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Evaluating the groundwater resource potential of the Dundas buried bedrock valley, southwestern Ontario; An integrated geological and hydrogeological case study.

A. F. Bajc, (corresponding author) andy.bajc@ontario.ca, tel: 705-670-5960, fax: 705-670-5905
A.S. Marich, andrea.marich@ontario.ca
E.H. Priebe, elizabeth.priebe@ontario.ca
D.R.B. Rainsford, des.rainsford@ontario.ca

Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario, P3E 6B5.
Abstract

Population growth in the groundwater-dependent municipalities of southwestern Ontario has prompted interest in the exploration for new, previously untapped, groundwater resources. In this study, the groundwater resource potential of the sediments infilling a deeply buried bedrock valley network centred beneath the Region of Waterloo and the counties of Brant and Hamilton-Wentworth are explored. The objectives of this study are to further refine valley location and geometry, understand infilling sediments and their hydrogeological properties, and characterize waters contained within the aquifers to inform future water management decisions. Results of a regional ground gravity survey were instrumental in locating buried bedrock valleys and guided follow-up drilling. Continuous sediment coring and monitoring well installations were completed to target thick and coarse grained sediment packages that, based on existing borehole data, showed aquifer potential. Hydraulic testing and groundwater sampling results provided valuable insights into groundwater quantity and quality. Highly transmissive aquifers, some worth investigating further, have been identified within portions of the valley network. The aquifers appear to occur at a number of stratigraphic positions and don’t necessarily occur as the deepest unit overlying bedrock. Bedrock topography likely played a role, however, in their preferential preservation. They are commonly overlain by thick sequences of relatively impermeable sediments providing excellent protection from anthropogenic contamination. Information from water chemistry, however, does suggest hydraulic connection to the surface at some locations. Groundwater quality and quantity information combined with a conceptual three-dimensional geologic model aids in the selection of groundwater resource exploration targets within the untapped resources of the deep, Dundas buried valley sediments.
Introduction

A deeply incised buried bedrock valley extending westward from the western end of Lake Ontario has intrigued geologists in southern Ontario for more than a century (Fig. 1) (e.g. Spencer 1890; Straw 1968; White and Karrow 1971; Flint and Lolcama 1985; Eyles et al. 1993, 1997; Gao 2011). Early conceptualizations envisioned this valley as part of a large preglacial drainage system centred over the Great Lakes basins (Fig. 1a) (Spencer 1890). Karrow’s (1973) compilation of bedrock topography of southwestern Ontario further refined the locations of buried bedrock features including prominent escarpments, broad, trough-like bedrock depressions and narrow gorges (Fig. 1b). In that compilation, he identified a continuous, buried bedrock valley system extending northwesterly from the west end of Lake Ontario towards the shores of Lake Huron, a distance of over 180 kilometers. Advances in geographical information systems (GIS) and digital interpolation software subsequently improved mapping capabilities and enabled more robust conceptualizations of the Dundas buried bedrock valley system (Figs. 1c,d) (Eyles et al. 1993; Gao et al. 2006; Gao 2011). Divergent interpretations on the origin of buried bedrock valleys in southwestern Ontario have clearly influenced the portrayal of the valley systems in these latter iterations. Although the reliability of valley definition has improved with time, the stratigraphic context and depositional history of valley fill sediments, as well as their geological and hydrogeological characterization has remained largely unstudied prior to this investigation. Local studies along the trend of the Dundas valley between Lake Ontario and Copetown have, however, resulted in an improved understanding of the geometry of the bedrock valley and the nature and age of infilling sediments (Finamore 1975; Edgecombe 1999; Greenhouse and Monier-Williams 1986, 1986; MacCormack et al. 2005).
Many buried bedrock valley systems in glaciated terrains contain sediment facies that host large and productive aquifers (e.g., Ritzi et al. 1994, Sheets et al. 1998, Panno et al. 1994). This region of southern Ontario is under moderate to high stress from a water supply perspective (Region of Waterloo 2008). As a result, there is considerable interest in identifying new groundwater resources to ensure a sustainable supply for years to come. Understanding the influence of buried bedrock valleys on regional groundwater flow and their importance to water budgeting exercises is critical as part of this long term assessment. Beyond this study, there is a general need for an improved understanding of buried valleys across Canada, one that integrates hydrogeological and geological interpretations (Russell et al. 2004).

The motivation for this integrated geological and hydrogeological study is to support the identification of groundwater resource exploration targets in the deep valley sediments. The study objectives are as follows:

- To further constrain the location and geometry of the Dundas buried bedrock valley network.
- To improve understanding of the geological and hydrogeological properties of the valley fill sediments.
- To identify potential groundwater resource exploration targets within the valley system.

**Geologic Setting**

The geologic feature referred to here as the Dundas buried bedrock valley extends from the west end of Lake Ontario, through the central part of the Region of Waterloo towards the Town of Wellesley (Fig. 1b). Beyond this point, the valley is referred to as the Wingham valley (Karrow 2008).
1973, Gao 2011) extending northwestward towards Lake Huron. Similar gorge-like features have been identified further to the north in the Walkerton, Mount Forest, Elora and Rockwood areas (Gao 2011).

**Bedrock Geology**

Collectively, the Dundas and Wingham valleys are located on and adjacent to the interlake peninsula; a broad bedrock upland bordered by the basins of lakes Ontario, Erie and Huron (Fig.1d). The bedrock valleys cut through southwest-dipping Ordovician, Silurian and Devonian siliciclastic, carbonate and evaporitic successions of the Michigan basin, their contacts occurring at the Niagara and Onondaga escarpments, respectively (Fig. 2). Between Hamilton and Niagara on the Lake, the Niagara Escarpment forms an impressive cuesta measuring over 100 m high. Here, Early Silurian Lockport Group dolostones form the resistant caprock of the Niagara Escarpment (Brunton 2009) and overlie soft, distinctive red and green shales of the Queenston Formation (Armstrong and Carter 2010). Interbedded green shales, gypsum and subordinate dolostone of the Upper Silurian Salina Group overlie the Lockport Group carbonates extending both west and south to the base of the Onondaga Escarpment, the brow of which is defined by dolostones and cherty limestones of the Bass Island/Bertie and Bois Blanc formations, respectively. The Onondaga Escarpment, which occurs as a well-defined step of the bedrock surface measuring 25 to 45 m high, is largely concealed beneath thick deposits of glacial sediment throughout much of the area covered by this study (Gao et al. 2006). Devonian limestones and dolostones of the Detroit River Group extend both to the west and south from the Onondaga Escarpment towards the shores of lakes Huron and Erie, respectively (Armstrong and Carter 2010).
The Modern Niagara River as a Possible Analog

The Niagara River fluvial system, linking Lake Erie to Lake Ontario, displays a number of important morphological characteristics that may inform an interpretation on the origin of the Dundas buried bedrock valley. Between Lake Erie and Niagara Falls, a distance of just over 25 km, the river bed primarily transects the Upper Silurian Salina Formation with the Onondaga Escarpment occurring at the south end just north of the shores of Lake Erie. The river occurs as a bifurcating channel network with channels measuring between 500 and 2000 m in width.

