosity/very low permeability limestone formations with a shaly formation at the base. Their combined volume occupies close to 29% of the entire modelled volume of sedimentary bedrock (see Table 3). Karst and contact aquifers can occur in subcropping limestone formations of this HSU. The entirety of the 3-D boundary is set to an aquitard background. Intera et al. (2011) have classified the Trenton Group limestones as an aquiclude, with average porosity of 2.4% and horizontal hydraulic conductivity of 4×10^{-15} to 1×10^{-14} m/s, and the Black River Group as an aquitard, with average porosity of 1.4% and horizontal hydraulic conductivity of 2×10^{-11} to 1×10^{-12} m/s. Carter et al. (2021a) combine the Trenton and Black River Group into a single regional aquitard. The karst aquifer, contact aquifer and unsaturated bedrock outcrop zones were developed in the same way as described for other HSUs above.

HSU14 Cambrian Aquifer – Fluid Zones

Apart from a minor area on the eastern extremity of the study area to the east, the vast majority of the Cambrian does not subcrop in the model area. The bulk of the Cambrian Aquifer is sandstone with subordinate dolostone. All water intervals reported in petroleum well records are "salt water" (brine) with TDS values ranging from 174,000 to 423,000 mg/L (Carter et al. 2021a). Only the small outlier of Cambrian to the east is subdivided into fresh water zones and unsaturated bedrock outcrop. The

Cambrian Aquitard is divided into 1-Unsaturated Bedrock Outcrop, 2-Fresh Water Contact, 3- Fresh Water Undifferentiated and 4-Brine. The entirety of the 3-D boundary is first set to a brine water background. Using manual editing, the small portion to the east is classified as undifferentiated fresh water using an 'erosional' contact type. The contact aquifer zone and unsaturated bedrock outcrop zone are lastly applied similarly as described above.

HSU15 Precambrian Aquitard

The crystalline Precambrian basement forms the base of the 3-D model beneath the entire study area. It is classified everywhere as an aquitard and it forms the lower boundary of the hydrostratigraphic model.

Static Water Level (SWL) Surfaces

Stable isotopic compositions of oxygen and hydrogen for the three hydrochemical groundwater regimes indicate two origins for the water in these hydrochemical regimes: 1) ancient, evaporated seawater (brine) and 2) meteoric water originating either as modern precipitation or as glacial meltwater (fresh+sulphur water) (Dollar 1988, Dollar et al. 1991, Skuce 2014, Skuce et al. 2015, Carter et al. 2021a). Consequently Static Water Surfaces (SWL) surfaces for these two populations of water were interpolated separately. This also reduced somewhat the density effects of varying TDS on the observed static levels. The resulting static level surfaces have not been corrected for density, consequently, flow directions cannot be reliably inferred, however, these surfaces give the user a realistic sense of the fluid level to be expected should a borehole be drilled and cased to a specific HSU.

Static level data recorded in the petroleum well records was used to construct five SWL surfaces for the confined bedrock aquifers: 1) Lucas-Dundee Aquifer –fresh+sulphur, 2) Bass Islands Aquifer – fresh+sulphur, 3) Guelph Aquifer – brine, 4) Guelph Aquifer – fresh+sulphur, and 5) Cambrian Aquifer – brine. A separate data set was created for each aquifer, within which the data was filtered to include only the water types being interpolated. The filtered data used for each static level surface is included in the model as a data layer (e.g., Static_Water_Level_Guelph_brine_data_points).

Anomalous data points were identified visually and removed during examination of preliminary interpolated SWL surfaces in 3-D context. Data points were identified as anomalous if they were single wells and if the reported static level differed by greater than 50 m from neighbouring wells. In the typical Leapfrog 3-D model workflow, 3-D volumes are developed after first estimating contact surfaces from borehole logs and/or 3-D vector objects. For the static water level, only the contact surfaces are of interest. Surfaces were interpolated using SWL point data sets as the only input source and without topographic DEM boundary constraints. To facilitate data vetting, preliminary surfaces are snapped closely to the data points, however this is relaxed for final surfaces. These surfaces can show the inferred potentiometric surface of these confined aquifers and when viewed in 3-D context with the surficial sediment DEM areas of groundwater discharge and potential artesian conditions may be identified.

The static level data for Guelph Aquifer brine has a range of several hundreds of metres for wells that are located only a few km apart within Lambton County, Huron County, Kent County, and western Middlesex and Elgin counties, corresponding to the interpinnacle Guelph paleokarst region of Carter et al. (2021a). This extreme range is interpreted to be the result of insufficient time provided for stabilization of static water levels before the measurements were taken, combined with considerable variation in permeability from well to well. Most of the wells in this area were drilled to total depth in the Guelph Formation and plugged and abandoned one to seven days later. To accommodate the data range a data volume (Guelph Aquifer: Static_Water_Level_Data_Range_Guelph_Aquifer_Brine) was constructed with an upper and lower surface constraining the range in observed values. The upper surface is interpreted to most accurately represent the static level of the Guelph Aquifer brine.

Lucas-Dundee Artesian Wells

Artesian flow of groundwater to the surface from confined bedrock aquifers is reported for a number of petroleum wells. Where these artesian flows comprise sulphur water (H_2S) they may constitute drilling hazards and risks to public safety. This is particularly common for the Lucas-Dundee Aquifer in Norfolk County along the Lake Erie shoreline and in the valleys of Big Creek and Big Otter Creek. This same sulphur water constitutes a corrosion hazard for steel casings and unprotected concrete infrastructure. Artesian conditions are recorded by a -1 value for the static level in OPDS. The location of wells for which artesian conditions are reported for the Lucas-Dundee Aquifer are included as a data layer in the 3-D model.

3-D Petroleum Pools

Although gas and oil occurrences ('shows') are documented in the OPD borehole database they are not used to generate pool boundaries as many record small quantities of hydrocarbons that occur outside the boundaries of commercially viable reservoirs. A rough estimated volume was developed separately for each pool from known pool extents as documented by OGSRL (2019). These 2-D pool extents were compiled over decades of petroleum exploration and research as documented above and assembled into a set of attributed digital polygons by OGSRL staff.

Preliminary attempts indicated that the sparse depth control for the producing intervals in petroleum wells within each pool, coupled with the relatively small size of many pools, made developing pool geometry based on borehole data impractical for a regional scale model. In addition, recorded petroleum occurrences and well completion intervals in boreholes often provide only the top depth of the productive interval, and many well completions are 'open hole' resulting in an overestimate of the productive interval. Without a well-defined bottom, the shape and lateral extent of pools are not possible to render with any reliability. Extensive seismic survey information would be needed to render plausible petroleum reservoir geometry, and the data that exists is proprietary and not centralized with the OGSRL.

The digital 2-D petroleum pool boundaries in the current version of the Pools and Pipelines map (OGSRL 2019) were used to generate the geographic boundaries for petroleum-producing or past-producing zones for this modelling project. A simple vertical wall model boundary was developed based on grouped 2-D petroleum boundary polygons to produce 3-D pool volumes. Polygons were grouped based on petroleum type (i.e., oil / natural gas) and on unique combinations of top and bottom productive formations as recorded in OGSRL records and reviewed and confirmed by project geologists. From the lithostratigraphic model layer volumes, all productive formations from the uppermost to the bottom were imported and merged for each combination. Merged formations were then limited horizontally to the extents of corresponding pool boundaries to produce the petroleum pool volumes.

Vertical wall petroleum pool zones are over-estimations of the actual pool volume as the sides and vertical extents are set to maximum pool extents. Actual pool thicknesses will likely taper outward horizontally from the centre of the pool, and they may also terminate above the base, or below the top, of merged formations. Because these pool volumes are overestimated and are not accurately rendered, they are developed separately and do not impact the development of the Fluid Zones. Only pool areas greater than 500 m^2 were used for this exercise to reduce computational complexity.

TDS Lockport

The TDS data (see above) for the Lockport Group has been interpolated as a 2-D isolines map to illustrate the downdip hydrochemical zonation of groundwater within the Lockport Group and the Guelph Aquifer. This map is displayed as five simple 2-D layers in the 3-D model (TDS Lockport), one for each contour level from <100,000 mg/L to >400,000 mg/L. Supplementing the 2-D layers, a 3-D interpolant, Water Lockport TDS contour mg/L, has been constructed as described above for HSU09 Guelph Aquifer Fluid Zones. Data points are represented in Water Lockport TDS data points.

Results

Like the 3-D lithostratigraphic model, the hydrostratigraphic model can be explored using free viewer software available from the developer's website as of publication date at https://www.seequent.com/products-solutions/leapfrog-viewer/. It is an invaluable tool for visualization of regional hydrostratigraphic relationships and observation of regional trends. Leapfrog® Viewer includes simple tools that can be used to view the model, create slices, export views, rotate or zoom the model, add/remove layers, add transparency, etc. Additionally, model layer volumes are available in Open Mining Format (OMF) and 3-D DXF file formats. These file formats allow some flexibility for importing the model into 3-D geological modelling applications (e.g. SKUA-GOCAD™, MODFLOW) to support more advanced analysis such as numeric groundwater modelling (e.g., Sykes et al. 2011; Khader et al. 2020).

Hydrostratigraphic Units

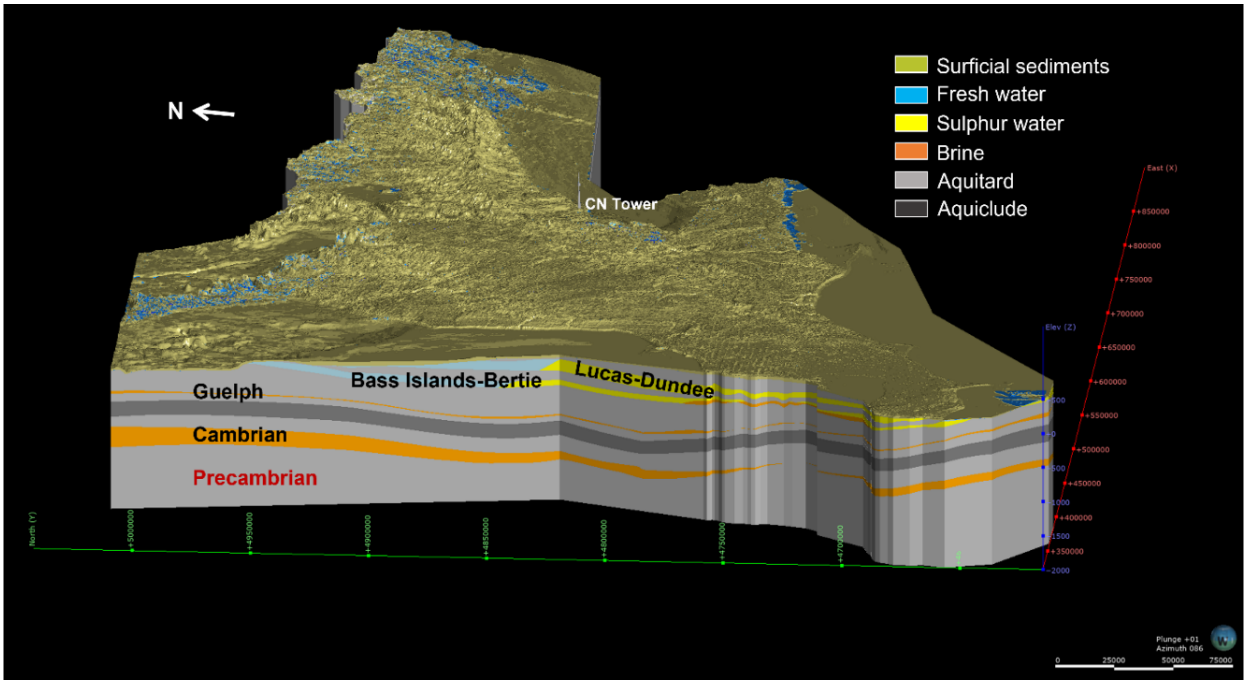


Figure 9. 3-D model of the hydrostratigraphy of southern Ontario looking east from Lake Huron showing thin regional aquifers confined by thick regional aquitards. Dominant water type within the aquifers is shown by colour coding. Model orientation was chosen to best illustrate downdip transition from fresh water to brackish sulphur water and brine in the Bass Islands-Bertie and Lucas-Dundee aquifers. Surficial sediments comprise a complex system of aquitards and aquifers which are modelled as a single layer with no subdivisions.

The final model is published with a vertical exaggeration of 20× to provide a practical display for viewing such a large geographic area with relatively thin HSUs and accentuates the apparent vertical size of HSUs and apparent dip. The sample model views (Fig. 9-16) are extracted from the model using Leapfrog Viewer and are chosen to illustrate some of the principal regional features of the model.

Shallow Inferred Karst

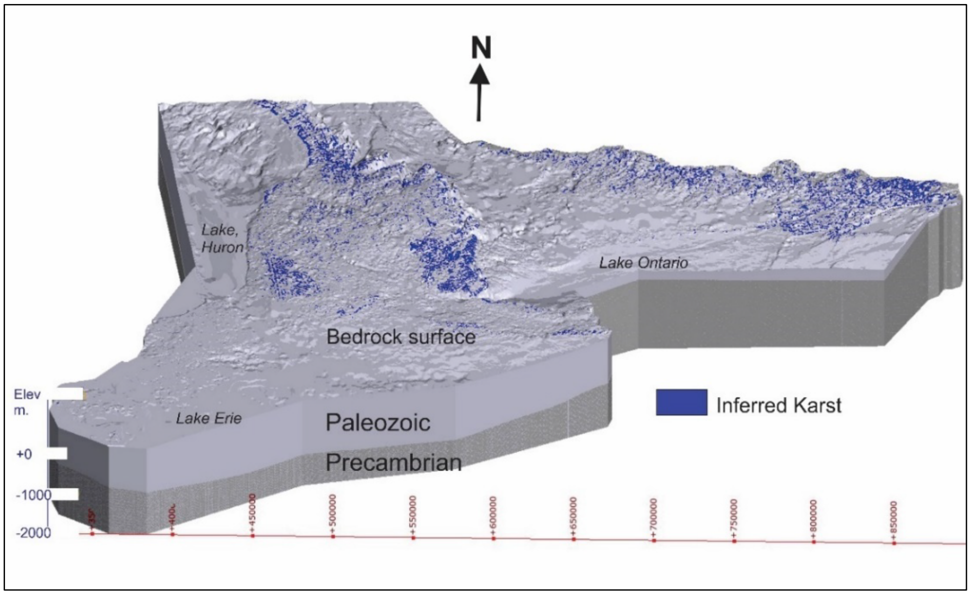


Figure 10. 3-D view of shallow inferred karst in subcropping bedrock in southern Ontario. The view looks north from the international border beneath Lake Erie.

