1. INTRODUCTION

In 2003, the Ontario Geological Survey (OGS) released a fully attributed, seamless surficial geology map of southern Ontario; the first of a series of thematic maps published in support of the Clean Water Act (2006). This provincially-mandated piece of legislation is designed to protect the safety of Ontario’s drinking water. A number of other important publications in the same series, including bedrock geology, physiography, drift thickness, bedrock topography and a karst potential map were subsequently released.

Following the release of these baseline geoscience datasets, the focus of the Groundwater Program turned to subsurface mapping of Quaternary and Paleozoic strata as well as the characterization of the waters contained within them. Three-dimensional (3D) geologic mapping projects have been and are currently being undertaken primarily in areas of projected population growth that are heavily reliant on groundwater for municipal, rural and agriculture use. These include areas identified in the Places To Grow Act (2005) within and around the Greater Golden Horseshoe of southern Ontario. Concurrently, Conservation Authorities have been charged with developing watershed-based Source Water Protection Plans in support of the Clean Water Act (2006) to identify and assess risks to the quality and quantity of drinking water sources, develop plans as to how these risks will be addressed, implement the plans through land use planning and regulatory requirements and finally, the monitoring and ongoing assessment of the effectiveness of measures carried out to protect sources of drinking water. A good understanding of the distribution and properties of subsurface geologic materials is required if one is to develop sound, science-based plans for implementation. The activities undertaken and products developed as part of the OGS’s 3D mapping program are designed primarily to meet this need for geoscience information. Additionally, robust exploration models are being developed as part of the 3D mapping programs to assist in the search for new municipal water supplies.

The 3D mapping and characterization of Quaternary-aged aquifers and aquitards has been ongoing for close to a decade with projects either completed or ongoing in the Waterloo (Bajc and Shirot 2007), Barrie-Oro (Burt and Dodge 2011), Brantford-Woodstock (Bajc and Dodge 2011) Orangeville-Fergus and South Simcoe areas (in progress) (Figure 1). The Brantford-Woodstock, Waterloo and Orangeville-Fergus study areas lie along an important interlobate zone along which significant stratified moraines were constructed during the final retreat of the Laurentide Ice Sheet from southern Ontario. These stratified moraines contain important aquifers capable of either meeting or contributing to the water needs of local municipalities and settlements. The Barrie-Oro project area is centred on the Oro moraine which forms both a regional aquifer recharge area and the headwaters for 4 major watersheds. Adjoining this area to the south is the South Simcoe study area, an area of thick drift underlain by the Laurentian buried bedrock valley; a bedrock depression extending from Georgian Bay in the north to Lake Ontario. All of these areas are poised to receive accelerated population growth as they have been identified in the Places To Grow Act (2005) and lie just outside of the Green Belt; a swath of land lying within the Greater Golden Horseshoe that is being protected from additional development.

The main objectives of these projects are to develop interactive 3D models of Quaternary geology that can: 1) aid in studies involving groundwater extraction, protection and remediation; 2) assist with the development of policies surrounding land use and nutrient management; and 3) help to better understand the interaction between ground and surface waters. More specifically, a better understanding of the geometry and inherent properties of the Quaternary sediments that overlie the bedrock surface within these regions will assist with the development of source water protection plans and with the development of a geoscience-based management plan for the groundwater resource.
2. EVOLUTION OF THE PROGRAM

2.1 The Waterloo Region Pilot Project

In 2002, a pilot project of 3D mapping of Quaternary deposits was initiated within the Regional Municipality of Waterloo (Bajc and Shirota 2007). This area was chosen for the initial study as the region is almost exclusively reliant on overburden and bedrock aquifers for its potable water supply and represents one of the largest municipal users of groundwater in Canada. Intense pressures are being placed on the groundwater supply as urban sprawl and population growth threaten important recharge areas and tax an already stressed groundwater system. Having a better understanding of the distribution and properties of both near surface and deeply-buried aquifers will assist with the management and protection of the groundwater resource.

![Figure 1. Location of OGS-led 3D mapping of Quaternary geology projects in southern Ontario. From north to south: Barrie-Oro, South Simcoe, Orangeville-Fergus, Waterloo Region and Brantford-Woodstock. Base map is from the provincial digital elevation model.](image)

The Waterloo project was undertaken in 4 important stages which included: 1) data compilation; 2) acquisition of new geophysical and geological information to infill data gaps and assist with the development of a conceptual geological model for the study area; 3) data interpretation and the construction of a fully attributed 3D block model; and 4) preparation of a Groundwater Resources Study that describes the geologic setting of the region, outlines the protocols developed for the construction of the 3D block model and contains a description of the distribution and properties of the geologic units modelled. Discussions of important recharge areas and aquifer vulnerability were also included within the report. Other deliverables include structural contour and isopach maps of all modelled units, west-east and south-north cross-sections at 2.5 kilometre intervals and a depth to aquifer map that can be used to assess aquifer vulnerability and recharge areas.