Available outcrop and borehole data (Gao et al. 2006) used together with NOAA (National Oceanic and Atmospheric Administration) bathymetric charts along the river suggests bedrock channels approaching 40 m deep in the vicinity of the Onondaga Escarpment near Lake Erie and diminishing to less than 20 m in the immediate vicinity of the falls. The gradient of the river bed along this stretch is approximately 0.5 m/km. At Niagara Falls, the river bed drops abruptly by 110-115 m. The plunge pool at the base of the falls accounts for about half of the total drop. The Niagara gorge, which extends from the falls northward to the brow of the Niagara Escarpment, incises through the Lockport, Clinton and Medina groups and into Queenston Formation shales at the base. The gorge is approximately 9 km long and measures between 200 and 400 m wide. Variations in gorge width have been attributed to changing rates of gorge recession (Tinkler et al. 1994). The river bed along this stretch drops by greater than 40 m suggesting a gradient of 4-5 m/km. Between the Niagara Escarpment and Lake Ontario, a distance of 11.5 km, the Niagara River continues to incise through Queenston Formation shales.
producing a channel measuring between 600 and 800 m in width. Information on the depth of the bedrock channel along this portion of the river is not available.

**Quaternary Geology**

The Dundas buried bedrock valley system is located in southwestern Ontario within a region that has received a fair amount of both detailed Quaternary mapping and subsurface investigations over the last half century. Regional assessments of large morainic complexes in southwestern Ontario date back to the latter part of the 19th century with the works of Taylor (1899, 1913). As a result, there is significant information available on the distribution, age, genesis, physical properties and stratigraphic significance of Quaternary deposits preserved within this region. This information serves to assist with the placement of stratigraphic units recovered as part of this study into a regional stratigraphic context. The following section will attempt to summarize the current understanding of Quaternary geology of the region prior to the start of this study.

Quaternary sediments within the region encompassing the Dundas buried bedrock valley range from less than 10 to greater than 200 m in thickness (Gao et al. 2006). They overlie a broad, east-facing, amphitheatre-shaped, bedrock depression (Fig. 1d) that slopes gently from a high in the northwest of approximately 300 m asl to a low in the east, below the Niagara Escarpment, of greater than 100 m below sea level (Gao et al. 2006). The bedrock valley system straddles a well-documented interlobate zone within which the Waterloo moraine was constructed during the initial break-up of Late Wisconsin ice (Taylor 1913). This zone of hummocky to rolling topography forms a broad topographic high within the west-central part of the survey area (Fig. 3). The ground surface declines gently to the east with more abrupt, step-like drops in elevation occurring along the eastern margins of the Paris-Galt moraines and the
Niagara Escarpment. Landforms (moraines, drumlins, eskers) and sediments associated with late lobate ice flowing out of the Huron and Erie-Ontario lake basins are mapped both northwest and east of the Waterloo moraine, respectively (Fig. 3) (Chapman and Putnam 1984; Cowan 1972, 1975; Feenstra 1975; Karrow 1968, 1987, 1993).

The Late Wisconsin record accounts for a significant proportion of the sediments preserved within the region of the Dundas buried bedrock valley (Fig. 4). Regionally extensive Catfish Creek Till floors the Late Wisconsin sequence and serves as a stratigraphic marker bed that assists in regional correlations. The pre-Late Wisconsin record is, for the most part, fragmentary and poorly understood. It is defined primarily on widely spaced surface exposures (lake bluffs, river cuts and quarry exposures) and, more recently, in cored borings. Broadly speaking, Pre-Late Wisconsin deposits can be subdivided into 3 main units: 1) a lower unit of stony, silty to sandy diamicton and related stratified sediments; 2) a middle unit of stone-poor, variably-textured diamicton often displaying a reddish hue and regionally correlated to Canning Till (Cooper 1975); and 3) an upper unit of organic-bearing, alluvial, lacustrine, pond and bog deposits laid down during a non-glacial interval that transitions upward into stratified deposits of glacial origin (Fig. 4). Radiocarbon ages on wood recovered from the non-glacial deposits range between 23 500 and >50 500 $^{14}$C years BP (Bajc et al. 2009). The non-glacial interval spans the Middle Wisconsin and possibly extends into the Sangamonian interglacial (Fig.4).

As mentioned earlier, Catfish Creek Till was deposited during the Late Glacial Maximum (LGM) when the ice margin of the Laurentide ice sheet stood in southern Ohio 17-25 ka BP (Karrow 1988). It occurs primarily in the subsurface although it is exposed in deep excavations and river cuts within the Dundas valley study area (Fig. 3). The thickness of this till, as defined
in recent 3-D modelling efforts, generally ranges between 15 and 40 m (Bajc and Shirota 2007; Bajc and Dodge 2011; Bajc et al. 2014). Subglacial facies of the till are generally dry, dense and overconsolidated, display a silty to sandy matrix and contain abundant faceted and striated clasts ranging from pebble- to boulder-size (Bajc et al. 2014). Lithologies derived from the north shore of Lake Huron, including Gowganda Formation tillite and jasper conglomerate, are commonly encountered within this northern-derived till and aid in its positive identification (Karrow 1988). Both early and late lobate facies of the till, occasionally finer-grained and containing fewer clasts, have been recognized further complicating positive identification of the unit based on grain size alone (Hicock 1992; Bajc and Dodge 2011; Dreimanis et al. 2014). In addition, interbedding of diamict and fine-grained, waterlain deposits has been observed in the upper and lower parts of Catfish Creek Till in a number of cored boreholes drilled along the interlobate zone as part of regional aquifer mapping projects (Bajc and Dodge 2011). The interbedding of stratified deposits with the upper part of Catfish Creek Till marks the early stages of formation of the interlobate zone in southwestern Ontario.

The Waterloo moraine was constructed in this interlobate setting between the retreating Huron and Erie-Ontario ice lobes (Fig. 3, 4). Interbedded deposits of sand and silty sand with lesser amounts of gravel, silt, clay and muddy diamict accumulated in what was likely an ice-walled lake fed by a series of converging subglacial conduits (Bajc et al. 2014). Waterloo moraine deposits, approaching 100 m in total thickness, have been intercepted in drilling programs within the Region of Waterloo (Gautrey 1996). Permeable sandy and gravelly facies serve as important aquifers for both the municipal and rural water supply needs of the region (Hodgins et al. 2012). Fine-grained facies, including massive to well laminated silts and clays
and pebbly clays, occur as discontinuous sheets of variable thickness at a variety of stratigraphic
positions within the moraine sequence (i.e. at the base, within and capping). The massive
diamicts have been formally referred to as Maryhill Till and are tentatively assigned to the Erie-
Ontario ice lobe based on the presence of Grenville marble clasts sourced to the east and the
close association with stratified sand and gravel deposits in the moraine with paleoflow
indicators to the west (Karrow 1974; Bajc and Karrow 2004). The fine-grained units are
hydrogeologically important as they confine aquifers and control groundwater flow at both local
and regional scales.

A series of progressively younger tills were deposited northwest and southeast of the
interlobe zone during slight oscillations of the retreating Huron-Georgian Bay and Erie-Ontario
ice lobes, respectively (Figs. 3, 4). Important to this study are the variably-textured Port Bruce
Stadial tills (Elma, Mornington, Stratford and Tavistock tills) deposited by the Huron-Georgian
Bay ice lobes (Karrow 1993) and the sandy to clayey Port Stanley Till of similar age deposited
by the Erie-Ontario ice lobes (Karrow 1987, Cowan 1972) to the southeast. These tills onlap the
Waterloo moraine around its peripheries and prevent the rapid infiltration of surface waters into
the subsurface.