Water Interval Data Cloud

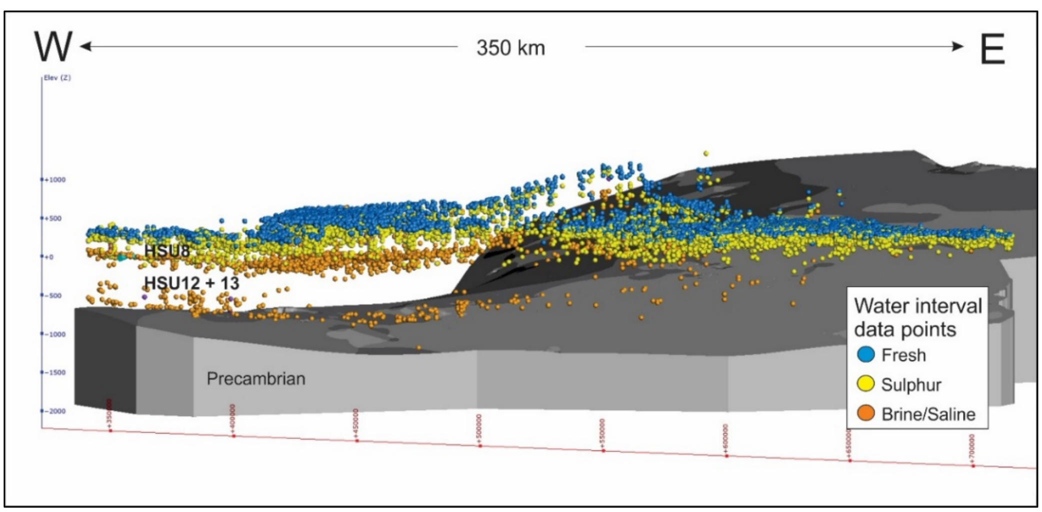


Figure 11. 3-D data cloud showing locations of recorded water intervals, colour-coded by water type, in petroleum wells in southern Ontario. The view looks north from the international border beneath Lake Erie. The hydrochemical zonation by depth is clearly displayed.

Static Level Surfaces

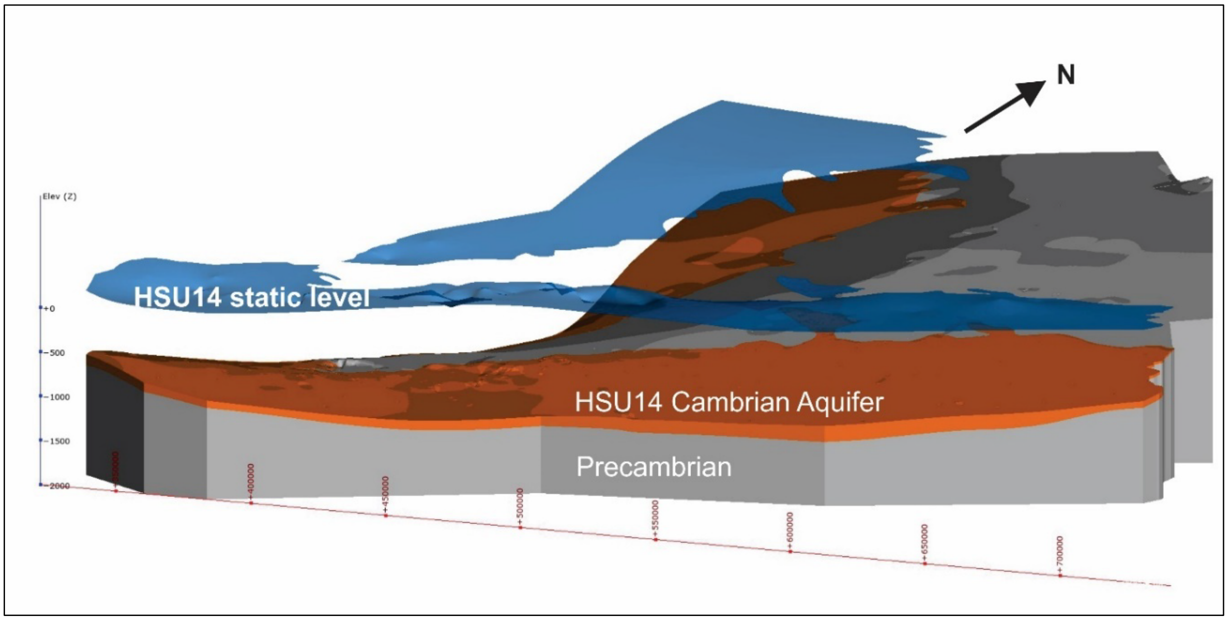


Figure 12. 3-D view of interpolated groundwater level of HSU14 Cambrian Aquifer brine, several hundred metres above the top of the aquifer. Data points used to construct the surface have not been corrected for density. The view looks northwest from the international border beneath Lake Erie.

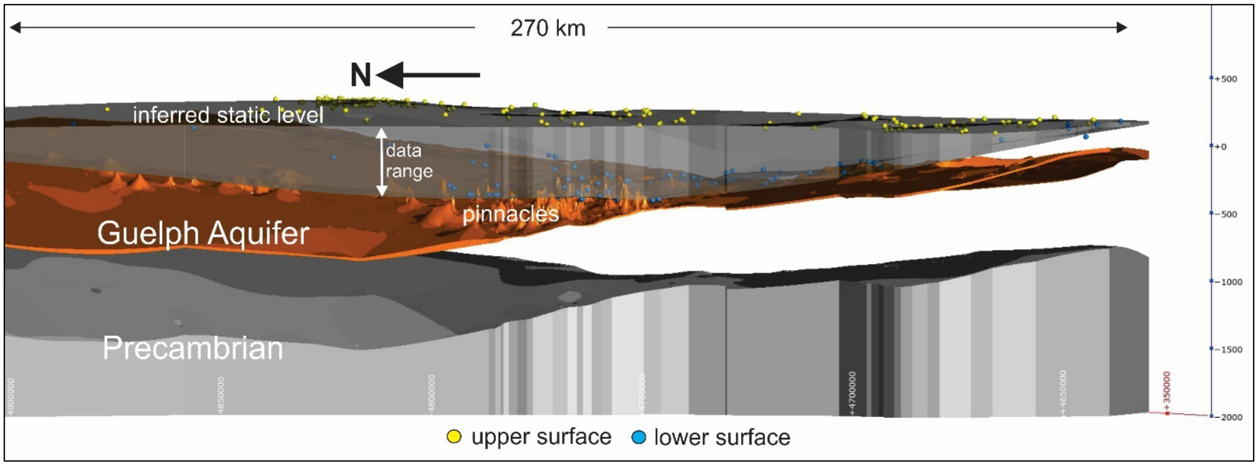


Figure 13. 3-D view of interpolated data range of reported static level values from petroleum well records for HSU09 Guelph Aquifer brine, showing interpolated surfaces of the upper and lower data limits. Data values have not been corrected for density. The view looks east from the international border with Michigan.

3-D Oil and Gas Reservoirs

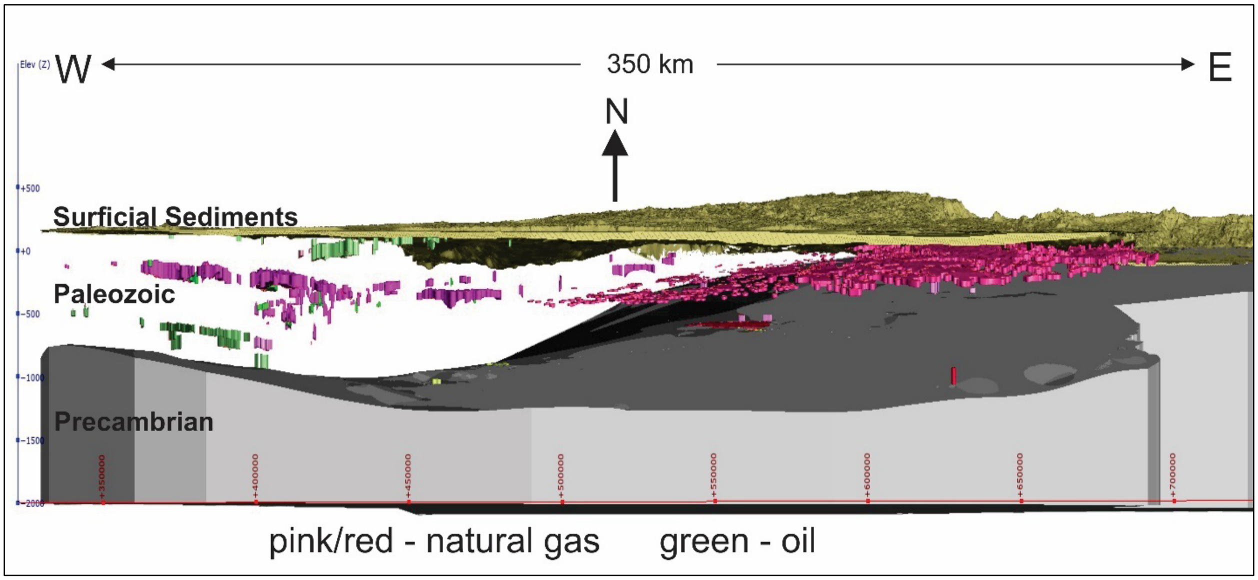


Figure 14. 3-D view of oil and gas reservoirs in southern Ontario, colour coded as oil (green) and natural gas (pink, red). The view looks north from the international border beneath Lake Erie.

Oil and Gas Intervals Data Cloud

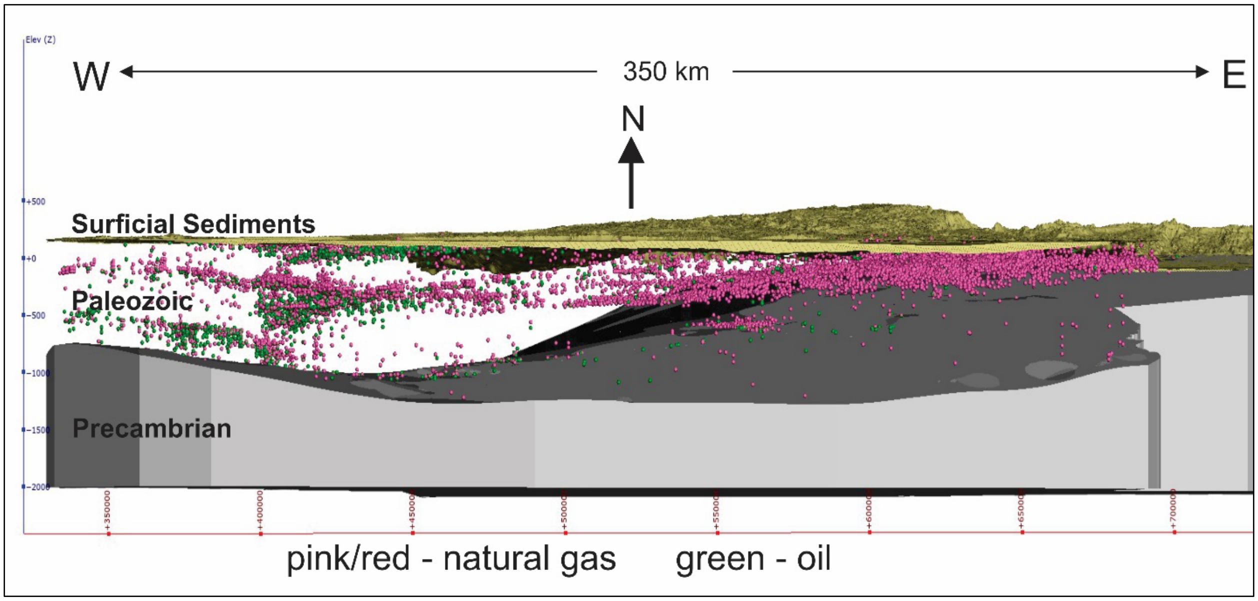


Figure 15. 3-D data cloud showing locations of recorded oil and gas intervals, colour coded as oil (green) and natural gas (pink, red). The view looks north from the international border beneath Lake Erie.

TDS Lockport Group

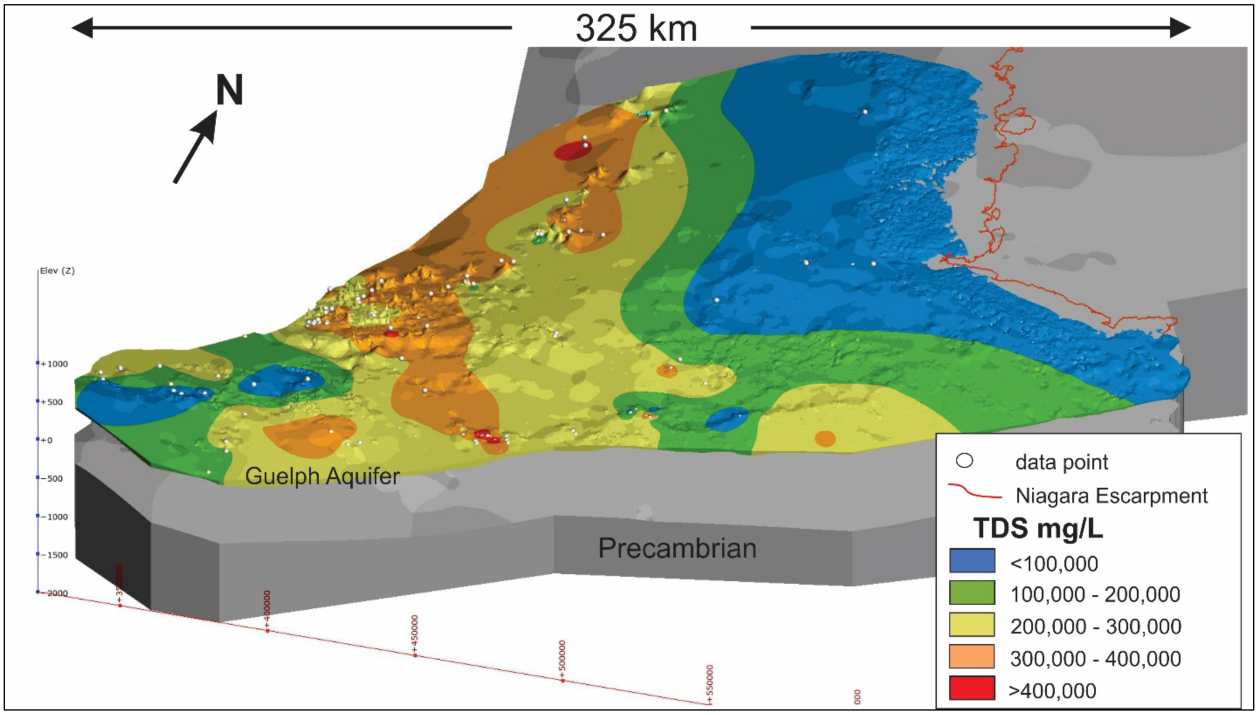


Figure 16. 3-D interpolant of petroleum industry TDS analytical data from the Lockport Group of formations. The view looks northwest from the international border beneath Lake Erie.