As the margin of the Erie-Ontario ice lobe retreated eastward, extensive braided stream
deposits were laid down within the northern Grand River valley (Fig. 4). To the south, these
sand and gravel deposits fed large deltas where meltwater streams entered a series of high level
Erie basin lakes (Barnett 1985). To the north, a slight re-advance of the retreating Erie-Ontario
ice lobe at 13.4 $^{14}$C ka BP resulted in the deposition of the coarse-textured (stony and silty to
sandy) Wentworth Till over these glaciofluvial deposits and the construction of the Paris and
Galt moraines (Figs. 3, 4) (Barnett 1985; Bajc and Karrow 2004; Bajc and Dodge 2011). Erie basin water levels continued to decline as the ice margin pulled back from the Niagara Escarpment opening a series of low-level outlets to the east establishing the Ypsilanti low phase in the Lake Erie basin (Kunkle 1963). The Dundas valley may have acted as a drainage outlet for meltwater during this period of ice withdrawal possibly removing the sediment record of previous ice flow events in the region.

A late-glacial readvance of the Erie-Ontario ice lobe during the Port Huron Stadial (~13.0 $^{14}$C ka BP) to a position just west of the brow of the Niagara Escarpment resulted in the construction of the Waterdown moraines and the deposition of stone-poor, silty, Halton Till (Figs.3, 4) (Karrow 1987; Feenstra 1975). Closure of the eastern outlets during this readvance resulted in a basin-wide transgression and the establishment of the Whittlesey and Warren shorelines in the Lake Erie basin. By 12.0 $^{14}$C ka BP, the ice margin had once again retreated into the Lake Ontario basin uncovering a series of low-level outlets resulting in declining Erie basin water levels and the establishment of present-day drainage conditions (Barnett 1992).

**Methodology**

**Data Compilation and Preliminary Conceptualization**

The present study was initiated by compiling all available subsurface information and creating an updated bedrock topography surface. A variety of data sources were used to support the updated interpretation including the Ontario Ministry of Environment and Climate Change (MOECC) water well database, the Ontario Ministry of Natural Resources and Forestry (MNRF) Oil and Gas database, the Ontario Ministry of Transportation (MTO) Geocres database as well as a number of logs of continuously cored boreholes drilled as part of ongoing 3-D mapping projects.
by the Ontario Geological Survey. Published Quaternary geology maps and orthoimagery were also visually scanned to identify areas of thin drift and exposed bedrock. An updated bedrock topography surface was created using the nearest neighbour interpolation process with a 50 m grid cell size. Records resulting in anomalous peaks and hollows in the bedrock surface were manually inspected and, in critical areas, field checked to verify the authenticity of the record. A preliminary rendering of valley locations was completed and served as a basis for subsequent geophysical and geological testing.

**Ground Gravity Survey**

A regionally-based ground gravity survey was conducted across the study area to refine the possible locations of bedrock depressions along strategically placed transects. Measurements were acquired at approximately 3350 stations spaced at 100-200 m using LaCoste and Romberg Model G and Scintrex CG-5 gravimeters. The stations lie along 33 road traverses totalling 397 line km (Fig. 5). Station elevation data were acquired to an accuracy of ± 3 cm using a real time differentially-corrected global positioning system (GPS) receiver. The slope around each station was measured using an inclinometer so that close-in terrain corrections could be applied during processing. The processing of the gravity data consisted of standard tide, latitude, free air, bouguer and terrain corrections. A description of these corrections can be found in many geophysical textbooks (e.g. Telford et al. 1990, Parasnis 1962). A regression analysis using a range of bouguer densities against topographic elevation indicated that the appropriate bouguer density is 2.1 g/cm$^3$. This is consistent with measurements of local till densities from the area (Bajc and Dodge 2011). Regional gradients were estimated by upward continuation of the observed field and subtracted from the Bouguer gravity values to obtain the residual gravity.
The residual gravity data were then plotted in profile form along the road transects to generate a graphical representation of where possible buried bedrock valleys are located. Negative residuals were assessed and ranked according to shape and amplitude and screened against water well data, where available. The results of the ground gravity survey were subsequently used to revise the location of bedrock valleys in areas lacking depth to bedrock information.

**Overburden Drilling and Hydrogeological Testing**

To target areas for follow-up drilling, a series of cross-sections were constructed along the revised valley segments to identify areas, based primarily on water well records, where potentially significant, deeply buried aquifers exist. The results of this analysis resulted in the identification of 3 areas, based on bedrock and surficial geologic environment, for follow-up drilling. Drilling was undertaken using a track-mounted, mud-rotary rig equipped with a PQ coring system. The cores were logged in detail (cm scale), photographed and sampled for grain size and carbonate content with analyses performed at the Ontario Ministry of Northern Development and Mines Geoscience Laboratories in Sudbury.

Piezometers were installed in each of the cored boreholes for hydraulic testing and groundwater sampling. Each well was constructed with a 3 m long well-screen placed across the deepest and coarsest basal sediments. At two of the sites (DV-04 and DV-05), multi-level observation wells were installed close to the original coring sites to provide instrumentation for hydraulic testing to facilitate an evaluation of hydraulic connectivity between stratigraphic units. Sites DV-04 and DV-05 were selected for further study because they are proximal to Region of Waterloo municipal centres. Slug tests and/or short term pumping tests of up to 8 hours in duration were conducted at each of the sites.
Hydraulic conductivity estimates were made from pumping and slug test analyses using the Cooper and Jacob (1946) and Hvorslev (1951) methods, respectively. These methods were selected to represent the confined conditions of the deeply buried aquifers. Hydraulic conductivity estimates were also made for each sediment package from the complete grain size distribution curves following the method of Alyamani and Sen (1993). This method is considered to be rigorous compared to commonly used methods (e.g. Hazen 1892) that rely on grain size statistics, such as effective diameter, rather than the complete grain size distributions used here to make hydraulic conductivity estimates (Alyamani and Sen 1993).

The hydraulic conductivity values for each aquifer were estimated with the weighted arithmetic mean shown in Equation 1. Here, $K_x$ is the mean horizontal hydraulic conductivity, $b$ is the aquifer thickness, $n$ is the number of samples and $K_i$ and $b_i$ are the hydraulic conductivity and thickness of each sediment layer respectively. This relation is based on a simplification of the Darcy (1856) equation for layered sediments where groundwater flow is assumed to be parallel to horizontal bedding.

$$K_x = \frac{1}{b} \sum_{i=1}^{n} K_i b_i$$

(1)

The mean vertical hydraulic conductivities ($K_y$) of aquitard units overlying the deep aquifers of the study were estimated using the following relation simplified from the Darcy (1856) equation and assumes predominantly vertical flow orthogonal to bedding in these fine-grained units.
Groundwater sampling was conducted at each site to characterize groundwater chemistry within the deep valley aquifer zones. Samples were analyzed for dissolved metals, general chemistry parameters and isotope tracers, specifically $^{18}$O, $^2$H and $^3$H (enriched). Dissolved metals and general chemistry analyses were performed by Maxxam Analytics of Mississauga and Waterloo, Ontario (MacDonald and Greer 2009; Veale and Freymond 2010; Veale 2010). Isotope analyses were performed by IT2 Technologies of Waterloo, Ontario, with full results reported in Marich et al. (2011). The general chemistry and metals results were compared with Ontario Drinking Water Standards (Ontario 2002) to identify any water quality issues that might influence future water supply development. The isotope tracer results were interpreted to better understand recharge timing into the deep groundwater systems under investigation.

**Results and Interpretation**

**Ground Gravity Survey**

The results of the ground gravity survey are presented as residual gravity profiles superimposed on a shaded bedrock topographic base constructed as part of the initial compilation (Fig. 6). The negative residuals are presumed to correspond to bedrock depressions infilled with lower density glacial sediment. A good correlation exists between areas where the bedrock valley is well constrained using borehole information and the location of negative residuals. Areas of particularly good correlation include the north-south profile just west of Copetown and the north-northeast profile just west of Wellesley. A number of broad, east-west trending...
anomalies have also been identified. In these cases, it is difficult to determine whether the negative residual anomalies are responding to broad bedrock valleys or perhaps narrower valleys crossed by the survey at an oblique angle. In the northwest part of the gravity survey, close to the projected trend of the Onondaga Escarpment, there is excellent correspondence between the pattern of both positive and negative gravity residuals and the locations of what are interpreted as steep-walled mesas. The results of the ground gravity survey were used to assist in the delineation of buried bedrock valleys, especially in areas lacking subsurface data (Fig.6).

**Continuous Coring of Sediments**

Potential aquifer units were identified in 52 of the 62 cross-sections drawn along the axes of interpreted bedrock valleys. Twenty-five of those occur at depths that suggest they are confined to the bedrock valley system (Fig. 7). Three target areas were identified for follow-up drilling (west, central and east) each representing a unique surficial and bedrock environment within the valley system. Eight continuously cored boreholes were drilled to bedrock by the OGS in 2008 and 2009 and an additional 2 boreholes were drilled in the communities of Copetown and Lynden as part of collaborative studies with the City of Hamilton at around the same time (Fig. 5). Over 600 m of PQ size (85 mm) core was recovered from the 10 boreholes with depths ranging between 45 and 198 m. Coring at each site was terminated following the successful recovery of 2 to 3 m of competent bedrock. Unfortunately, bedrock was not intersected in the Copetown borehole as challenging drilling conditions were encountered at depth.

**Valley Geometry**

The data collected as part of this study allows for an improved understanding of the geometry of the Dundas buried bedrock valley system. At its eastern extent, the Dundas valley occurs as a
prominent re-entrant of the Niagara Escarpment measuring over 10 km wide in the central part of Hamilton Harbour then narrowing westward to less than 5 km at the town of Dundas. Depth to bedrock on the Burlington Bar below the Niagara Escarpment and along the valley axis exceeds 210 m putting the base of the valley at greater than 138 m below sea level (A. Burt, personal communication 2016). The total depth of the valley at this location, including the exposed portion of the Niagara Escarpment, is therefore inferred to be greater than 375 m. West of the escarpment’s brow, at Copetown, the valley widens to 9 km and appears benched. Its edges become less well defined within this area as the valley is concealed beneath thick deposits of glacial sediment and has no surface expression. A cored borehole at Copetown extended just under 200 m without intersecting bedrock, providing additional information on the depth to bedrock at this location.

Between Copetown and the south end of Kitchener, the location of the Dundas valley and its tributaries is poorly defined. Deep gorge-like features, as exist between Copetown and Lake Ontario, have not been identified in this region. In fact, Greenhouse and Monier-Williams (1986) reported closure of the bedrock gorge just west of Copetown and suggested that a great waterfall occupied this location at some time in the past. The bedrock valley system within this region traverses Lockport Group dolostones and less resistant Salina Group shales, evaporites and dolostones. The valley network is largely defined by widely spaced bedrock intercepts and push-down wells improved upon locally by the results of the ground gravity survey in areas lacking depth to bedrock information. Infrequent bedrock intercepts within the area of the Waterloo moraine limits the degree to which the valley system can be defined as well. It is represented here by a series of broad, shallow, linear depressions measuring 5-10 km in width.
and 10-30 m deep. A single trunk valley with branching tributaries is conceptualized based on
the data available, however, it is recognized that multiple interpretations of the bedrock valley
system are possible. The valley bottom between Copetown and the south end of Kitchener, a
distance of approximately 40 km, rises by just over 75 m (~2 m/km); a gradient approximately
four times greater than that observed along the Niagara River between Fort Erie and Niagara
Falls.

The bedrock surface changes between the south end of Kitchener and the town of Wellesley
becoming a zone of highly irregular bedrock topography best described as a series of plateaus
incised by narrow valleys 30-40 m deep. This zone, which is well defined by borehole records
and confirmed by the results of the ground gravity survey, likely reflects an area of detached
mesas beyond (east of) the Onondaga Escarpment.

At Wellesley, the valley once again becomes a single gorge-like feature measuring 2-4
kilometers wide and 40-50 m deep. The bedrock surface on either side of the gorge is concealed
beneath 35-60 m of glacial sediment and there is no surface expression of the feature within this
region (Bajc and Karrow 2004). This abrupt change in valley character is a reflection of the
valley entering the region of the buried Onondaga Escarpment where cherty limestones and
dolostones form the resistant cap rock.

**Valley Fill and Hydrogeology**

The 10 boreholes drilled as part of this study are subdivided into 3 main groupings based on their
location (bedrock and Quaternary geology) and preserved stratigraphic record (Figs. 5, 8 and 9).
Figure 4 provides the stratigraphic context for the following discussions and Table 1 summarizes
the grain size and carbonate content data for each of the main till units that act as regional stratigraphic markers. The western and central zones contain a record that both predates and spans the Late Wisconsin whereas the eastern zone contains largely a deglacial sequence.

Of greatest interest to this study are the deeply buried, coarse-grained sediments within the valley confines that contain groundwater in sufficient quantity and quality to support resource development. These deep aquifers were identified locally in each of the cored boreholes, with evidence of their continuity identified in 25 of the 62 cross-sections interpreted as part of this study (Marich et al. 2011). Our interpretations suggest that these deep aquifers are discrete and fragmented rather than continuous bodies within the bedrock valley system (Fig. 7). Important aquifers have been identified beneath Canning Till at the western end of the valley system, between Catfish and Canning tills in the western and central portions of the valley and in close association with Port Stanley and Wentworth tills at the eastern end.

Hydraulic conductivity values for these deep aquifers and overlying aquitard sediment packages are presented in Table 2. The correlation between hydraulic conductivity estimates made from grain size data and hydraulic test analyses is not perfect for each site, varying by nearly two orders of magnitude for some comparisons. However, the commonly reported trend of lower hydraulic conductivity estimates with decreasing test volume or scale (e.g. Rovey and Cherkauer 1995) was not observed. The variability between the two types of estimates is likely a result of differences in the length of the test interval for each method, which consisted of the 3 m screen length for the monitoring wells and the full aquifer thickness for the grain size estimates.

The geochemical signature of the underlying bedrock was observed in the hydrochemistry at some, but not all groundwater sampling locations. Some groundwater samples collected from
wells overlying the Salina evaporites in the central part of the valley contained elevated
dissolved sulphates presumably from gypsum. In the eastern part of the valley, elevated salt
centrations were reported for some samples collected from aquifers overlying the Queenston
Formation shales (Marich et al. 2011). These geochemical trends are visible in the water types
shown in Figure 10. Despite this, many deep aquifers showed excellent water quality from a
groundwater supply perspective.

Tritium values for the deep groundwaters in the valley ranged from <0.8 tritium units (TU) to
11.3 TU, representing pre-1952 to modern recharge timing (Clark and Fritz 1997) with the oldest
recharge occurring in the aquifers at the extreme eastern and western valley extents. The $^{18}\text{O}$
range of -12.2 to -9.9 ‰ measured in valley groundwater samples falls within the range of values
expected for shallow modern groundwater (Fritz et al. 1987). There was no isotopic evidence of
Pleistocene-age recharge in the valley sediments, like those reported for the Alliston aquifer in
the Laurentian buried bedrock valley system northeast of the study area (Aravena and Wassenaar
1993).