Discussion

Priorities for further data acquisition and data issues to reduce uncertainty about the accuracy/reliability of model layers include:

- extreme variations in static levels recorded in petroleum well records for closely spaced wells, in particular for the Cambrian Aquifer and the brine component of the Guelph Aquifer
- low data density in many parts of southern Ontario
- sparse petroleum wells and water interval data in the area between the shallow fresh water regime and the intermediate sulphur water regime
- compilation and verification of petroleum industry hydrochemical data for aquifers in addition to the Guelph Aquifer

Further research is recommended on:

- Confirmation of inferred flow directions for the Cambrian Aquifer and the brine component of the Guelph Aquifer.
- Microbial activity in subsurface aquifers and its role in development of observed hydrochemical relationships.
- Hazard mapping of groundwaters with hydrochemistry that is corrosive to steel and concrete infrastructure, and areas where these waters exhibit artesian flow at the ground surface.

- Mapping of springs and artesian flow from confined aquifers.
- Timing of dissolution of salt beds of the Salina Group and implications for subsurface fluid movement and pathways for fluid movement.
- Interpolation of petroleum industry analytical data for all confined bedrock aquifers.
- Groundwater age simulation for each aquifer.
- Uncertainty analysis

The user should be aware that the digital model is very large at 1.5 Gb. The viewer software may demand more graphic performance than many mid-range personal computers possess. Consequently, viewing may require an upgraded graphics card to optimize performance. There are 134 entries in the model legend with names that are intended to be self-explanatory. Nevertheless this number of legend entries is challenging to navigate in the limited space of the column view and it is highly recommended that the report be used as a guide when using the model.

The 3-D bedrock model has been adopted as a teaching tool in undergraduate geology at the University of Waterloo (Johnston et al. 2020; Kamutzi et al. 2020; Kamutzi 2020; Worthington 2019) and at the University of Toronto at Scarborough (Heidi Daxberger, personal communication, 2022). It is anticipated that the 3-D hydrostratigraphic model will have similar value as an educational resource (e.g., Russell et al. 2022).

Summary

A 3-D hydrostratigraphic model of the bedrock of southern Ontario has been completed utilizing Leapfrog Works©, an implicit modelling application. There are 15 modelled HSUs of which 13 represent aquifers and aquitards in the Paleozoic bedrock with additional layers representing the Precambrian basement and overlying unconsolidated Quaternary sediments. Model spatial resolution is 400 m. with a 20× vertical exaggeration. Borehole records in Ontario's public petroleum well database (OPDS) are the principal data source, supplemented with MECP water well records. The model was based on HSUs defined and described by Carter et al. (2021a) and constructed from lithostratigraphic units in Carter et al. (2021b). In addition to the 15 modelled HSUs, the 3-D model includes:

- hydrochemical fluid zones within each HSU
- hydrostratigraphic chart
- 3-D data points for all oil gas and water intervals in the OPDS petroleum well records
- static level surfaces for the principal confined bedrock aquifers (not corrected for density)
- the base of fresh water and inferred shallow karst
- the contact aquifer
- 3-D oil and gas reservoirs
- petroleum wells exhibiting artesian flow of sulphur water from the Lucas-Dundee Aquifer
- a 3-D interpolant of TDS data for the Lockport Group showing downdip increase in salinity within the Guelph Aquifer

Further improvements to the geological/hydrogeological data infrastructure of southern Ontario have been made, building on previous improvements. Perhaps most importantly, the model illustrates the value of properly designed and maintained borehole data sets for regional geologic and hydrogeologic modelling. Without these data sets it would not have been possible to construct this model.

Acknowledgements

This project could not have been completed without the extensive archive of physical and digital petroleum well data collected, managed, and maintained by the Petroleum Operations Section of the NDMNRF and the OGSRL. The Ontario Oil, Gas and Salt Resources Corporation, through the Ontario Petroleum Institute, is thanked for providing administrative and management support to the OGSRL in its role as Trustee of the Oil, Gas and Salt Resources Trust.

An internal review at the GSC by Nicolas Benoit is much appreciated. Funding for this project was provided by Nuclear Waste Management Organization (NWMO) and GSC. This work was completed as part of the GSC Open Geoscience Program, Canada 3-D project and Groundwater Geoscience Program.

References

This reference list does not include citations in the Appendices.

Armstrong, D.K. and Carter, T.R. 2010. The subsurface Paleozoic stratigraphy of southern Ontario; Ontario Geological Survey, Special Volume 7, 301p.

Armstrong, D.K. and Dodge, J.E.P. 2007. Paleozoic geology of southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 219.

Bailey Geological Services Ltd. and Cochrane, R.O. 1984a. Evaluation of the conventional and potential oil and gas reserves of the Cambrian of Ontario; Ontario Geological Survey, Open File Report 5499, 72p.

——— 1984b. Evaluation of the conventional and potential oil and gas reserves of the Ordovician of Ontario; Ontario Geological Survey, Open File Report 5498, 77p.

——— 1985. Evaluation of the conventional and potential oil and gas reserves of the Devonian of Ontario (Volume 1); Ontario Geological Survey, Open File Report 5555, 178p.

——— 1986. Evaluation of the conventional and potential oil and gas reserves of the Silurian sandstone reservoirs of Ontario; Ontario Geological Survey, Open File Report 5578, 275p.

———1990. Geology of selected oil and gas pools in the Silurian carbonates of southern Ontario; Ontario Geological Survey, Open File Report 5722, 50p.

Banks, W.D. and Brunton, F.R. 2017 Collaboration between Ontario Geological Survey, consultants and municipal staff results in discovery and development of a safe and sustainable bedrock groundwater supply for the Town of Shelburne, southern Ontario; *in* International Association of Hydrogeologists Canada, GeoOttawa 2017 – 70 years of Canadian Geotechnics and Geosciences, p.1-6.

Brunton, F.R. 2009a. Karst mapping and groundwater of southern Ontario; *in* Groundwater and Geology – Foundation for Watershed Planning, Latornell Conference, pre-meeting core workshop, November 17, 2009, p.1-15.

——— 2009b. Update of revisions to the Early Silurian stratigraphy of the Niagara Escarpment: Integration of sequence stratigraphy, sedimentology and hydrogeology to delineate hydrogeologic units; *in* Summary of Field Work and Other Activities 2009, Ontario Geological Survey, Open File Report 6240, p.25-1 to 25-20.

——— 2013. Karst and hazards lands mitigation – Some guidelines for geological and geotechnical investigations in Ontario karst terrains; *in* Summary of Field Work and Other Activities, 2012; Ontario Geological Survey, Open File Report 6290, p.37-1 to 37-24.

Brunton, F.R., Belanger, D., DiBiase, S., Yungwirth, G., and Boonstra, G. 2007. Caprock carbonate stratigraphy and bedrock aquifer character of the Niagara Escarpment – City of Guelph region, southern Ontario; *in* Diamond Jubilee Canadian Geotechnical Conference and the 8th Joint CGS/IAH-CNC Groundwater Conference, Ottawa, Ontario, October 21–24, 2007, p.371-377.

Brunton, F.R., and Brintnell, C. 2011. Final update of early Silurian stratigraphy of the Niagara Escarpment and correlation with subsurface units across southwestern Ontario and the Great Lakes Basin. Ontario Geological Survey, Summary of field work and other activities, p.30-1 to 30-11.

Brunton, F.R. and Brintnell, C. 2020. Early Silurian sequence stratigraphy and geological controls on karstic bedrock groundwater flow zones, Niagara Escarpment region and the subsurface of southwestern Ontario; Ontario Geological Survey, Groundwater Resources Study 13.

Brunton, F., Brintnell, C., Jin, J., and Bancroft, A., 2012. Stratigraphic architecture of the Lockport Group in Ontario and Michigan - A new interpretation of early Silurian basin geometries and Guelph pinnacle reefs; Ontario Petroleum Institute, Proceedings, 51st Annual Conference, 37 p.

Brunton, Frank R., Carter, T.R., Logan, C., Clark, J., Yeung, K., Fortner, L., Freckelton, C., Sutherland, L., and Russell, H.A.J. 2017. Lithostratigraphic compilation of Phanerozoic bedrock units and 3D geological model of southern Ontario; in Regional-scale Groundwater Geoscience in Southern Ontario: an Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario open house, compiled by H.A.J Russell, D. Ford and E.H. Priebe, Geological Survey of Canada, Open File 8212, p.3.

Brunton, F.R. and Dodge, J.E.P. 2008. Karst of southern Ontario and Manitoulin Island; Ontario Geological Survey, Groundwater Resources Study 5.

Brunton, F.R., Priebe, E.H., and Yeung, K.H. 2016. Relating sequence stratigraphic and karstic controls of regional groundwater flow zones and hydrochemistry within the Early Silurian Lockport Group of the Niagara Escarpment, southern Ontario; *in* Regional-Scale Groundwater Geoscience in Southern Ontario: An Ontario Geological Survey and Geological Survey of Canada Groundwater Geoscience Open House, Geological Survey of Canada, Open File 8022, p.4. https://doi.org/10.4095/297722.

Carter, T.R. 2012. All is well – Regional groundwater systems in southern Ontario; Ontario Oil & Gas 2012, Ontario Petroleum Institute, p.44-48.

Carter, T.R., Brunton, F.R., Clark, de Kemp, E. L., Logan, C.E., and Russell, H.A.J. 2020. 3-D geological and hydrogeological modelling of the bedrock geology of southern Ontario. Canadian Society of Petroleum Geologists, Geoconvention 2020, abstract.

Carter, T.R., Brunton, F.R., Clark, J., Fortner, L., Freckelton, C.N., Logan, C.E., Russell, H.A.J., Somers, M., Sutherland L., and Yeung, K.H. 2017. Status report on three-dimensional geological and hydrogeological modelling of the Paleozoic bedrock of southern Ontario; *in* Summary of Field Work and Other Activities, 2017, Ontario Geological Survey, Open File Report 6333, p.28-1 to 28-15.

——— 2019. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario. Ontario Geological Survey, Groundwater Resources Study 19 / Geological Survey of Canada, Open File 8618. https://doi.org/10.4095/315045

Carter, T.R. and Clark, J. 2018. Base of fresh water, inferred bedrock karst, and the contact aquifer in southern Ontario, as interpreted from water well records; Oil, Gas and Salt Resources Library, Open File Data Release 2018-1, 16p.

Carter, T.R., Clark, J., Colquhoun, I, Dorland, M., Phillips, A., 2016a. Ontario oil and gas plays 1 – exploration, production and geology. Canadian Society of Petroleum Geologists, Reservoir 43, issue 08, 19-25.

Carter, T.R. and Fortner, L. 2012. Regional bedrock aquifers and a geological groundwater model for southern Ontario; International Association of Hydrogeologists, 39th International Congress, Session TH1-G, Abstract 369, p.238.

Carter, T.R., Fortner, L.D., Russell, H.A.J., Skuce, M.E., Longstaffe, F.J., and Sun, S., 2021a. A hydrostratigraphic framework for the Paleozoic bedrock of southern Ontario. Geoscience Canada, v. 48, p. 23-58, https://doi.org/10.12789/geocanj.2021.48.172

Carter, T.R., Fortner, L., Skuce, M.E., and Longstaffe, F.J. 2014. Aquifer systems in southern Ontario: Hydrogeological considerations for well drilling and plugging; abstract, Canadian Society of Petroleum Geologists, Geoconvention-2014.

Carter, T., Gunter, W., Lazorek, M., and Craig, R. 2007. Geological sequestration of carbon dioxide: A technology review and analysis of opportunities in Ontario; Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Climate Change Research Report CCRR-07, 24p.

Carter, T.R., Hamilton, D., Phillips, A., Dorland, M., Colquhoun, I., Fortner, L., and Clark, J. 2016b. Ontario oil and gas 3. Silurian and Devonian conventional plays; Canadian Society of Petroleum Geologists, Reservoir v.43, issue 10, p.18-26.

Carter, T.R., Logan, C.E., Clark, J.K., Russell, H.A.J., Brunton, F.R., Cachunjua, A., D'Arienzo, M., Freckelton, C., Rzyszczak, H., Sun, S., and Yeung, K.H., 2021b. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario—version 2. Geological Survey of Canada, Open File 8795, 1 .zip file. https://doi.org/10.4095/328297

Carter, T.R., Russell, H.A.J., Fortner, L.D., Clark, J.K., Logan, C., and Sun, S., 2020b. Development of a 3-D hydrostratigraphic model for the bedrock of southern Ontario. Geological Society of America, Abstracts with Programs 52, no.6.

Carter, T.R. and Sutherland, L. 2018. Mapping the interface between the intermediate sulphur water regime and deep brine in the Paleozoic bedrock of southwestern Ontario; Oil, Gas and Salt Resources Library, Open File Data Release 2018-2, 22p.

——— 2020. Interface mapping of hydrochemical groundwater regimes in the Paleozoic bedrock of southwestern Ontario; *in* Russell, H.A.J. and Kjarsgaard, B.A. (eds.), Summary of Southern Ontario Groundwater Project 2014–2019; Geological Survey of Canada, Open File 8536. https://doi.org/10.4095/321078

Carter, T.R., Wang, D., Castillo, A.C., and Fortner, L. 2015a. Water type maps of deep groundwater from petroleum well records, southern Ontario; Ontario Oil, Gas and Salt Resources Library, Open File Data Release 2015-1, 10p., 89 maps.

——— 2015b. Static level maps of deep groundwater from petroleum well records, southern Ontario; Ontario Oil, Gas and Salt Resources Library, Open File Data Release 2015-2, 11p., 17 maps.

Clark, J.K., Carter, T.R., Brunton, F.R., Fortner, L., Freckelton, C.N., Logan, C.E., Russell, H.A.J., Somers, M., Sutherland L., and Yeung, K.H. 2020. Improving the 3-D geological data infrastructure of southern Ontario: Data capture, compilation, enhancement and QA/QC; *in* Russell, H.A.J. and Kjarsgaard, B.A. (eds.), Summary of Southern Ontario Groundwater Project 2014–2019; Geological Survey of Canada, Open File 8536. https://doi.org/10.4095/321078

Dollar, P.S. 1988. Geochemistry of formation waters, southwestern Ontario, Canada and Michigan, USA: Implications for origin and evolution. University of Waterloo, Ontario, unpublished MSc thesis, 129 p.

Dollar, P.S., Frape, S.K., and McNutt, R.H. 1991. Geochemistry of formation waters, southwestern Ontario, Canada and Michigan, USA: Implications for origin and evolution. Ontario Geological Survey, Open File Report 5743, 72 p.

Dorland, M., Colquoun, I, Carter, T.R., Fortner, L, Clark, J., and Hamilton, D. 2016. Ontario oil and gas: Cambrian and Ordovician conventional plays; Canadian Society of Petroleum Geologists, Reservoir v.43, issue 09, p.18-25.

Freckelton, C.N. 2012. A physical and geochemical characterization of southwestern Ontario's breathing well region; University of Western Ontario, unpublished MSc thesis, electronic thesis and dissertation repository, 1105, https://ir.lib.uwo.ca/etd/1105

Gao, C., Shirota, J., Kelly, R.I., Brunton, F.R., and Van Haaften, S. 2006. Bedrock topography and overburden thickness mapping, southern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 207.

Hobbs, M.Y., Frape, S.K., Shouakar-Stash, O. and Kennell, L.R. 2011. Regional hydrogeochemistry—Southern Ontario; Nuclear Waste Management Report NWMO DGR-TR-2011-12, Toronto, Canada.

Husain, M.M., Cherry, J.A., and Frape, S.K. 2004. The persistence of a large stagnation zone in a developed regional aquifer, southwestern Ontario; Canadian Geotechnical Journal, v.41, p.943-958.

Intera Engineering Ltd. 2011. Descriptive geosphere site model. Nuclear Waste Management Organization, Report NWMO DGR-TR-2011-24, 425 p.

Itasca Consulting Canada Inc. and AECOM Canada Ltd. 2011. Three-dimensional geological framework model; Nuclear Waste Management Organization, Report DGR-TR-2011-42, 16p. PDF document, accessed at: http://www.opg.com/generating-power/nuclear/nuclear-waste-management/Deep-Geologic-Repository/Pages/Project-Development.aspx, under "Geoscience Reports".

Johnston, J.W., Kamutzki, J., and Worthington, Q., 2020, A new learning framework that integrates the new three-dimensional geological model of Ontario's Paleozoic geology into undergraduate education of future geoscientists and engineers at the University of Waterloo. Geological Society of America Abstracts with Programs, Vol 52, No. 6 doi: 10.1130/abs/2020AM-358555; https://gsa.confex.com/gsa/2020AM/meetingapp.cgi/Paper/358555

Kamutzki, J. 2020. Using the new 3D digital model of Ontario's Paleozoic geology to bridge gaps in the traditional education framework, Undergraduate BSc Honours Thesis, Department of Earth Sciences, University of Waterloo, Waterloo, Ontario, UWSpace. http://hdl.handle.net/10012/15747

Kamutzki, J., Worthington, Q., and Johnston, J. 2020. Using the new 3D digital model of Ontario's Paleozoic geology to bridge gaps in the traditional education framework, In Priebe, E.H., Holysh, S., Ford, D., Russell, H.A.J. and Nadeau, J.E. (compilers), Regional-scale groundwater geoscience in southern Ontario: An Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Geoscientists Open House. Ontario Geological Survey, Open File Report 6361, 46p.

Khader, O., Frey, S.K., Taylor, A., Lapen, D., Sudicky, E.A., Berg, S., and Russell, H. 2020. Transitioning a regional-scale geological model to a workable 3-dimensional hydrostratigraphic model for large-scale integrated groundwater-surface water modelling. Geological Society of America, Programs with Abstracts, 52, no.6.

Lemieux, A., Sharp, K., Shkarupin, A., 2019. Preliminary assessment of underground hydrogen storage sites in Ontario, Canada. Int. J. Hydrogen Energy 44, 15193–15204. http://dx.doi.org/10.1016/j.ijhydene.2019.04.113.

Logan, C.E., Russell, H.A.J., Bajc, A.F., Burt, A., Mulligan, R.P.M., and Sharpe, D.R. 2020. A three-dimensional surficial geology model of southern Ontario: progress report. Geological Survey of Canada, Open File 8536, Southern Ontario groundwater project 2014-2019: summary report, pp. 49–64, Natural Resources Canada. https://doi.org/10.4095/321078

Maxey, G.B. 1964. Hydrostratigraphic units; Journal of Hydrology v.2, p.124-129.

McNutt R.H., Frape S. K. and Dollar P. 1987. A strontium, oxygen and hydrogen isotopic composition of brines, Michigan and Appalachian Basins, Ontario and Michigan. Applied Geochemistry 2, 495-505.

Muhammed, N.S., Haq, B., Shehri, D.A., Al-Ahmed, A., Rahman, M.M., Zaman, E., 2022. A review on underground hydrogen storage: Insights into geological sited, influencing factors and future outlook. Energy Reports 8, 461-499,

Nuclear Waste Management Organization, 2011. Geosynthesis; Nuclear Waste Management Report NWMO DGR-TR-2011-11, PDF document, accessed at: http://www.opg.com/generating-power/nuclear/nuclear-waste-management/Deep-Geologic-Repository/Pages/Project-Development.aspx, under "Geoscience Reports", accessed on June 30, 2014.

Nuclear Waste Management Organization, 2018. Implementing Adaptive Phased Management 2018 to 2022. Nuclear Waste Management Organization, at: https://www.nwmo.ca/~/media/Site/Reports/2018/03/27/21/54/EN_Implementing_APM_2018_to_2022_final_web.ashx?la=en

Oil Gas and Salt Resources Library, 2019. Oil & gas pools and pipelines of southern Ontario. Oil, Gas and Salt Resources Library, map, 1:400,000

Priebe, E.H. and Brunton, F.R. 2016. Regional-scale groundwater mapping in the Early Silurian carbonates of the Niagara Escarpment: Final Update; *in* Summary of Field Work and Other Activities, 2016; Ontario Geological Survey, Open File Report 6323, p.29-1 to 29-10.

Priebe, E.H., Brunton, F.R., Rudolph, D.L., and Neville, C.J. 2019. Geologic controls on hydraulic conductivity in a karst-influenced carbonate bedrock groundwater system in southern Ontario, Canada; Hydrogeology Journal, v.27, p.1291-1308.

Priebe, E.H., Frape, S. K., Jackson, R.E., Rudolph, D.L., and Brunton, F.R. 2021. Tracing recharge and groundwater evolution in a glaciated, regional-scale carbonate bedrock aquifer system, southern Ontario, Canada. Applied Geochemistry, 124.

Priebe, E.H, Neville, C.J., and Brunton, F.R. 2014. Evaluating the influence of geological features on hydraulic conductivity variability in Early Silurian carbonate rock aquifers of the Guelph region; *in* Summary of Field Work and Other Activities, 2014; Ontario Geological Survey, Open File Report 6300, p.35-1 to 35-8.

——— 2017. Discrete, high-quality hydraulic conductivity estimates for the Early Silurian carbonates of the Guelph Region; report *in* Ontario Geological Survey, Groundwater Resources Study 16, 45p., plus digital hydraulic test analyses.

Russell H.A.J., Clark, J., Daxberger, H. Johnston, J., and Carter, T.R. 2022. Visualizing the subsurface geology of southern Ontario: from virtual to tactile models; GAC/MAC annual meeting Halifax 2022. May 15-18th.

Seaber, P.R. 1988. Hydrostratigraphic units; *in* The Geology of North America, Hydrogeology; Decade of North American Geology series, v.O-2, Geological Society of America, p.9-14.

Shafeen, A., Croiset, E., Douglas, P., and Chatzis, I. 2004. CO2 sequestration in Ontario, Canada. Part I: Storage evaluation of potential reservoirs; Energy Conversion and Management v.45, issue 17, p.2645-2659.

Sharpe, D.R., Bajc, A.F., Burt, A.K., Logan, C., Mulligan, R.P.M., Russell, H.A.J., and Todd, B. 2017 Developments in a surficial stratigraphic framework for 3D geological modelling. Geological Survey of Canada, Open File Regional-scale groundwater geoscience in southern Ontario: an Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario open house, Natural Resources Canada. doi:10.4095/299800

Sharpe, D.R., Piggott, A., Carter, T., Gerber, R.E., MacRitchie, S.M., de Loë, R.C., Strynatka, S., and Zwiers, G. 2014. Southern Ontario hydrogeological region; *in* Canada's Groundwater Resources, Fitzhenry & Whiteside, p.443-499.

Singer, S.N., Chen, C., and Scafe, M.G. 2003. The hydrogeology of southern Ontario (2nd edition). Ministry of Environment, Hydrogeology of Ontario Series Report 1, 402 p.

Skuce, M.E. 2014. Isotopic fingerprinting of shallow and deep groundwaters in southwestern Ontario and its applications to abandoned well remediation; unpublished MSc thesis, University of Western Ontario, London, Ontario, Electronic thesis and dissertation repository, article 1926, 276p.

Skuce, M., Longstaffe, F.J., Carter, T.R. and Potter, J. 2015. Isotopic fingerprinting of groundwaters in southwestern Ontario: Applications to abandoned well remediation; Applied Geochemistry, v.58, p.1-13.

Skuce, M., Potter, J., and Longstaffe, F.J. 2015. The isotopic characterization of water in Paleozoic bedrock formations in southwestern Ontario; Ontario Oil, Gas and Salt Resources Library, Open File Data Release 2015-3.

Somers, M.R. 2017. Paleozoic bedrock geology of southern Ontario; Oil, Gas and Salt Resources Library, Open File Data Release 2017-2, pdf file, accessed at https://s3.amazonaws.com/downloads.ogsrlibrary.com/open/OFDR-2017-2-OGSR-Petroleum-Well-Subcrop-Revision.pdf, 2020-01-30.

Sykes, J.F., Normani, S.D., and Yin, Y. 2011. Hydrogeologic modelling, 2011; OPG's Deep Geologic Repository for low & intermediate level waste, NWMO DGR-TR-2011-16, 428p. accessed at: http://www.opg.com/generating-power/nuclear/nuclear-waste-management/Deep-Geologic-Repository/Pages/Project-Development.aspx , under "Geoscience Reports", accessed on June 30, 2014.

Waterloo Institute for Sustainable Energy 2021. Visioning workshop: CCS planning for southwestern Ontario for 2030. University of Waterloo, https://www.youtube.com/watch?v=6VVU9mYUtQ0

Worthington, Q. 2019, Comparing the Effectiveness of Different Learning Tools to Convey Geologic Concepts in a Second-Year Stratigraphy Course at the University of Waterloo, Undergraduate BSc Honours Thesis, Department of Earth Sciences, University of Waterloo, Waterloo, Ontario.

Appendix 1: Revised water interval assignments

Water types reported from petroleum wells are subjective descriptions by drillers of groundwater encountered during drilling and are the same as those recorded for water wells in WWIS.

Water Records Statistics

Formation/Unit	Totals	Water Records: Black		Brackish		Fresh		Loss of Circ.		Mineral		Salt		Sulphur		Sub-Totals		Unknown Water Type
		Type	Static Level	Type	Static Level	Type	Static Level	Type	Static Level	Type	Static Level	Type	Static Level	Type	Static Level	Type	Static Level	
Sum	**34633**	**1811**	**1375**	**116**	**72**	**14032**	**9970**	**107**	**2**	**171**	**65**	**4722**	**2030**	**12127**	**8475**	**33086**	**21989**	**1547**
Drift	**5399**	19	16	6	4	5062	3055	1		10	5	25	19	173	134	5296	3233	103
Port Lambton Group	**28**					24	13					1		2	2	27	15	1
Kettle Point	**1028**	4	3	1		960	520					15	9	27	19	1007	551	21
Hamilton Group	**947**	3		2		631	403			2	1	61	37	128	78	827	519	120
Dundee	**4029**	20	10	18	13	1632	1342	2		22	10	335	185	1901	1342	3930	2902	99
Columbus	**641**	18	8	2	2	25	19			5	4	130	86	446	251	626	370	15
Detroit River Group																		
Lucas	**3847**	45	28	23	18	387	262	22		35	19	449	251	2760	1847	3721	2425	126
Amherstburg	**2306**	82	70	5	4	1233	1021	5		16	4	24	8	737	546	2102	1653	204
Onondaga	**21**					4	4	1				1	1	13	9	19	14	2
Sylvania	**47**	6	3			6	5	1		3	1	1		27	18	44	27	3
Bois Blanc (total)	**1888**	68	53	16	4	605	496	3		11	4	69	33	1058	786	1830	1376	58
Bois Blanc	**1864**	67	52	16	4	603	495	3		11	4	67	31	1040	774	1807	1360	57
Springvale	**24**	1	1			2	1					2	2	18	12	23	16	1
Bass Islands	**3004**	369	288	8	4	756	602	23	1	18	5	163	63	1532	1021	2869	1984	135
Salina Group																		
G Unit	**141**	3	3	1		47	38	2		1	1	11	4	74	54	139	100	2
F Unit (total)	**1506**	130	98	2	1	769	662	4		6		27	8	479	368	1417	1137	89
F Unit	**1497**	129	97	2	1	768	661	4		6		24	8	477	366	1410	1133	87
F Salt	**9**	1	1			1	1					3		2	2	7	4	2
E Unit	**1311**	109	80	3	3	661	567	3		2		20	7	433	349	1231	1006	80
D Unit	**1**					1		1								2		
C Unit	**372**	25	20			169	146	1		3	2	2	2	134	116	334	286	39
B Unit (total)	**525**	41	29			272	225	3		2		26	15	148	111	492	380	33
B Unit (B Marker)	**470**	38	27			251	208	2		2		16	9	134	102	443	346	27
B Salt	**11**											9	5	1		10	5	1
B Equvialent	**7**	1	1			2	2	1				1	1	1	1	6	5	1
B Anhydrite	**37**	2	1			19	15							12	8	33	24	4
A-2 Unit (total)	**632**	22	12	2	2	146	111			2		281	80	151	117	604	322	28
A-2 Carbonate	**597**	22	12	2	2	144	109			2		255	72	147	115	572	310	25
A-2 Shale	**11**					2	2					8	3	1	1	11	6	
A-2 Anhydrite	**16**											10	3	3	1	13	4	3
A-2 Salt	**8**											8	2			8	2	
A-1 Unit (total)	**570**	6	6	2	2	50	43	2		5	2	353	130	117	74	535	257	35
A-1 Carbonate	**553**	6	6	2	2	50	43	2		5	2	337	122	116	74	518	249	35
A-1 Evaporite	**17**											16	8	1		17	8	
Lockport Group																		
Guelph	**4848**	815	630	14	11	391	304	4	1	21	6	1814	731	1622	1133	4681	2816	167
Eramosa	**54**	4	4			14	11					2	1	32	29	52	45	2
Goat Island	**186**			1		3	3	2		1		120	54	51	25	178	82	8
Gasport	**166**	1				6	3	1				123	48	31	18	162	69	4
Clinton Group																		
Rochester	**67**	15	11			2		1		2		20	6	19	13	59	30	8
Irondequoit	**28**	3	2			5	5					16	2	1		25	9	3
Reynales/Fossil Hill	**49**	2	1			8	7	1				9	5	4	1	24	14	25
Thorold	**13**											5	2			5	2	8
Medina Group																		
Grimsby	**43**					1						22	9	3	1	26	10	17
Cabot Head	**26**			1		11	7					10	6	3		25	13	1
Manitoulin	**11**					6	4					3	1	1	1	10	6	1
Whirlpool	**40**			2	1	3	2					31	5	3	3	39	11	1
Queenston	**96**			3	3	73	58			1		10	4			87	65	9
Georgian Bay-Blue Mountain	**68**			2		38	16					17	3	5	4	62	23	6
Trenton Group																		
Trenton (unsubdivided)	**56**					10	5			2		29	10	6	4	47	19	9
Collingwood	**5**					1	1					1		1		3	1	2
Cobourg	**94**	1				7	7	1				53	8			62	15	31
Sherman Fall	**56**					2		3				32	9	1	1	38	10	18
Kirkfield	**31**					3	1	2				16	4			21	5	10
Black River Group																		
Black River (unsubdivided)	**16**					2	1					11	3	1		14	4	2
Coboconk	**50**					2		6				33	7	1		42	7	8
Gull River	**62**			2		2		9				38	6	1		52	6	10
Shadow Lake	**23**					1		2				18	10	1		22	10	1
Cambrian																		
Cambrian (unsubdivided)	**245**							1		1	1	242	123			244	124	1
Mount Simon/Potsdam	**9**					1	1					8	5			9	6	
Eau Claire/Theresa	**11**											10	9			10	9	1
Trempealeau/Little Falls	**37**											35	21			35	21	1

Appendix 2: QA/AC of oil, gas and water analyses and water intervals assigned to the Dundee Formation and Lockport Group formations

Report by: Candace Freckelton, Alex Cachunjua, Ramen Tolo and Zohreh Ghorbani

Geology by: Candace Freckelton, Alex Cachunjua, Hanna Rzyszczak, Ramen Tolo, and Zohreh Ghorbani
Statistics by: Maryrose D'Arienzo and Andrew Koberstadt

Executive Summary

A Quality Assurance and Quality Control (QA/QC) review has been completed to; improve the accuracy of oil, gas and water analytical data recorded for petroleum wells in the Ontario Petroleum Data System (OPDS), review and verify the formation assignments for water intervals currently attributed to the Dundee and Lockport Group formations, and document potential errors for 35,000 reported water intervals encountered by petroleum wells. This work supports the development of a 3-D hydrostratigraphic model for Southern Ontario. This data is managed by the Oil Gas and Salt Resources Library (OGSRL) in London, Ontario.