**Western Dundas Valley Aquifer Zone**
The western valley aquifer zone is located in the northwest corner of the study area above the
Onondaga Escarpment and was intersected in test holes DV-06 and DV-08 (Fig. 8). This area is
underlain regionally by Devonian limestones and dolostones however the two boreholes drilled
along the trend of the interpreted valley penetrated the underlying Silurian shales and dolostones
of the Salina Formation (Fig. 11b). The deeply-buried aquifers in this zone occur at the highest
elevations of any aquifers within the valley system. Boreholes DV-06 and DV-08 each
intersected bedrock at ~77 m depth and have correlatable stratigraphic sequences (Fig. 8).
The oldest sediments present within the western zone are attributed to the pre-Late Wisconsin and correlate to deposits previously described by Bajc and Dodge (2011) in a borehole a few kilometers to the west along the same gorge-like feature (OGS-03-05). These sediments were identified within borehole DV-06 and consist of interbedded sand and gravel and grey, compact, slightly cemented, stony, silty fine- to medium-textured sand (Fig. 11c). These sediments were evaluated for their water supply potential at the DV-06 location. Hydraulic conductivity (K) estimates for this sub-Canning aquifer (OD in Fig. 8) yielded values of $3 \times 10^{-5}$ m/s and $1 \times 10^{-6}$ m/s from hydraulic test analyses and grain size data, respectively (Table 2). Major ion chemistry for groundwater samples collected at DV-06 falls within the freshwater, Ca/Mg-HCO3 zone of the Piper tri-linear plot (Fig. 10). The water quality of groundwater samples collected from DV-06 met all health-related parameter levels, with values for some aesthetic objectives (iron, hardness, manganese) measuring above the ODWQ standard (Ontario 2002). The tritium isotope analyses for the site fell below the detection limit of 0.8 tritium units, indicating that these waters were likely recharged prior to 1952 (Clark and Fritz 1997). The $^{18}$O analyses fall within the range of values for modern, shallow groundwater in southern Ontario (Fritz et al. 1987).

Canning Till was observed in both boreholes in the western zone and ranges from 10 to 23 m thick. The till is a stone-poor, sandy silt diamicton with a reddish hue and is less compact than the older diamicton units (Fig. 11d). The red hue is attributed to the incorporation of Queenston Formation shale and suggests an Erie-Ontario source lobe (Cooper 1975; Krzyszkowski and Karrow 2001; Bajc and Dodge 2011; Bajc et al. 2015). The upper surface of this till in borehole DV-06 is oxidized and weathered suggesting a period of subaerial exposure and further supports
the interpretation of this unit being attributed to either the Early Wisconsin or the Illinoian
glaciation. A hydraulic conductivity of $3 \times 10^{-7}$ m/s was estimated for the Canning Till based on
grain size data from DV-06. This value falls within the range of hydraulic conductivity values
expected for silt, as described by Freeze and Cherry (1979).

A significant, well bedded gravelly to sandy sub-Catfish aquifer (SCA, Fig.8), measuring
approximately 20 m thick, overlies Canning Till in borehole DV-08. Facies observed include
pebble gravel at the base, in places displaying open framework (Fig. 11e), horizontally laminated
sands with minor silt (Fig. 11f) in the central part and cobble gravel at the top of the unit (Fig. 11g). In borehole DV-06, the aquifer was not present. Instead, Catfish Creek Till rests directly
on Canning Till, the upper surface of which is deeply weathered. This sub-Catfish Creek Till
aquifer system was also identified in 42 water well records along 4 interpreted bedrock valleys in
the western reaches of the study area at an elevation range between 310 and 385 m asl (Marich et
al. 2011). These SCA sediments were evaluated for their water supply potential at the DV-08
location in the western portion of the valley. Based on grain size data, the hydraulic conductivity
estimate for this location is $3 \times 10^{-5}$ m/s and falls within the range of values for sand (Freeze and
Cherry 1979). Specific capacity values were calculated from the MOECC water well record
data for 24 wells screened in the sub-Catfish Creek sediments. These values range from 1 to 298
L/min/m with a mean of 30 L/min/m and a median of 7 L/min/m. This mean specific capacity
value falls just above the 50th percentile range of 5 to 25 L/min/m reported for the overburden
aquifers of the Grand River watershed (Singer et al. 2003). Results of groundwater sampling at
DV-08 mirrored those collected in the lowest aquifer at DV-06 (Figs. 10 and 13).
Thick sequences (up to 15 m) of olive-grey, dense and over consolidated stony and sandy till interpreted to be Catfish Creek Till were observed in both holes DV-06 and DV-08 (Fig. 11h). At the DV-08 location, the hydraulic conductivity is estimated to be $4 \times 10^{-7}$ m/s from the grain size distribution (Table 2). This value falls within the silt range, as described by Freeze and Cherry (1979).

Overlying Catfish Creek Till (CCT) is up to 35 m of Erie and/or Port Bruce Stadial deposits (Waterloo moraine equivalents and Mornington Till) (Fig 3). The Waterloo moraine equivalents overlie Catfish Creek Till in borehole DV-06 and consist of a coarsening upward sequence of well laminated silts, clays and gritty clays grading upwards into well bedded and laminated fine-to very fine-grained sands (Fig. 12a) interpreted to be of a glaciolacustrine origin. These deposits were not encountered in DV-08. Rather, 30 m of clay-rich Mornington Till (Huron Lobe) containing beds and laminations of fine-textured glaciolacustrine deposits overlie Catfish Creek Till in this borehole. Approximately 7 m of Mornington Till caps the sedimentary sequence in DV-06 providing a low permeability confining layer at surface (Fig. 12c).

Central Dundas Valley Aquifer Zone

Boreholes DV-04 and DV-05 occur in the central zone where the valley crosses Salina Group shales and evaporites and is buried beneath thick deposits of the Waterloo moraine which often exceed 100 m (Fig. 3). Although the bedrock and physiographic setting of this region is different from the western aquifer zone, the two areas share a common pre-Catfish Creek Till stratigraphic record that includes deep aquifers (Fig. 8).

Bedrock was encountered at 75.8 and 105.4 m depth in boreholes DV-04 and DV-05, respectively. The oldest stratigraphic unit observed in these boreholes is the Canning sediment
package which includes both diamicton and fine-textured glaciolacustrine sediments. Approximately 8 m of diamicton and laminated glaciolacustrine deposits was recovered in borehole DV-05 with a much thinner intercept occurring in DV-04. The Canning diamictons of boreholes DV-04 and DV-05 are not unlike those described in the discussion of the western aquifer zone.

Overlying Canning Till in both boreholes is the sub-Catfish Creek Till aquifer (SCA) which ranges between 16 and 30 m in thickness and consists of well-bedded sand and gravel with lesser laminated silt. A significant portion of the SCA is confined to the bedrock valley in both boreholes (Fig. 8). In borehole DV-04, detrital wood fragments contained within a silty, very fine sand facies of the unit returned a radiocarbon age of 46 400 ± 2000 \(^{14}\)C years BP (NZA-33617). Fossil molluscs contained within an organic-stained paleosol and associated colluvial unit were also encountered at the base of the aquifer sequence just above the presumed Canning Till. 3D modelling efforts by Bajc and Dodge (2011) indicates that this aquifer is regionally present and likely connected in the subsurface. Hydraulic conductivity values for the SCA in the central zone range by about 2 orders of magnitude, from \(4 \times 10^{-5}\) m/s to \(1 \times 10^{-7}\) m/s (Table 2).