A total of 1,759 records for oil, gas and water analyses from 967 wells have been reviewed and updated. This includes examining, verifying and updating the depth interval and formation assignment for all 245 oil analyses, 491 gas analyses and 1,023 water analyses.

Previous QA/QC reviews had identified a large number of wells penetrating the Dundee Formation which also penetrate underlying Devonian formations but do not have formation tops recorded for the deeper formations. This included, but was not limited to, the Columbus, Lucas, Sylvania, Amherstburg/Onondaga, and Bois Blanc formations. Consequently, water intervals encountered in these wells may have been incorrectly assigned to the Dundee Formation. A total of 1,403 water intervals assigned to the Dundee Formation were reviewed for 692 wells. QA/QC results showed 974 water formation assignments were confirmed, 409 water formation assignments were edited, and 8 were added, having not been previously recorded. A total of 12 water intervals were deleted as a result of erroneous data entry. Additionally, water interval assignments were reviewed for Lockport Group formations for which recent formation top edits were completed (Carter et al. 2021b). A total of 1415 Lockport water intervals for 713 wells were reviewed, and 44 water intervals were removed/deleted either as a result of typographic errors or record duplications in the database. Prior to QA/QC, there were 304 waters assigned to the Lockport group, 297 of which were designated as Guelph formation. Following QA/QC review, the Lockport group had 278 water assignments, with 226 assigned to the Guelph formation.

A QA/QC review to identify sources of error for 35,000 water intervals records has been completed, but a full data review and update has not been completed. Sources of error include digital entry typographical errors, incorrect and/or outdated formation water interval assignment, imperial to metric unit conversion errors, missing data, and lack of data for the bottom depths of water intervals.

Introduction and Purpose

The principal source data for identification and modelling of groundwater aquifers and aquitards in the subsurface Paleozoic bedrock of southern Ontario are records of water intervals intersected during drilling of petroleum wells. These same wells also record the occurrence of crude oil and natural gas which occur in association with, and is buoyant within, the water intervals, locally forming accumulations known as reservoirs or pools which have supported production of oil and natural gas. This data is managed in a relational database known as the Ontario Petroleum Data System (OPDS).

This QA/QC project focusses on three aspects of this data: (1) A review of petroleum well records for oil, gas and water analyses and their corresponding formation and sample depth from which the sample was obtained; (2) a review of the formation assignments for water intervals currently attributed to the Dundee Formation; (3) a review of the formation assignments for water intervals currently attributed to the Lockport Group Formation that had previously undergone geological QA/QC, and (4) analysis of potential errors for approximately 35,000 water intervals recorded in OPDS.

The project contributes to development of a 3-D hydrostratigraphic model of southern Ontario. The updated and corrected data are added to the model to improve the representation and understanding of the occurrence of these fluids in the subsurface.

When the recorded formation top depths in OPDS are in error or are missing, oil, gas and water intervals and any chemical analyses of these fluids may be assigned to the incorrect formation. Two water-bearing intervals with known errors related to missing formation top picks are (in ascending stratigraphic order) the Gasport, Goat Island, Eramosa and Guelph formations of the Lockport Group, and the Devonian carbonates of the Bois Blanc, Amherstburg, Onondaga, Lucas and Dundee formations.

For many wells which penetrated the full thickness of the Lockport Group within pinnacle structures, formation tops were only recorded for the Guelph Formation, consequently all water intervals were initially assigned to the Guelph Formation. Carter et al. (2021b) reviewed 4,433 formation top picks of the Lockport Group for 587 wells and added 3,101 new formation top picks to OPDS. Similarly, for a large number of wells penetrating through the Dundee Formation into underlying Devonian formations, formation tops were only recorded for the Dundee Formation. As a result, water intervals encountered in the deeper Devonian formations were incorrectly assigned to the Dundee Formation. The QA/QC process and results for review of water interval assignments are presented below.

1. QA/QC of Oil, Gas, and Water Analyses

The OGSRL maintains hard copy and digital records of oil, gas and water analyses completed by the petroleum industry for fluid samples obtained from petroleum wells in southern Ontario. The primary objective of this study was to complete a quality assurance review of the digital records to:

- Confirm the accuracy and completeness of the digital records by comparison to the hard copy source records and make necessary corrections, and.
- review, correct and add formation assignments of the analyses corresponding to the depth from which the oil, gas and water samples were obtained.

1.1 Data Sources and Methodology

In accordance with the Provincial Operating Standards, all companies that drill or operate petroleum wells in Ontario are required to submit copies of oil, gas and water analyses to the Ministry of Northern Development, Mines, Natural Resources and Forestry (NDMNRF), which are then provided to the OGSRL for public access after the expiry of the confidentiality period. The OGSRL catalogues the industry reports in hardcopy binders and scanned images and has recorded the data in Excel spreadsheets. Individual well files also contain copies of the reports relevant to that well.

During review, the scanned analytical reports were digitally linked to the corresponding well licences documented in the spreadsheets. Data parameters that were reviewed include: well licence number, sample depth, sample formation, sample date, major chemical parameters analyzed and sample properties (i.e. critical temperature, gross heating value, pressure, density). The sample depths for each analysis were confirmed and, and cross referenced to the appropriate geologic formation in OPDS using a QGIS database containing the most up-to-date geological formation top picks from recent QA/QC projects (Carter et al. 2019, 2021).

1.2 QA/QC Results

A total of 1,759 chemical analysis records were reviewed from 967 petroleum wells, which includes 245 oil analyses, 491 gas analyses and 1,023 water analyses. Updates to the fluid analysis digital records are summarized in Table 1. A total of 190 sample depths and 375 formation assignments were updated, 155 of which required edits to both the sample depth and formation. The updated and corrected data are recorded in three separate Excel spreadsheets which are available from the OGSRL.

A significant number of formation updates and corrections were a result of the revised formation top picks made by Carter et al. (2019, 2021b). The Sherman Fall Formation (Trenton Group) has the highest number of recorded oil analyses (58), followed by Cobourg Formation (52 analyses). The Cobourg Formation has the highest number of recorded gas analyses (83), followed by Sherman Fall (63) and the A-1 Carbonate (62). The Cambrian (unsubdivided) had the highest number of water analyses (173), followed by the Reynales/Fossil Hill Formation (113) and the Guelph Formation (92). Detailed QA/QC results are presented in Table 2.

Table 1. Summary of updates to fluid analysis records for Ontario petroleum wells, by record type.

Fluid Type	# of analyses	# of wells	# Revised Licence Number	# Revised Depth	# Revised Formation Assignment	# Revised Depth *and* Formation
Oil	245	144	1	25	48	24
Gas	491	314	40	113	168	88
Water	1,023	509	20	52	159	43
Total	**1,759**	**967**	**61**	**190**	**375**	**155**

Table 2. Summary of oil, gas and water analysis reports per geological formation, net change post QA/QC.

	Oil Analyses			**Gas Analyses**			**Water Analyses**		
Formation	# analyses before QA/QC	# analyses after QA/QC	Net Change	# analyses before QA/QC	# analyses after QA/QC	Net Change	# analyses before QA/QC	# analyses after QA/QC	Net Change
Drift	0	0	0	1	3	2	27	25	-2
Port Lambton Group	1	0	-1	0	0	0	0	0	0
Kettle Point	0	0	0	0	0	0	3	3	0
Hamilton Group	2	4	2	0	3	3	5	9	4
Dundee	8	8	0	3	4	1	27	23	-4

Columbus	3	2	-1	0	0	0	4	4	0
Lucas	1	1	0	2	2	0	44	49	5
Amherstburg	0	0	0	1	0	-1	11	11	0
Sylvania	1	1	0	0	0	0	1	2	1
Bois Blanc	0	0	0	0	0	0	9	7	-2
Springvale	0	0	0	0	1	1	0	0	0
Oriskany	0	0	0	0	0	0	1	2	1
Silurian	0	0	0	0	11	11	13	0	-13
Bass Islands/Bertie	0	0	0	0	0	0	25	27	2
G Unit	0	0	0	0	0	0	9	8	-1
F Unit	0	0	0	0	0	0	1	2	1
E Unit	0	0	0	4	5	1	4	3	-1
C Unit	0	0	0	0	0	0	0	3	3
B-Unit	0	0	0	1	3	2	0	0	0
B Salt	0	0	0	0	0	0	0		0
A-2 Carbonate	0	0	0	16	15	-1	23	17	-6
A-2 Shale	0	0	0	1	0	-1	0	0	0
A-2 Anhydrite	1	0	-1	0	0	0	15	19	4
A-2 Salt	0	1	1	0	0	0	0	0	0
A-1 Carbonate	6	8	2	45	62	17	53	61	8
A-1 Evaporite	0	0	0	2	2	2	1	1	0
Guelph	24	22	-2	71	58	-13	107	92	-15
Goat Island	2	2	0	2	1	-1	20	32	12
Gasport	1	1	0	1	1	0	2	5	3
Rochester	0	0	0	6	7	1	12	12	0
Irondequoit	0	0	0	7	6	-1	5	8	3
Reynales/Fossil Hill	0	1	1	25	35	10	93	113	20
Thorold	0	0	0	9	23	14	13	12	-1
Grimsby	1	1	0	49	30	-19	38	28	-10
Cabot Head	2	3	1	5	5	0	9	11	2
Manitoulin	0	0	0	1	1	0	1	0	-1
Whirlpool	1	1	0	5	7	2	6	5	-1
Ordovician	0	0	0	0	1	1	0	0	0
Queenston	0	0	0	1	1	0	1	1	0
Georgian Bay-Blue Mountain	0	0	0	1	1	0	2	3	1
Trenton Group	2	4	2	8	0	-8	5	4	-1
Collingwood	0	0	0	0	0	0	0	1	1
Cobourg	47	52	5	41	83	42	35	33	-2
Sherman Fall	50	58	6	39	63	24	28	27	-1
Verulam	0	0	0	2	0	-2	0	0	0

Kirkfield	5	9	4	2	2	0	5	10	5
Black River Group	3	1	-2	3	0	-3	5	3	-2
Coboconk	3	3	0	1	4	3	11	10	-1
Gull River	3	4	1	1	3	2	7	12	5
Shadow Lake	0	3	3	5	8	3	4	10	6
Cambrian	10	14	4	28	30	2	174	173	-1
Trempeleau/Little Falls	2	2	0	4	4	0	16	16	0
Eau Claire/Theresa	0	0	0	0	0	0	2	5	3
Mount Simon/Potsdam	0	0	0	0	0	0	1	1	0
Precambrian	0	0	0	2	2	0	12	12	0
Attawapiskat	0	0	0	1	0	-1	0	0	0
Carlsbad	0	0	0	0	0	0	1	1	0
NULL	66	39	-27	95	4	-91	147	107	-40
Total Formation Count	245	245	-2	491	491	2	1,038	1,023	-15

1.2.1 Oil Analysis Results

There are 245 documented oil analyses records (Fig. 1). A total of 216 oil analyses were reviewed for 144 wells. The remaining 29 analyses could not be assessed because of insufficient data, pertaining to missing licence numbers, sample analysis formation depths and/or sample formation name.

Commonly corrected issues consisted of oil analyses with missing or incorrect well licence numbers, outdated well licence numbers, missing formation name and/or sample depth, and wells plotting outside the southern Ontario study area. Oil analyses with missing licence numbers are particularly problematic because it is impossible to verify the depth, formation, or location of the samples.

QA/QC resulted in correction of the well licence number for one record, and revision of 25 depth intervals and 48 formation assignments (*see* Table 1 above). Of the 48 oil analyses records that were updated, the most significant edits were to 27 analyses that previously had a "Null" formation assignment (*see* Table 2 above). Subsequent to QA/QC there are still 26 analyses with missing licence s, 39 analyses with no formation assignment and 35 analyses missing sample depths (Table 3).

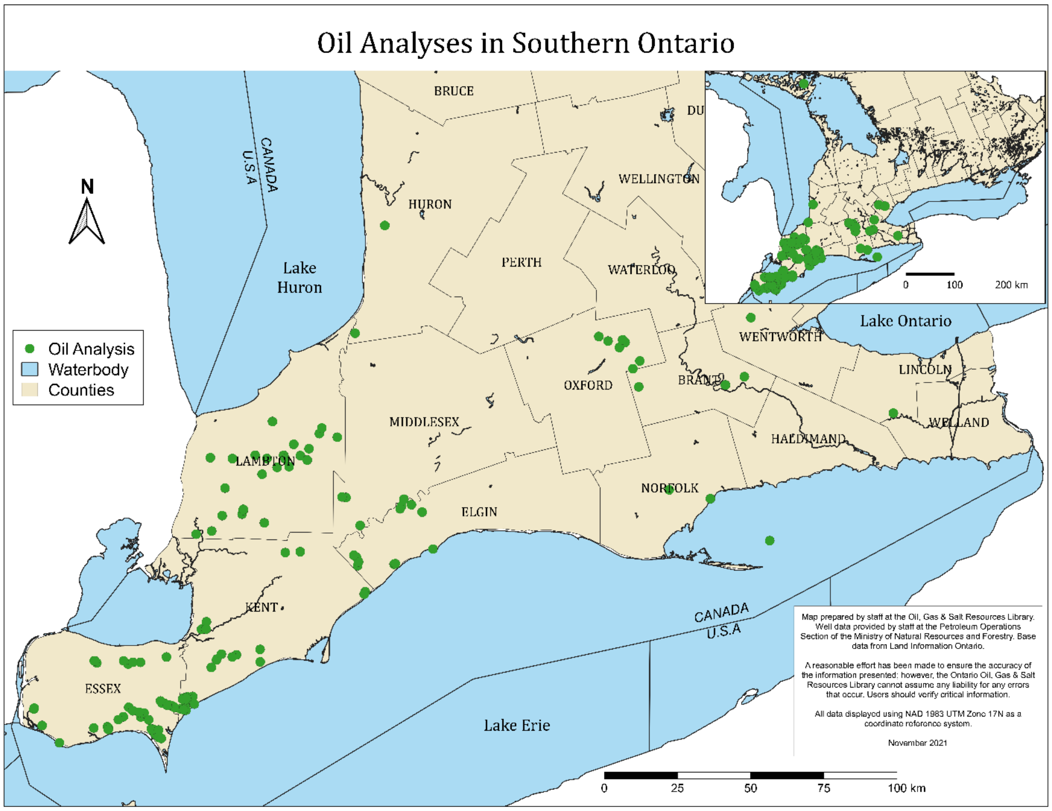


Figure 1. Location of OPDS well containing oil analyses.

Table 3. Common data quality issues in oil analyses records, before and after QA/QC.

Data Quality Issues - Oil Analyses			
Error Issues	**# before QA/QC**	**# after QA/QC**	**Net Change**
Missing Licence #	26	26	0
No Formation Assignment	66	39	-27
Missing Sample Depth	59	35	-24

1.2.2 Gas Analysis Results

A total of 491 gas analyses were reviewed for 314 petroleum wells (Fig. 2). A total of 468 analyses verified and/or updated, the remaining 23 analyses were unable to be verified as a result of missing well licence s. During the QA/QC process a total of 50 previously undocumented gas analyses were added to the gas analysis spreadsheet from hard copy well records or from scanned records.

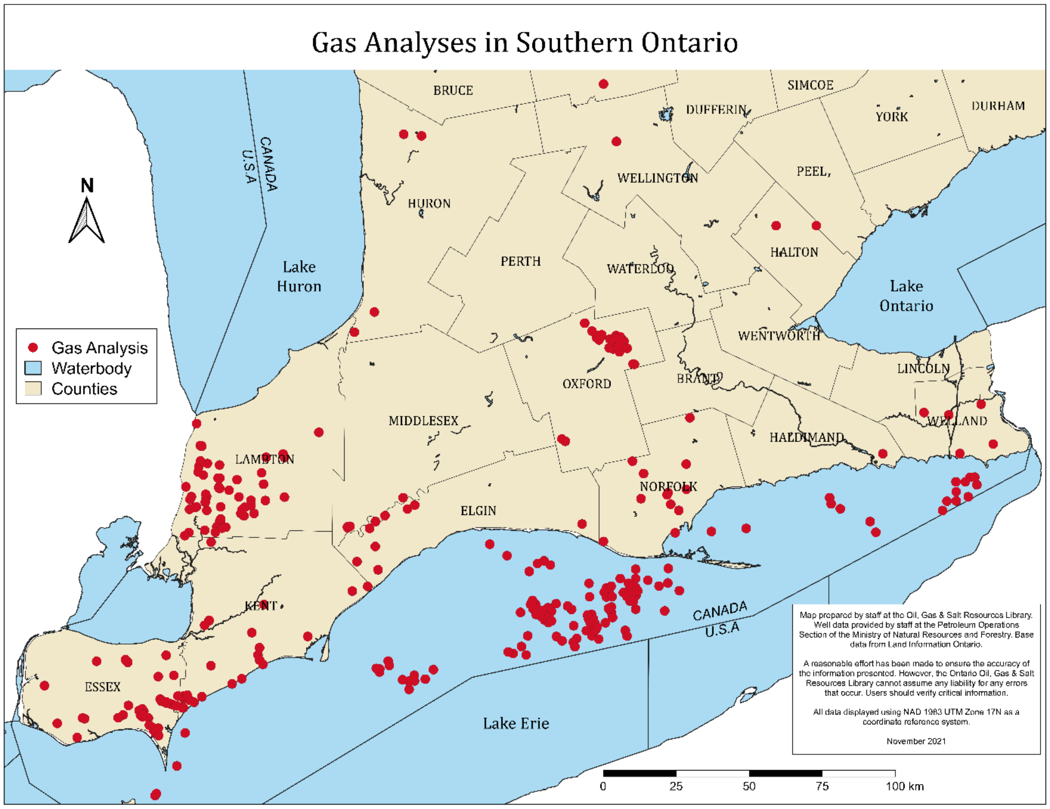


Figure 2. Location of petroleum wells in OPDS wells with gas analysis records.

For each gas analysis, the recorded sample depth and formation assignment were reviewed and verified using well file data. If formation top picks were not available, they were interpreted from geophysical logs, or occasionally by interpolation from nearby wells. Updates were made for: 40 well licence numbers, 113 sample depths, and 168 sample formation assignments, of which 88 reports required edits for both sample depth and formation. Oil analysis records with a "Null" formation assignment decreased from 95 to 4. Other QA/QC updates include a decrease in Grimsby (49 to 30) and Guelph (71 to 58) formation assignments and increased formation assignment for the Cobourg Formation (41 to 83), Sherman Fall Formation (39 to 63) and A-1 Carbonate (45 to 62) (*See* Table 2 above).

Common data quality issues included unidentifiable/missing licence numbers, formation assignments and sample depths, and misfiled/undocumented analyses. The total of unidentifiable/missing licence numbers for gas analyses decreased from 28 to 23 (*see* Table 4 below). This issue often occurred when the gas analysis was obtained from a *non*-petroleum well, or the gas analysis report did not have sufficient information to identify the well's licence number, name, or location. The number of gas analyses with missing formation tops decreased from 95 to 4, most of which appeared to be a result of initial poor-quality data entry. Records with missing sample depths decreased from 125 to 19. Well licence numbers/locations could not be determined for the remaining 19 missing sample depth records.

1.2.3 Water Analysis Results

The water analysis spreadsheet contains 1,023 documented analyses for 509 wells (Fig. 3).

A total of 895 water analyses were verified and/or updated during QA/QC. The remaining 128 water analyses were not able to be verified and/or updated as a result of: the analyses pertaining a well located beyond the study area (82 analyses); key information was missing, such as the sample depth (24 analyses); or the analyses appeared unreliable or anomalous, which would include samples being obtained at depths deeper than the total depth of the well (7 analyses) or the well licence could not be found/verified in OPDS (15 analyses).

The QA/QC results include revisions to: 20 well licence numbers, 52 sample depths and 159 formation assignments, including 43 records with updates for both sample depth and formation.

Table 4. Common data quality issues in gas analysis records, before and after QA/QC.

Data Quality Issues - Gas Analyses			
Error Issues	**# before QA/QC**	**# after QA/QC**	**Net Change**
Missing Licence #	28	23	-5
No Formation Assignment	95	4	-91
Missing Sample Depth	125	19	-106

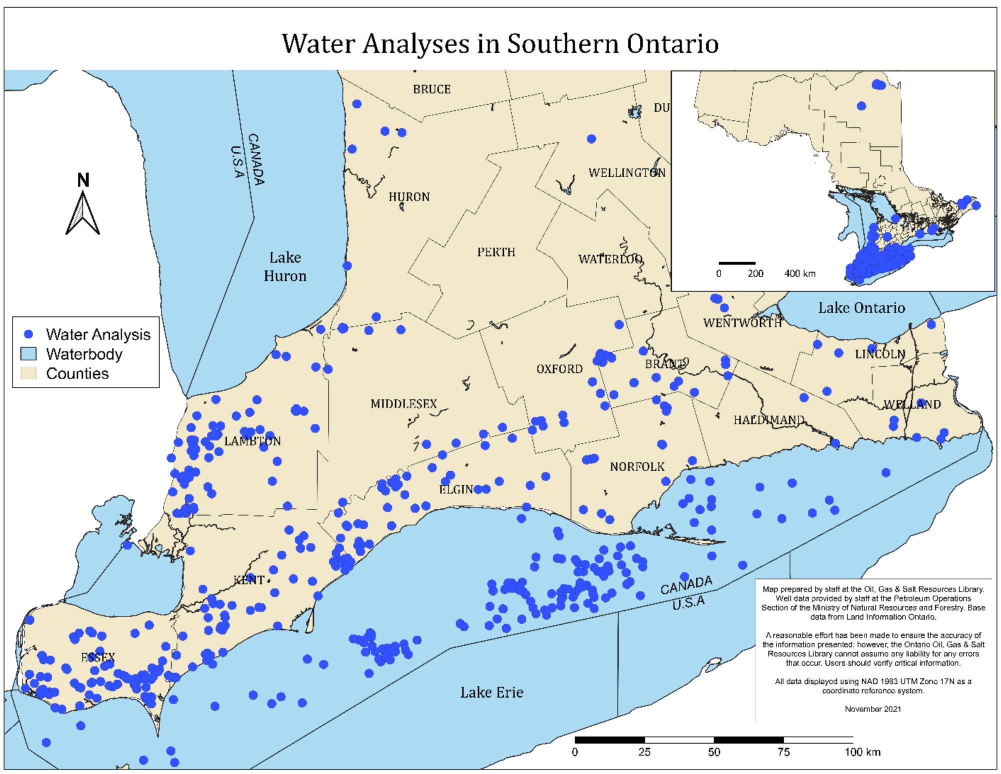


Figure 3. Location of petroleum wells with water analyses.

Of the 161 updated formation assignments, records with a "Null" assigned formation decreased from 147 to 107 and records with a Guelph Formation assignment decreased from 107 to 92. Records assigned to the Reynales/Fossil Hill Formation increased from 93 to 113, followed by Goat Island Formation assignments increasing from 107 to 92 (*See* Table 2 above). No water analyses had missing licence numbers prior to QA/QC; however, 20 licence record numbers were revised. Records with missing sample depths decreased from 117 to 68 (Table 5).

Table 5. Common data quality issues in water analysis records, before and after QA/QC.

Data Quality Issues - Water Analyses			
Error Issues	**# before QA/QC**	**# after QA/QC**	**Net Change**
Missing Licence #	0	0	0
No Formation Assignment	147	107	-40
Missing Sample Depth	117	68	-49

1.3 Discussion and Summary

A recurring issue encountered in the three oil, gas and water analysis data sets was the discovery of undocumented or misfiled analyses. Undocumented gas analyses were found either in a well file being reviewed for a known gas analysis or discovered in a scanned hardcopy binder report. In the gas analyses, misfiled analyses for liquid hydrocarbon fluids, and drift gas analyses from water wells would sometimes be found. It should be mentioned that not all well files containing a fluid analysis, either oil, gas or water, were individually examined for potential undocumented analyses, therefore it is likely that more 'undocumented' analyses exist within the well file records.

The most common issue encountered was when the sample depth interval recorded in the spreadsheet did not correspond to formation depth in OPDS or when the sample depth interval and/or formation top were missing. To resolve this, scans of hard copy reports found on the OGSRL website and in the well files were reviewed. Specifically, information recorded on drilling and completion records would indicate any initial gas/water records under the "Water Record" or "Initial Gas Records" section.

Missing sample depths and/or formations could often be identified from data recorded in the sections '*Initial Gas/Oil Records'* and/or '*Final Production Results'* found on the MNR Form 7 "Drilling and Completion Record". To interpret the formation most likely sampled, the value provided in the *Final Results* was matched to the flow amount and corresponding interval in the *Initial Gas Records* table. In the example below (Fig. 4), the *Final Results* show a gas flow of 177.4 McfD (thousand cubic feet per day), which correlates to the natural flow and depth interval 1750' found in the *Initial Gas Record*. The formation was then identified by matching the depth interval to the formation top depths recorded in OPDS

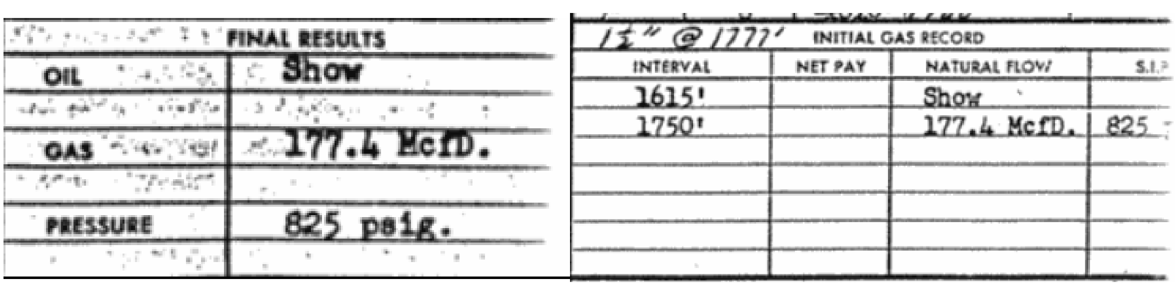
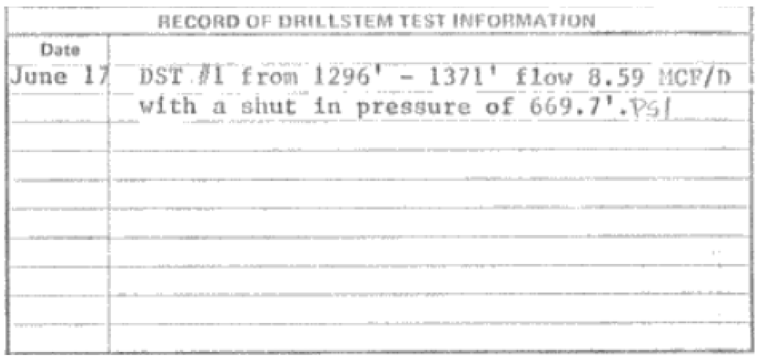


Figure 4. Example of Final Results and Initial Gas Records data fields in a drilling and completion record.

For cases where these sections were empty, notes found in the "Remarks"/ "Results" section would typically indicate if a Drill Stem Test (D.S.T) was completed for a specific interval. Oil, gas and water intervals and corresponding formations would be listed in this section or found in a separate scan about the D.S.T and its findings (Fig. 5). The top depth is used from this information and matched with the corresponding formation recorded in OPDS or hard copy records, except where this depth interval straddles a formation contact. A hypothetical example would be a D.S.T. of 1,296-1,371', with Formation X from 1,272-1,299 and Formation Y from 1,299 -1,368'. In this case the lower Formation Y is chosen as the sample formation as the largest proportion of the test interval occurs within Formation Y.



RECORD OF DRILLSTEM TEST INFORMATION

Date	
June 17	DST #1 from 1296' - 1371' flow 8.59 MCF/D
	with a shut in pressure of 669.7'.PSI

Figure 5. Example of a D.S.T. record corresponding to a gas analysis sample.