Specific capacity values were calculated from MOECC water well record data for 58 wells screened in the SCA sediments. These values range from 1 to 168 L/min/m with a mean of 20 L/min/m and a median of 7 L/min/m. This mean specific capacity value falls within the 50\(^{th}\) percentile range of 5 to 25 L/min/m reported for the overburden aquifers of the Grand River watershed (Singer et al. 2003). In general, the hydraulic conductivities and specific capacities for the SCA are lower and more variable than those reported for the same aquifer in the western zone.
Water chemistry results for the SCA are variable, with fresh, bicarbonate-rich groundwater chemistry measured at the DV-05 location and sulphate-rich, Ca-Mg-SO$_4$ groundwater measured at the DV-04 site (Fig. 10). The dissolved sulphate concentrations measured in groundwater samples collected from the DV-04 location wells ranged from 1100 to 1460 mg/L. The source of these elevated sulphate levels is likely the underlying Salina Group bedrock, which is an evaporite and shale-dominated, gypsum-bearing bedrock unit (Armstrong and Carter 2010). Sulphate levels in groundwater tend to decrease where well screens in the SCA are separated from the Salina Group bedrock by the Canning glacial sediment.

The tritium isotope analyses for groundwater samples taken from DV-04 and DV-05 wells yielded values that ranged between 1.3 and 12.5 TU, indicating that recharge timing ranged from post 1952 to present day (Clark and Fritz 1997). Stotler et al. (2011) reported tritium values ranging between <0.8 and 36 TU in the SCA and bedrock interface aquifers of the central zone. The tritium analyses of both this study and Stotler et al. (2011) suggest that the CCT is a leaky aquitard in places. The $^{18}$O analyses yielded values of -11.38 ‰ VSMOW and -11.10‰ VSMOW, for DV-04 and DV-05 respectively, which reflects modern climatic conditions (Fritz et al. 1987).

Catfish Creek Till and associated stratified deposits occur as a nearly continuous stratigraphic horizon beneath the Waterloo moraine (Bajc et al. 2014). They were encountered in both boreholes and range between 12 and 23 m in thickness. In DV-04, the till occurs as a massive, overconsolidated unit with a few seams or interbeds of stratified sediment. In borehole DV-05, it is interbedded with stratified deposits of clay, silt, sand and gravel suggesting deposition, in part, within a glaciolacustrine setting. Together, the lower, fine-grained facies of the Waterloo
moraine (lower Maryhill facies) (Fig. 11j) and the underlying Catfish Creek Till account for a
confining layer ranging between 23 and 38 m in total thickness. Bajc and Shirota (2007) did,
however, identify discontinuities or windows in these units under parts of the Waterloo moraine
as part of their regional 3D aquifer mapping study. The lateral extent and continuity of this
confining unit is not known but is inferred to be nearly continuous on a regional scale. The
hydraulic conductivity of the CCT confining unit is estimated to be $1 \times 10^{-8}$ m/s and $4 \times 10^{-7}$ m/s for
DV-05 and DV-04, respectively. These hydraulic conductivity estimates fall within the range of
values expected for silt (Freeze and Cherry 1979).

Well laminated silt and clay abruptly overlain by variably-textured stratified sand (Fig. 11i)
overlies Catfish Creek Till in both DV-05 (50 m) and DV-04 (25 m). These sediments are
attributed to the Waterloo moraine and were likely deposited in a subaquatic fan setting by rapid
lobe switching in an ice-supported lake (Russell et al. 2007; Bajc et al. 2014). Facies changes
are rapid within this depositional setting and may influence groundwater flow. In borehole DV-
05, the Waterloo moraine aquifer is largely unconfined whereas in DV-04, it is capped by
approximately 5 m of silty to clayey Port Stanley Till and associated stratified deposits. The
aquifers in both boreholes are likely connected hydrogeologically in the subsurface and serve as
important sources of groundwater both municipally and domestically in unserviced areas.

Eastern Dundas Valley Aquifer Zone
The eastern zone of the Dundas valley is at the lowest end of the buried bedrock valley system
and is underlain predominantly by shales and gypsum of the Salina Group and dolostones of the
Lockport Group. The valley-filling sequence consists of a shorter and much simpler
stratigraphic record consisting primarily of stratified glaciofluvial and glaciolacustrine deposits
with subordinate diamictons laid down during the final phases of deglaciation. Depths of the boreholes drilled in this zone range between 42 and 72 m with the anomalous Copetown borehole extending to a depth of 192 m with no bedrock encountered.

In the west, boreholes DV-07 and DV-03 are situated just west of the Paris moraine (Fig. 3) in an area where the surficial deposits are attributed primarily to the retreating Erie-Ontario ice lobe responsible for the deposition of Port Stanley Till (Port Bruce Stadial) (Fig. 4). Catfish Creek Till occurs as a thin layer of stony, silty to sandy diamicton at the base of DV-07 and is missing in DV-03. Sandy, ice-proximal, glaciolacustrine deposits grading upwards into laminated, basinal silts and clays then back into regressive sands account for the majority of the sequence in DV-07. These sediments were deposited in a series of post-Catfish Creek Till, Erie basin glacial lakes. The fining upward trend is likely a reflection of a retreating ice margin.

Similar deposits occur in DV-03 immediately overlying bedrock but, in this case, are capped by interbedded gravels and silty to sandy Port Stanley flow tills (Fig. 12b). In DV-03, the Port Stanley succession is capped by approximately 28 m of Grand River outwash deposits (Fig. 12d,e) that serve as an excellent unconfined aquifer in the region.

The basal aquifer (Lower Port Stanley aquifer in Table 2) in DV-03 and DV-07 ranges between 10 and 20 m thick. Hydraulic conductivities range from $3 \times 10^{-5}$ to $4 \times 10^{-6}$ m/s with the overlying aquitard ranging from $1 \times 10^{-8}$ to $6 \times 10^{-10}$ m/s. Specific capacity values were calculated from MOECC water well records for 27 wells screened in deep aquifers along this part of the buried bedrock valley. They range from 2 to 44 L/min/m with a mean of 15 L/min/m and a median of 12 L/min/m. In general, the specific capacity values in the eastern valley aquifers are
lower and have a narrower range than those calculated for the western and central valley aquifers.

The groundwater quality for the lower Port Stanley aquifers in DV-03 and DV-07 is excellent, falling within the fresh, Ca-Mg-HCO$_3$ range (Fig. 10). Tritium isotope values for samples collected from the Port Stanley aquifer were 6.6 TU and 10.4 TU, suggesting a mixed signature of modern and pre-1952 recharge (Clark and Fritz 1997). The $^{18}$O isotope ratios for wells screened in Port Stanley aquifers in the eastern zone range from -10.6 to -9.93 VSMOW, which is the low-end of the $^{18}$O range measured for the entire valley, likely reflecting seasonal recharge and the influence of the lower elevation at this sampling point compared with western valley samples.

In the easternmost part of the valley system, Wentworth Till and associated ice-proximal stratified sediments as well as younger, Erie-Ontario basin glaciolacustrine deposits account for the vast majority of the sediments infilling the buried bedrock valley system (Fig. 9). The bedrock valley is eroded into Lockport Group dolostones within this part of the valley network (Fig. 11a). Wentworth Till occurs as thin, stony, silty to sandy debris flow units within a predominantly stratified succession. The stratified units consist of well bedded coarse sand (Fig. 12f) to sandy, cobble gravel (Fig. 12g). The thickness of the lower aquifer sequence in DV-02 and the Copetown borehole ranges between 12 and greater than 14 m. Based on its coarseness and poorly sorted nature, this unit was likely deposited proximal to the retreating Erie-Ontario ice lobe. Occasional, thin layers of diamicton, interpreted as flow tills within the aquifer sequence attest to ice proximity. The transition upward to finer-grained basinal muds is interpreted as a result of a retreating ice margin in a glacial lake basin.
The lower Wentworth aquifer sequence was investigated for its groundwater resource potential at DV-01, DV-02, Lynden and Copetown. Hydraulic conductivities for the Wentworth aquifer range between $2 \times 10^{-4}$ m/s and $3 \times 10^{-7}$ m/s (Table 2). The water quality for the Wentworth aquifer is variable, ranging from very good to poor, with samples from two of the wells (DV-02 and Copetown) having elevated parameters (Cl, Na, TDS, hardness and Fe). The elevated sodium and chloride measured in groundwater samples likely represent the geochemical influence of the Queenston Formation shales, which were observed as shale sand grains and granules in the sediment cores from these holes. Tritium isotope values for the Wentworth aquifer are <0.8 TU and 1.5 TU, suggesting older, pre-1952 recharge timing. The $^{18}$O isotope ratios range from -10.4 ‰ to -11.8‰ VSMOW, which fall within the range expected for modern recharge in Ontario (Fritz et al. 1987).