2. QA/QC of Water Records Assigned to the Dundee Formation

A preliminary scan of OPDS records showed that several hundred petroleum wells had only a Dundee Formation top pick recorded within the Devonian strata, despite records indicating the wells were deep enough to penetrate deeper formations. As a result, corresponding water records for such wells had a questionable assignment of water intervals to the Dundee Formation. For this project, the primary objectives were to add missing formation top picks for the underlying Columbus, Lucas, Sylvania, Amherstburg, Onondaga and Bois Blanc formations for wells with water intervals assigned to the Dundee Formation and update formation assignments of water intervals when new formation top picks were added to the database.

2.1 Data Sources, Selection Criteria and Methods

Source data is contained in hard copy well files and digital data in OPDS including: well licence number, well name, county and township, latitude, longitude, total depth date, ground elevation, total vertical depth (TVD), status, sample tray number, core identification, formation tops, and water interval depths, static level and water type. The geographic information system QGIS was used to spatially view, and query data extracted from OPDS. Online data at www.ogsrlibrary.com was used to confirm well file information, such as drilling and completion reports, geophysical logs, oil/gas/water records and sample tray numbers.

Priority for QA/QC was determined primarily by reviewing petroleum wells with a recorded water interval assigned to the Dundee Formation where the recorded water interval depth exceeds the regional thickness of the Dundee Formation. Three priority groups were established (Table 6).

Table 6. Summary of selection criteria used in each of the three priority groups.

Selection criteria for review	Priority 1	Priority 2	Priority 3
Dundee Formation picked	X	X	X
Lucas Formation *NOT* picked	X	X	
Bois Blanc Formation picked		X	
Only wells with cutting samples examined		X	
Dundee Formation water interval	X	X	X
Top of water interval is at a depth >30m from top of Dundee Formation*	X		
MNR geology source	X	X	X
Latitude and longitude of the wells are not 'Null'	X	X	X
Well not in Priority 1		X	X
Well not in Priority 2			X

* The average thickness of the Dundee Formation ranges between 35 to 45m (Armstrong and Carter, 2010)

To accurately determine the correct formation assignment the water interval depths were compared to the formation top depths. Formation tops reviewed include (*in descending order*); Dundee, Columbus Sands, Lucas, Amherstburg, Sylvania, Onondaga and Bois Blanc. The Columbus equivalent was not being considered for this project. Wells with cuttings were prioritized for review since most of the Devonian units have either an unresponsive and/or unreliable gamma- ray log signature. Well files, specifically drillers logs and notes, were reviewed for wells that did not have samples. If the formation assignment for the water interval could not be determined/confirmed, formation top picks from nearby petroleum wells were used to interpolate a 'best estimate' of the formation. This was then confirmed with the 3-D bedrock geology model of southern Ontario (Carter et al. 2021b). Review priority was given to wells located in Bruce and Huron counties.

Formation top picking criteria and standards for identification was based on Armstrong and Carter (2010). During review each geological formation top was assigned a quality assurance and quality control code (the code table is available in Carter et l. 2021b).

2.2 QA/QC Results by Priority Group

The data selection query yielded a total of 4,065 water interval records.

- *Priority Group 1*: water records from wells with a Dundee Formation pick but the Lucas Formation is NOT picked, where the top depth of the Dundee water interval is greater than 30m below the top of the Dundee Formation (330 water records);
- *Priority Group 2*: water records for wells where the formation tops for the Dundee and Bois Blanc formations are picked but with no picks for the Lucas Formation, with a Dundee water interval and is not listed in Priority Group 1, and has cuttings samples available (260 water records), and;
- *Priority Group 3:* water records for wells not listed in either Priority Group 1 or 2 (3,475 water records).

Due to time constraints, it was not possible to review all 4,065 water records, however all records for both Priority Group 1 and 2 lists were reviewed, along with the most anomalous water intervals in Priority Group 3.

2.2.1 Priority Group 1

Priority Group 1 consisted of 330 water interval records for 298 wells; 143 wells with cutting samples and 155 wells without cuttings. For the 155 wells with no cuttings, drillers logs/notes combined with interpolation of geology from surrounding wells were used to determine the formation corresponding to the water interval depth. For the remaining 143 wells with drill cuttings, determination of formation tops was completed using standards established in Armstrong and Carter (2010). In 9 of the 143 wells with cutting samples, the sample quality was very poor and therefore drillers logs/ notes and interpolation from neighbouring wells were used to determine formation top and water interval assignment. This resulted in a final total of 164 wells reviewed by driller logs/notes and interpolation from neighbouring wells.

For the wells reviewed by sample cuttings, it was noted that some wells did not penetrate formations deeper than the Dundee and therefore water interval assignments were not changed. Regionally, in the counties of Lambton, Kent, and Essex the geological formations are easily identifiable and formation top data in these areas are reliable.

Regional observations of the Lucas Formation include a sandy dolostone that occurred near formation top and anhydrite beds present mid-unit in Lambton County (Fig. 6), a white, creamy dolostone/limestone interbedded with evaporites in Kent and Essex Counties, and thinning and pinch out of the Lucas in western Norfolk County.

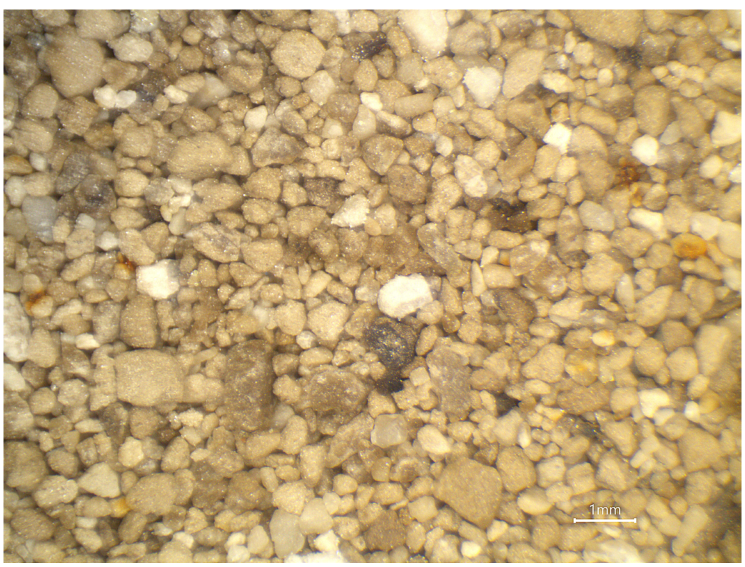


Figure 6. Sandy limestones/dolostones with anhydrite of the Lucas Formation, Lambton County, Moore Township (T005930), at a depth of 209m (10x magnification). Photo courtesy of Alex Cachunjua.

2.2.2 Priority Group 2

Priority Group 2 was comprised of 260 water interval records for 260 wells. A total of 85% of the wells were located in Norfolk County (Charlotteville, Woodhouse, Windham, Middleton, Bayham, Houghton and Walsingham townships), where the Onondaga Formation is present in subcrop and surface exposures. Wells in this group have formation top picks for both the Dundee and Bois Blanc formations top picks but no pick for the Lucas Formation. Additionally, these water records were from wells that did not appear in Priority list 1 *and* all wells have cuttings samples.

In Norfolk County, cuttings samples are not available most wells for the uppermost 10-15 metres below the recorded top of bedrock. In these cases, the top of bedrock was confirmed using drillers notes in the well files. The Lucas Formation does not occur in most of Norfolk County (with the exception of Charlotteville township) due to pinchout. The Amherstburg Formation was readily picked in most of Norfolk County, and the Onondaga Formation was found to occur in wells located in Haldimand-Lake Erie shores and Walsingham-Lake Erie shores. Additionally, revised formation top picks for the Bois Blanc Formation were generally deeper than previously recorded, as per the formation top picking standards of Armstrong and Carter (2010). Some Norfolk wells (T001465, T001667, T002283) had cuttings samples of the Dundee Formation that had a dark colour appearance with abundant black chert, usually near the lower contact boundary with the underlying Amherstburg Formation (Fig.7).

Figure 7. Dundee Formation drill cuttings from Norfolk County, Charlotteville Township (T002283), at a depth of 59.7m (196ft) (10x magnification). Photo courtesy of Alex Cachunjua.

The Onondaga Formation was observed in wells located in Lake Erie and along the Norfolk and Haldimand county shores. In cuttings, the Onondaga limestone appeared to consist of variably dark grey cherty fossiliferous or argillaceous limestone with dark matrix. (Fig. 8).

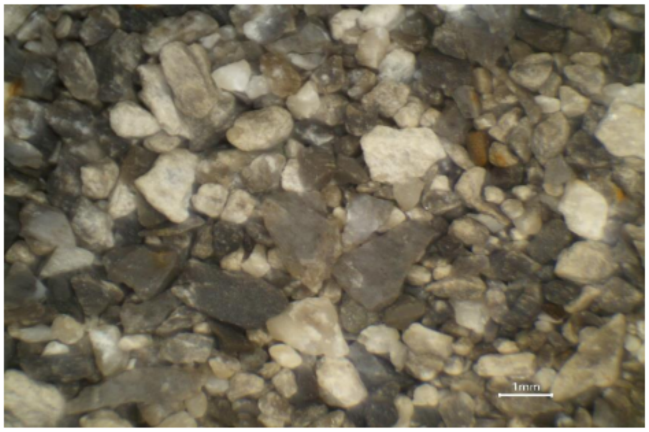


Figure 8. Onondaga Formation drill cuttings from Haldimand County, Lake Erie township (T001398), at a depth of 49.7m (163ft) and Norfolk County, Lake Erie township (T001474), at a depth of 131.7m (432ft) (10x magnification), respectively. Photos courtesy of Alex Cachunjua.

2.2.3. Priority Group 3

Priority Group 3 comprised of 3,475 water interval records for 2,922 wells and were not previously reviewed in Priority lists 1 or 2. It was not possible to review all water record queried, so the data was sorted by depth of the recorded water interval below the top of the Dundee Formation. Wells with water interval depths exceeding 40m below the Dundee top or which occurred at depths above the Dundee Formation, were given priority for review. Of the corrected water records, 77 had depth intervals ranging between 67.3m to 40.5m below the top of the Dundee Formation and were prioritized for review.

2.3 Discussion and Summary

In summary, Priority Group 1 consists of 330 water intervals for 298 wells; formation tops for 134 wells were reviewed using sample cuttings and 164 were reviewed by driller logs/notes and interpolation from neighbouring wells. In Priority Group 2, 260 water intervals for 260 wells were reviewed only by sample cuttings and Priority 3 Group had 813 water intervals for 134 wells reviewed, by either examining driller logs/notes and/or interpolation from neighbouring wells (*See* Table 7 below).

Table 7. Summary of Devonian wells and water intervals examined

	Well Count			
	Well Total	# of Wells Reviewed by Samples	# of Wells Reviewed only by Well Record	Water Interval Count
Priority Group 1	298	134	164	330
Priority Group 2	260	260	0	260
Priority Group 3	134	0	134	813
Total	692	394	298	1403

A total of 1,403 water intervals for 692 OPDS wells were reviewed. Formation assignments were confirmed for 974 water intervals, updated/edited for 409 water intervals and added for 8 water intervals. Twelve water intervals were deleted as a result of erroneous data entry recording.

Of the 409 updated water interval records, 308 water intervals previously assigned to the Dundee Formation were reallocated to other Paleozoic formations, the largest proportion (201) being assigned to the Lucas Formation (*See* Table 8).

Table 8. Summary of edits to 409 formation water intervals.

Formation	Water Interval Count Before QA/QC	Water Interval Count After QA/QC	Net Change
Drift	6	11	5
Mistuskwia Beds	1	0	-1
Kettle Point	0	2	2
Hamilton Group	1	10	9
Marcellus	1	1	0
Dundee	325	17	-308
Columbus	4	41	37
Lucas	11	212	201
Amherstburg	26	56	30
Onondaga	0	20	20
Sylvania	2	0	-2
Bois Blanc	29	26	-3
Oriskany	2	2	0
Bass Islands/Bertie	1	4	3
Guelph	0	5	5
Gasport	0	2	2
Water Record Sum	**409**	**409**	

General issues encountered in wells reviewed using only drillers logs/notes include:

- Well record errors in recorded geology, water type and/or water interval depths that resulted in incorrect Dundee water formation assignments. This was typically a result of well file typographic errors in data entry, including discrepancies in converting imperial to metric units (feet to meters).
- Historical nomenclature variation of rock lithology. Several petroleum wells in Norfolk County (Woodhouse, Windham and Middleton townships) have driller records reporting ‘flint’ as the subcropping formation lithology due to the presence of abundant chert. In the past, this description was translated into OPDS as the ‘Bois Blanc Formation’, but chert occurs in the Dundee, Amherstburg and Bois Blanc formations in this area making consistent identification of the Devonian formations problematic, especially when cuttings are not available.

Challenges and issues encountered with wells reviewed by sample cuttings include:

- Poor sample quality or no samples found to be associated with well record.
- Eastward lithofacies changes and regional thinning making formation tops more difficult to pick in Norfolk and Haldimand counties resulting in greater uncertainty for formation assignment of water intervals. For example, the sample cuttings from well T007655 display a rapid change of colour in the Dundee Formation, from grey to tan to brown, fossiliferous limestones with minor dolostones to very dark limestones and dolostones rich in organic materials (Fig.9).

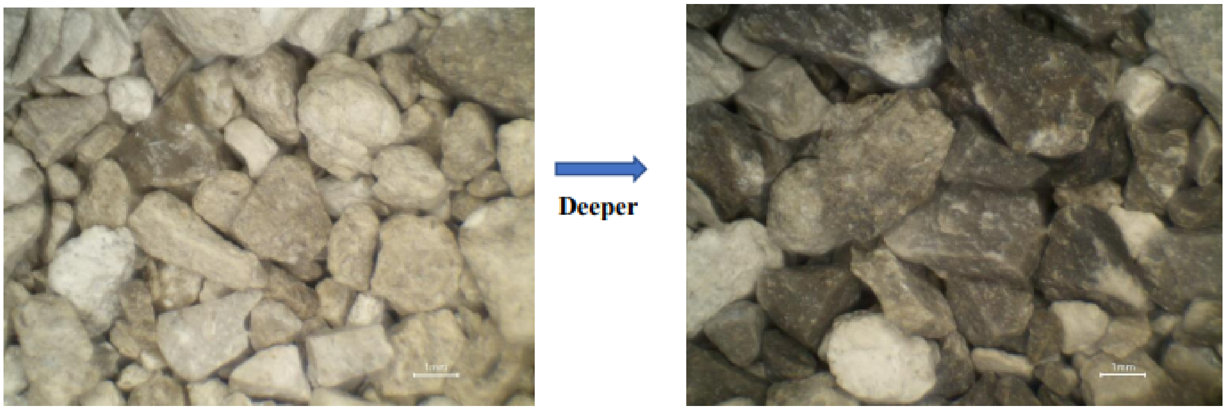


Figure 9. Dundee Formation drill cuttings from Norfolk County, Woodhouse township (T007655), at depths of 96m and 97.8m (10x magnification). Photos courtesy of Alex Cachunjua.