Overlying the Wentworth glacial sequence is a thick succession of well-laminated silts, clayey silts and silty clays with some sandy interbeds. These sediments were likely deposited in high level precursors of Lake Erie and are collectively referred to as Erie basin glaciolacustrine deposits (Fig. 12h,i, j). The vast majority of the sediment sequence in boreholes DV-01, DV-02 and the Lynden borehole consist of these well-laminated glaciolacustrine deposits. Nearly 100 m of similar glaciolacustrine sediments were encountered within the central and lower portions of the Copetown borehole. Technically, one could argue that the Copetown valley fill sequence was deposited within the Lake Ontario basin however the water body into which the sediments were deposited was probably an extension of an Erie basin lake into the re-entrant.
The hydraulic conductivity of the Erie basin glaciolacustrine aquitard deposits was estimated to be $3 \times 10^{-8}$ m/s and $2 \times 10^{-8}$ m/s based on grain size distributions for DV-01 and DV-02, respectively (Table 2).

The coarsening facies in the upper part of the stratigraphic sequence of the Copetown borehole reflects approaching ice during the Halton readvance. Here, a 60 m thick package of interbedded sand and silty to sandy diamicton cap the sedimentary sequence and mark the outer limit of the Port Huron ice advance. Sandy glaciolacustrine facies at the tops of the Lynden borehole and DV-02 may similarly reflect the approaching ice sheet and/or final drainage of the lake.

**Discussion**

Multiple hypotheses have been proposed for the origin of buried bedrock valleys in southern Ontario. Spencer (1890) (Fig. 1a) and Grabeau (1901) identified bedrock valley networks that they attributed to relict preglacial drainage systems centred over the Great Lakes basins. Gao (2011), alternatively favoured varying degrees of glacial and subglacial meltwater modification of a pre-glacial landscape for the development of the bedrock valley system in southern Ontario with some of the deep, gorge-like features in the interlake zone being interpreted as tunnel valleys and the re-entrant valleys along the Niagara Escarpment and broad, trough-like depressions such as the Laurentian Valley being formed by multiple cycles of glacial erosion possibly enhanced by subglacial meltwater activity. Many workers, including us, however, favour a polygenetic origin for the valley network invoking numerous cycles of glacial modification of a preglacial drainage system that may, in part, be controlled by structurally-controlled joint sets and deep-seated terrane boundaries in the underlying Precambrian basement.
(Straw 1968, White and Karrow 1971; Karrow 1973; Eyles et al. 1997; Edgecombe 1999; Sharpe et al. 2013). Mechanical erosion by glacial ice may have served to modify the pre-existing valley system, in places deepening and widening the bedrock valley. This mechanism is particularly important when the direction of ice flow was parallel to the trend of the valley axis as existed during late, lobate flow out of the Ontario and Huron lake basins. The orientation of the valley system during the LGM would have been orthogonal to the valley minimizing the effects of glacial scouring. The complex pattern of bifurcating and crossing bedrock valleys suggests the possibility for valley systems of multiple ages. An analog for this would be the St. Davids buried gorge with its pre-Late Wisconsin fill and the modern Niagara River gorge that intersect the buried valley at the Whirlpool rapids. During periods of deglaciation, large volumes of subglacial meltwater stored within the basins of the Great Lakes could have re-occupied some of the bedrock valleys, further deepening and modifying their longitudinal profiles. Kor and Cowell (1998) have reported significant modification of re-entrant valleys by subglacial outburst floods further to the northwest along the Bruce Peninsula. In fact, they have postulated significant back wastage of the escarpment’s brow due to erosion of soft shales at the base and subsequent collapse of resistant caprock. The varying depths and widths of the Dundas buried bedrock valley within the study area suggest that the rate and extent of erosion was not consistent across the entire valley system. Resistance to erosion of the underlying rock formations likely served as the main controlling factor. Similar morphologies have been recognized along the modern course of the Niagara River with deep, narrow gorges upstream of major escarpments and broad, shallow, sometimes diverging channels below in areas dominated by shale bedrock.
The oldest deposits encountered within the Dundas valley system predate the main Late Wisconsin, extending as far back as Illinoian or possibly earlier. At least portions of the valley system are therefore inferred to be older than the last glaciation. Similar pre-Late Wisconsin sediment fills were observed in the Georgetown (Meyer and Eyles 2007), Rockwood (Burt and Dodge 2016; Greenhouse and Karrow 1994) and Hockley valleys (Bajc et al. 2015) further to the north along the Niagara Escarpment. To the east, in the Niagara Peninsula, the St. David’s buried gorge is infilled with sub-till, stratified deposits containing wood dated at 22.8-24.8 \(^{14}\)C ka BP (Hobson and Terasmae 1969; Barnett 1989; Bajc et al. 2009). Recent drilling in South Simcoe County and within the Oak Ridges Moraine along the trend of the Laurentian buried bedrock valley has resulted in the recognition of widespread pre-Late Wisconsin deposits infilling the broad bedrock depression (Mulligan and Bajc 2017; Logan et al. 2008). In contrast, the eastern part of the Dundas and Caledon reentrants (Davies et al. 2008) appear to have been re-excavated and backfilled primarily with deglacial sediments. The agent responsible for the removal of pre-existing sediments within these valleys may be related to either subglacial meltwater activity, glacial erosion or a combination of the two. Sharpe and Russell (2016) have suggested that the fining upward sediment fills at Copetown and Caledon East are distal Oak Ridges Moraine equivalent meltwater deposits. The excavation of the Dundas valley below the Niagara Escarpment to depths well below sea level supports an interpretation of glacial modification of the valley system. Although the overall gradient of the valley system appears to be towards the east, the authors are of the opinion that this line of evidence is not sufficient to support a strictly fluvial origin for the valley. Upward gradients along stretches of the bedrock valley system have been reported and used as supporting evidence for a subglacial meltwater origin for the bedrock.
valleys (Gao 2011). We believe that the available subsurface data is not sufficient to support the identification of upward gradients as the precise locations of the deepest parts of the valley are not known. With additional drilling and geophysical surveying along the entire length of the valley system, there should come an improved understanding of the age and origin of the buried bedrock feature.

From a groundwater exploration perspective, the deep valley sediments hold variable resource potential across the study area, owing to the geological controls on groundwater quantity and quality. The most promising area for future groundwater resource exploration is in the western zone, in the sub-Canning and sub-Catfish Creek sediments. At these locations, the groundwater quality is fresh (Ca/Mg-HCO3), and isotope tracer values indicate that recharge timing was some time prior to the 1950’s but following deglaciation. Water level elevation data for multi-level wells, placed within the geological context, suggest that these aquifers are confined beneath regionally extensive aquitards. The SCA in the central zone yields water of variable and sometimes poor quality, with elevated dissolved sulphate levels influenced by the underlying gypsum-bearing Salina Formation bedrock. Isotope geochemistry results show that groundwater carries a more modern recharge signature in the SCA of this region. This can be attributed to windows in the CCT aquitard which may have been created by meltwater erosion events associated with the formation of the Waterloo moraine and/or postglacial erosion along modern river valleys (Bajc et al. 2014). Further evidence of breaches in the Catfish Creek aquitard and their hydrogeological significance was identified by Stotler et al. (2011), who report measurable quantities of dissolved oxygen and tritium isotope values that match modern rainfall, in several wells screened in the deep overburden aquifers that directly overlie bedrock within the
Waterloo moraine area. Johnston et al. (1998) also identified elevated nitrate levels, an indicator of surface contamination, in deep wells completed at the bedrock interface within the central portion of the study area. The variable groundwater quality results observed in the SCA, caused by both anthropogenic and natural geological sources, render the deep sediments of the central zone an unreliable target for future groundwater resource exploration. Moving eastward, the relatively young, glaciofluvial sediments overlying bedrock and confined by thick, fine-grained glaciolacustrine deposits show variable groundwater resource potential with a general decrease in specific capacity towards the east as the bedrock valley deepens and the aquifers become more deeply buried.

Through the development of a geological framework, it was possible to identify deeply buried aquifers, instrument them and evaluate their hydrogeological character. The integration of the geological and hydrogeological interpretations provides valuable insight into the geological controls on groundwater quality and quantity and helps us to predict, with some confidence, the hydrogeological conditions that exist between the monitored sites. Without conducting long-term pumping tests, it is not possible to determine the lateral extent and continuity of any buried valley aquifer. Should municipal groundwater resource exploration be conducted in any of the deep valley aquifers, such long term testing would be required, as well as further investigation to delineate where recharge to these deep systems is occurring, and how their discharge might support ecosystem function of surface water features. Certainly, the data in this paper support the development of groundwater resource exploration targets.

Understanding groundwater mean residence time is an essential consideration for long term groundwater supply development. In his buried valley work in the Canadian prairies, van der
Kamp (1986) suggests that evaluating how “modern”, or connected groundwaters are to the active hydrologic cycle, is an essential step in considering these deep features for water supply development. Deep buried valley aquifers often contain poor quality, mineralized groundwater, like that observed in the eastern wells of this study (DV-01 and DV-02). From a simple water budget perspective, recharge capacity of the system must match or exceed the rate of withdrawal a dynamic that might not be feasible for groundwaters with long residence times that are largely disconnected from the active hydrologic cycle.

The results of this study have further advanced our understanding of the Dundas buried bedrock valley; its location, geometry, infilling sediments and related hydrogeological properties. A series of potential aquifer targets have been identified providing a framework for future groundwater studies. We look forward to the continued evolution of understanding of this interesting geologic feature as new data are acquired, mapping methods improve and groundwater resource exploration continues in the region.

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Figure 1. Bedrock topography, valleys and escarpments of southern Ontario; an evolution of ideas. 

a) Proposed preglacial drainage system of the Great Lakes basin (after Spencer 1890). b) Karrow (1973) conceptualization of bedrock escarpments and valleys in southwestern Ontario. c) A further refinement of bedrock topography (Eyles, Boyce and Mohajer 1993) showing a more complex series of bedrock valleys that resembles a modern drainage system. d) Bedrock topography with inferred locations of buried bedrock valleys and bedrock escarpments (derived from Gao et al. (2006)).
Figure 2. Bedrock geology of southwestern Ontario highlighting the location of the Dundas buried bedrock valley study area. Bedrock geology draped over bedrock topographic hillshade (after Armstrong and Carter 2010).
Figure 3. Quaternary geology of the region surrounding the Dundas buried bedrock valley highlighting the main physiographic features mentioned in the text (derived from Ontario Geological Survey 2010).
Figure 4. Time-distance diagram highlighting the main stratigraphic units identified in the Dundas valley study area.

164x116mm (200 x 200 DPI)
Figure 5. Location of ground gravity survey lines and cored boreholes drilled as part of this study overlain on shaded bedrock topography (derived from Gao et al. 2006).

228x153mm (300 x 300 DPI)
Figure 6. Residual gravity profiles and interpreted bedrock valley locations superimposed on shaded bedrock topography. Negative residual anomalies highlighted as solid blue areas.

229x153mm (300 x 300 DPI)
Figure 7. Surface expression of deeply buried aquifers interpreted from MOECC water well records superimposed on interpreted bedrock valley locations and shaded bedrock topography.

229x153mm (300 x 300 DPI)
Figure 8. Stratigraphic logs for boreholes located in the western and central zones of the Dundas valley study area. The approximate elevation of the brow of the bedrock valley is indicated to the left of each borehole log.

108x85mm (300 x 300 DPI)
Figure 9. Stratigraphic logs for boreholes located in the eastern zone of the Dundas valley study area. The approximate elevation of the brow of the bedrock valley is indicated to the left of each borehole log. The Lake Ontario water level is also shown with a horizontal black line for reference.

270x206mm (300 x 300 DPI)
Figure 10: A Piper trilinear plot comparing major ion trends for groundwater samples taken in the Dundas valley study area wells. Abbreviations following well IDs: MWD, deep monitoring well; MWI, intermediate monitoring well; MWS, shallow monitoring well and PW, pumping well.
Figure 11. Photographs showing examples of each of the sedimentary units described in this study. Number cards represent depth in meters below ground surface. a) Guelph Formation dolostone (DV-02). b) Salina Formation dolomitic mudstone with gypsum crystals and casts (DV-03). c) overconsolidated and deformed silts and sands, older drift (DV-06). d) Canning Till (DV-08). e) sandy gravel, Sub-Catfish Creek Aquifer (SCA) (DV-05). f) laminated silty sand, SCA (DV-08). g) cobble gravel, SCA (DV-08). h) overconsolidated Catfish Creek Till (DV-04). i) bedded silts and sands, Waterloo moraine (DV-04). j) laminated silts and clays, basal Waterloo moraine (DV-05).
Figure 12. Photographs showing examples of each of the sedimentary units described in this study. Numbers represent depth in meters below ground surface. a) rippled sands, Waterloo moraine (DV-06). b) Port Stanley Till (DV-03). c) gritty silty clay, Mornington diamict (DV-08). d) gravelly sand, Grand River outwash (DV-03). e) coarse sand, Grand River outwash (DV-03). f) diffusely bedded sand, Wentworth aquifer (DV-01). g) sandy, cobble gravel, Wentworth aquifer (DV-01). h) laminated silts and clays, Erie basin glaciolacustrine deposits (DV-01). i) rhythmically bedded silts and clays, Erie basin glaciolacustrine deposits (DV-01). j) laminated silts and clays, Halton glacial sediment package (DV-02).
Figure 13. Isotopic composition of the deeply-buried Dundas valley aquifers. The local meteoric water line for Simcoe, Ontario, developed from the publically available International Association of Atomic Energy data set (2001) data, is shown for context. Each data point is marked by the borehole ID as well as the acronym for the associated aquifer sediment package. These acronyms are SCA = sub-Catfish Creek till aquifer, OD = older drift or sub-Canning aquifer, PSD = Port Stanley aquifer and WD = Wentworth aquifer.
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Table 1. Summary grain size and carbonate content values (means and ranges) for the important till units identified within the Dundas valley study area. Mean values reported in Karrow (1987, 1993) provided for comparison.

Table 2. Summary of hydraulic conductivity estimates for the deep valley aquifers and aquitards. For the aquifers, $K_h$ indicates horizontal hydraulic conductivity and for the aquitards, $K_v$ indicates vertical hydraulic conductivity.