- The determination of Amherstburg and Onondaga formations tops since the formations may display similar geological characteristics in rock chip samples, which increases uncertainty when differentiating between the two formations.

3. QA/QC of Water Intervals Records for the Lockport Group

Petroleum wells intersecting the Lockport Group within interpinnacle karst and carbonate platform facies underwent geological review in Carter et al. (2021b), to improve formation top picks in wells that only had a Guelph Formation top pick recorded. This resulted in addition of formation top picks for the Goat Island Formation and Gasport Formation in some wells. As a result, the water records for such wells had questionable assignments of water intervals for the Guelph Formation. The primary objective of this QA/QC review is to review, verify and/or update water intervals assigned to the Guelph Formation for wells that had previously undergone geological QA/QC.

3.1 Data Sources, Selection Criteria and Methodology

The study comprised two groups of wells:

- Group 1, 370 wells located within Lambton, Chatham-Kent and Essex Counties and western Lake Erie and;
- Group 2, 343 wells located east of the Algonquin Arch within the Carbonate Platform and Carbonate Bank/Reef lithofacies belt.

Source data is contained in hard copy well files and digital data is from OPDS including: well licence number, well name, county and township, latitude, longitude, total depth date, ground elevation, total vertical depth (TVD), status, formation tops, and water interval depths, static level and water type. The geographic information system QGIS was used to spatially view, and query data extracted from OPDS. Online data at www.ogsrlibrary.com was used to confirm well file information, such as drilling and completion reports, geophysical logs, oil/gas/water records and sample tray numbers. All water assignments reported for a well were reviewed and verified for water depth, water type, level from surface and geological formation assignment.

3.2 QA/QC Results

A total of 1,415 water intervals for 713 petroleum wells that intersect the Silurian Lockport group within interpinnacle karst and carbonate platform facies were reviewed.

In Group 1, 370 wells and 834 water intervals were reviewed. Prior to QA/QC 153 water intervals were assigned to the Lockport Group, including 149 water intervals for the Guelph Formation, and two water intervals for each Gasport and Goat Island formations. Following QA/QC, the total number of assigned Lockport water intervals decreased to 135, of which 116, 11, and 8 were designated to the Guelph, Goat Island, and Gasport Formations (Table 8).

In Group 2, 343 wells and 581 water intervals were reviewed. Prior to QA/QC, 151 of the 581 water intervals reviewed had Lockport Group formation assignments, 148 of which were Guelph, one to Goat Island and two to Gasport formation waters. Following QA/QC, water intervals assigned to the Guelph Formation decreased to 110, while intervals assigned to the Goat Island and Gasport formations increased to 24 and 9 respectively (Table 9).

Table 9. Lockport 1 and 2 water intervals counts before and after QA/QC, net change post QA/QC.

	Lockport 1 Water Interval Count			**Lockport 2 Water Interval Count**		
Formation Name	**Before QA/QC**	**After QA/QC**	**NET**	**Before QA/QC**	**After QA/QC**	**NET**
Drift	109	109	0	80	72	-8
Port Lambton Group	1	2	1	0	0	0
Kettle Point	42	45	3	0	0	0
Hamilton Group	15	16	1	5	3	-2
Marcellus	1	0	-1	2	0	-2
Dundee	45	65	20	39	41	+2
Columbus	53	47	-6	4	3	-1
Lucas	169	152	-17	33	29	-4
Amherstburg	9	14	5	23	13	-10
Onondaga	0	0	0	2	3	+1
Sylvania	3	3	0	0	0	0
Bois Blanc	18	16	-2	24	23	-1
Springvale	0	1	1	0	0	0
Oriskany	4	3	-1	0	0	0
Bass Islands/Bertie	44	46	2	41	42	+1
G Unit	0	0	0	7	6	-1

F Unit	8	4	-4	26	30	+4
E Unit	2	3	1	52	53	+1
C Unit	0	0	0	10	9	-1
B Equivalent	0	1	1	0	0	0
B Unit	1	0	-1	6	9	+3
B Anhydrite	2	0	-2	0	0	0
A-2 Carbonate	38	37	-1	11	7	-4
A-2 Anhydrite	4	0	-4	0	0	0
A-1 Carbonate	19	35	16	9	17	+8
Guelph	149	116	-33	148	110	-38
Goat Island	2	11	9	1	24	+23
Gasport	2	8	6	2	9	+7
Irondequoit	0	0	0	0	1	+1
Rochester	1	1	0	1	0	-1
Reynales/Fossil Hill	1	1	0	5	1	-4
Grimsby	0	0	0	1	1	0
Cabot Head	0	0	0	1	1	0
Georgian Bay-Blue Mountain	2	0	-2	1	0	-1
Trenton Group	4	1	-3	0	0	0
Cobourg	10	9	-1	1	0	-1
Sherman Fall	8	9	1	0	0	0
Kirkfield	2	1	-1	1	1	0
Black River Group	2	1	-1	0	0	0
Coboconk	8	5	-3	1	1	0
Gull River	6	6	0	4	4	0
Shadow Lake	1	5	4	2	4	+2
Cambrian	33	32	-1	27	25	-2
Trempealeau/Little Falls	12	14	2	3	4	+1
Eau Claire/Theresa	2	3	1	3	1	-2
Mount Simon/Potsdam	0	0	0	1	0	-1
Precambrian	0	1	1	2	1	-1
Null	2	0	-2	2	0	-2
Total	**834**	**823**	**-11**	**581**	**548**	**-33**

In total, the number of water formation assignments decreased from 1,415 to 1,371, which was a result of anomalous or duplicate water interval records being removed from the database. The total count of water assignments to the Lockport Group decreased from 304 to 278, which was a result of water interval reassignment to other Paleozoic formations, or the water interval was determined to be anomalous and deleted. Guelph Formation water assignments decreased from 297 to 226, and A-1 Carbonate, Goat Island and Gasport formation assignments increased (*See* Table 10 below).

Table 10. Lockport Group water interval assignments before and after QA/QC.

Formation	**Water Interval Count Before QA/QC**	**Water Interval Count After QA/QC**	**NET**
A-1 Carbonate	28	52	+24
Guelph	297	226	-71
Goat Island	3	35	+32
Gasport	4	17	+13
Lockport Group Total	**304**	**278**	**-26**

3.2 Discussion and Summary

Notable improvements to the 1,415 water intervals from the 713 Lockport wells that underwent QA/QC, include the removal of duplicated or anomalous water intervals, the addition of missing or non-documented water records and the verification and/or update to 1,371 water interval formation assignments.

Data quality issues include missing digital files, and data entry and unit conversion errors.

- Missing digital well files scans. In these cases, the original hardcopy well file was reviewed to validate the OPDS water records.
- Data entry errors between the original well file documents (i.e. Form 7 (Drilling and Completion Record), Form 10 (Plugging Record) and the digital OPDS records. Errors occurred in water intervals, water levels, water type, and formation assignment of the water interval, and typically consisted of incorrect information being transcribed, water intervals being entered more than once for the same well, and anomalous water intervals occurring for a well. These errors were corrected by transcribing information recorded from the original well file documents to the digital OPDS data.
- Imperial to metric unit conversion errors occurred for well file records older than 1975 in the water interval depths and/or static level. Discrepancies consisted of rounding errors and variations in the number of decimal places recorded, varying from 0 to 3 decimal places, which as a result affected the integral unit value reported. In these circumstances, units reported were updated to the second decimal place.

Other issues include water interval assignments to formations/units in OPDS that are not typically porous or permeable, such as the B Salt and A-2 Anhydrite and the historical variation in recording water types. Currently, there are nine water types: Black, Brackish, Fresh, Loss of circ., Mineral, Null, Salt, Brown, and Sulphur. Previously, when ‘Black’ water was listed on Form 7 Drilling and Completion records, it was inconsistently recorded in OPDS as either ‘Sulphur’ or ‘Black’. These discrepancies in OPDS from the source records have been corrected. Also, wells that experienced a loss of circulation while drilling were not always documented in the digital data. These variations in transcribing water types can create either an over or under-representation of water types in the OPDS database.

Additional challenges include when water intervals required a formation designation and no prior QA/QC had been performed on the well’s geological formation top picks. In these circumstances, the formation tops were confirmed or updated using a combination of drill cuttings and/or geophysical logs from borehole data at the OGSRL. Formation tops recorded for nearby wells were also used to help correlate and confirm formation assignments of water intervals. Some water intervals intersected more than one geologic formation. Review of formation tops could sometimes resolve the correct formation assignment. In other instances the formation corresponding to the top of the water depth interval was selected and in rare cases an expert judgement was made on the correct assignment. For example, if a water interval started at the base of the Gasport Formation but extended into the Rochester Shale, the water interval was assigned to the Gasport Formation.

4. Sources of Error of the Water Interval Records

There are approximately 35,000 water intervals recorded in the OPDS petroleum well records. Potential data errors include, but are not limited to, the following:

- Digital data entry errors of water intervals, static levels, water types and/or formation assignment. This tends to occur when the OPDS digital data and well file documents (ie. MNR Form 7 (Drilling and Completion Records), MNR Form 10 (Plugging of a Well Report), and/or Water Analyses) do not correspond.
- Water interval formation assignments not corresponding to well geology. Numerous updates to geological formation top picks have occurred in development of 3-D lithostratigraphic models over the past four years (Carter et al. 2019, 2021b), however corresponding formation assignments of the water intervals for the wells were not always verified and/or updated. QA/QC verification in the present study is limited to the Dundee and Guelph formations. It is recommended that water formation QA/QC continue for all updated wells used in the Hydrostratigraphic model.
- Imperial to metric unit conversion errors. Such errors were noted to commonly occur in older well files where information was originally recorded in imperial units. When the measured unit was converted to metric, the value may have been rounded too high and lower decimal units were disregarded, and in some instances created false significant figures in the data.
- Missing or absent data in OPDS, which is recorded as ‘Null’ for Water interval depths (Top and/or Bottom), Water Level, and Water Type.

- The top depths of water intervals are generally very well known for open hole wells drilled by cable tool methods as water freely enters the well bore, but bottom depths of water intervals are generally not known.

Updated water interval formation assignments are summarized in Appendix 1. Compared to Carter et al (2015a), principal changes are:

- Increase in water intervals assigned to Drift from 5,387 to 5,406
- Reduction of water intervals assigned to Dundee Formation from 4,311 to 4,001
- Increase in water intervals assigned to Lucas Formation from 3,647 to 3,855
- Increase in water intervals assigned to the Columbus sandstone from 607 to 645
- Increase in water intervals assigned to the Amherstburg Formation from 2,276 to 2,295
- Increase water intervals assigned to the Onondaga from 0 to 20
- Decrease in water intervals assigned to Guelph from 4,903 to 4,848
- Increase in water intervals assigned to Goat Island Formation from 151 to 186
- Increase in water intervals assigned to the Gasport Formation from 148 to 166

5. Summary and Conclusions

The QA/QC projects presented in this report support the development of a 3-D hydrostratigraphic model for southern Ontario by using data managed at the Oil, Gas and Salt Resources Library. Four projects were conducted and examined the following:

1. Oil, Gas and Water analytical data recorded for wells in OPDS
2. Formation assignments for water intervals attributed to the Devonian Dundee Formation
3. Formation assignments for water intervals attributed to the Silurian-Lockport Group formations
4. Potential errors for 35,000 reported water intervals

The QA/QC review of oil, gas and water analysis records from petroleum wells was completed to ensure accuracy and completeness of the digital records and review, correct and update formation assignments to the corresponding sample depth of the analyses. A total of 1,759 records were reviewed from 967 wells, which includes 245 oil analyses, 491 gas analyses and 1,023 water analyses.

The second QA/QC report reviewed petroleum wells with only a Dundee Formation top pick within the Devonian strata and corresponding water interval assignments. Missing formation top picks for the Columbus, Lucas, Sylvania, Amherstburg, Onondaga and Bois Blanc were added and water intervals were updated to match the revised formation assignments. A total of 1,403 water interval records for 692 wells were reviewed. Water intervals assigned to the Dundee Formation decreased by 308 whereas water intervals assigned to the Lucas Formation increased by 201 records.

Water interval records from petroleum wells that had recently undergone geological QA/QC on Silurian Lockport Group formations within interpinnacle karst and carbonate platform facies were reviewed to verify and/or update formation assignment of water interval. A total of 713 wells and 1,415 water intervals were examined. Updates include the removal of 44 water intervals that were identified as anomalous or duplicate in OPDS. The results showed that 71 water intervals previously assigned to the Guelph Formation were allocated to other Silurian-Lockport formations, such as the A-1 Carbonate, Goat Island, and Gasport.

The last report outlines potential errors in the 35,000 water zones which include digital data entry errors, incorrect and/or outdated formation water interval assignment, imperial to metric unit conversion errors, missing data and lack of data for the bottom depth of water intervals.

Future QA/QC work is suggested for the continued verification and updating of water interval formation assignments in OPDS, particularly for wells that have undergone recent geological QA/QC and for other geological formations known to have water zones, such as the Bass Islands Formation and Cambrian sandstones.

References

Armstrong, D.K., and Carter, T.R. 2010. The subsurface Paleozoic stratigraphy of southern Ontario. Ontario Geological Survey, Special Volume 7, 301 pp

Carter, T.R., Brunton, F.R., Clark, J.K., Fortner, L., Freckelton, C., Logan, C.E., Russell, H.A.J., Somers, M., Sutherland, L. and Yeung, K.H. 2019. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario. Ontario Geological Survey, Groundwater Resources Study 19 / Geological Survey of Canada, Open File 8618. https://doi.org/10.4095/315045

Carter, T.R., Fortner, L.D., Russell, H.A.J., Skuce, M.E., Longstaffe, F.J., and Sun, S., 2021a. A hydrostratigraphic framework for the Paleozoic bedrock of southern Ontario. Geoscience Canada, v. 48, p. 23-58, https://doi.org/10.12789/geocanj.2021.48.172

Carter, T.R., Logan, C.E., Clark, J.K., Russell, H.A.J., Brunton, F.R., Cachunjua, A.C.M., D'Arienzo, M., Freckelton, C., Rzyszczak, H., Sun, S., Yeung, K.H., 2021b. Three-Dimensional Geological Model of the Paleozoic Bedrock of Southern Ontario – Version 2. Geological Survey of Canada, Open File XXXX,

Carter, T.R., Wang, D., Castillo, A.C., and Fortner, L. 2015a. Water type maps of deep groundwater from petroleum well records, southern Ontario. Ontario Oil, Gas and Salt Resources Library, Open File Data Release 2015-1, 10 p. 89 maps.

Carter, T.R., Wang, D., Castillo, A.C., and Fortner, L. 2015b. Static level maps of deep groundwater from petroleum well records, southern Ontario. Ontario Oil, Gas and Salt Resources Library, Open File Data Release 2015-2, 11 pp. 17 maps.