Digital data also accompany the Groundwater Resources Study. The data consist of 1) portable document format (.pdf) versions of the contained plates; 2) comma-delimited text (.csv) files of both continuous and discontinuous surfaces on a 100 m grid; 3) 100 m ESRI® ArcInfo® structural contour grids of discontinuous surfaces; 4) a stripped-down version of the subsurface database (.mdb) containing borehole location and stratigraphic information, picks data and static water level and...
screen depth information; 5) new borehole information that includes graphic and written logs, grain size and carbonate data and photographs of the core; 6) a cross-section viewer (.exe) capable of drawing sections along user-defined lines drawn on a Microsoft® Windows® Virtual Earth® base map; and 7) a hypertext mark-up language (.kml) file that portrays transparent overlays of the structural contour and isopach maps as well as borehole locations and lithologic logs in a web-based (Google Earth™ mapping service) environment. This functionality allows for enhanced user interaction with the spatial data.

2.2 Modifications to the Program

Since completion of the Waterloo pilot project, a number of changes have occurred in both the field programs and to the Aquifer Mapping System developed to work with Datamine Studio software for the creation of the 3D block models. In the Waterloo area, a robust geophysical program consisting of ground penetrating radar, seismic reflection using both the GSC-owned mini-vibe and the more conventional inhole shotgun shell energy source as well as downhole geophysical profiling were all conducted to evaluate their usefulness for regional 3D modelling. Varying ground conditions within the Waterloo Moraine area resulted in marginal data quality, especially in the case of seismic imaging beneath dense, overconsolidated Late Wisconsin tills as well as in areas with depressed water tables. Conducting lengthy seismic lines for regional mapping was cost prohibitive and in most cases, was a risky proposition. In many cases, it was difficult to image the bedrock surface beneath the overconsolidated Catfish Creek Till. In the case of ground penetrating radar, depth of penetration resulted in visualization of the internal character of the upper hydrostratigraphic unit at most 10% of the entire stratigraphic sequence. Ground penetrating radar did in some cases assist with determining the origin of landforms and with reconstructing paleoflow directions. Borehole geophysics of cored holes allowed for the development of proxies that could be used to interpret records from non-cored holes. In this regard, the downhole geophysical program had excellent value as it assisted with the interpretation of a database of subsurface geophysical profiles assembled from a series of non-cored holes within the region.

2.2.1 Field Program

As a result of these observations, it was felt that resources could be used more effectively by redirecting them to the collection of additional continuously cored boreholes and more regionally-based geophysical programs. Cored boreholes are invaluable when it comes to developing conceptual geologic models and assisting with the interpretation of water well records and other lower quality sources of subsurface information. In the case of the Brantford-Woodstock study, the OGS collected continuous cores to bedrock at approximately 50 sites within an area of about 2700 square kilometers (i.e. approximately 1 hole per 54 square kilometers). In the case of the Orangeville-Fergus area, the ratio is approximately 1 hole per 37 square kilometers. These additional “golden spikes” served to greatly improve the quality of the interpretation of the subsurface data.

With regard to regional geophysical programs, the OGS has recently been undertaking and evaluating land-based gravity surveys to assist with the definition of the location and geometry of buried bedrock valleys in various study areas. There has been growing interest in evaluating deeply buried aquifers confined to bedrock valleys for their potential to host significant sources of groundwater for municipal use. Gravity surveys over the Dundas buried valley, at the west end of Lake Ontario, over the Rockwood valley within the Orangeville-Fergus study area and over the Laurentian valley within the South Simcoe survey area have been completed with reasonable success. The main goals of these surveys were to better define the position of bedrock valley thalwegs (Figure 2) and evaluate their sediment infill to determine whether the bedrock valleys host significant aquifers at depth. In the case of the Dundas and Rockwood valleys, follow-up drilling clearly showed that the bedrock valleys were host to significant aquifers that were potentially capable of supporting municipal water supplies. Follow-up hydrogeologic testing of deeply buried aquifers along the trend of the Dundas valley have yielded important information regarding aquifer transmissivity and specific capacity as well as information regarding water quality and age. Drilling of significant thalwegs along the Laurentian valley are currently ongoing and seem to suggest that there may be a spatial association between thick accumulations of older stratigraphic sequences, some of which contain highly transmissive sediments, and buried bedrock channels.

2.2.2 Modelling Protocols

Protocols for 3D modelling have evolved as well, following the completion of the Waterloo pilot project. The main advancements are with regard to weighting of borehole information of varying quality and modelling of deeply incised valley
fills. In the Waterloo study, all borehole data was weighted equally resulting in situations where both high and medium quality borehole records were not integrated into the model since there were no supporting borehole records within user-defined search radii of those holes. The new modelling scripts take data quality into account resulting in all cored borehole records as well as manually digitized picks being used to force specific geometry of units within the block model. A larger percentage of medium quality borehole records are also incorporated into the model using this new protocol as well. Maps highlighting the distribution of high, medium and low quality picks used for the creation of each modelled layer assist in visually depicting model confidence.

The new scripts also address areas where deeply incised valleys have been cut into older sediment sequences and back filled with late-glacial deposits. The previous modelling scripts resulted in steeply-dipping wedges extending from the uplands into the valleys to force pinchout of units. Graphically, these pinchouts do not appear geologically credible. Hydrogeologically, these wedges force impermeable barriers between aquifers that in reality are juxtaposed along valley walls. The new scripts allow the user to model the uplands and valley fill sequences separately then recombine them into a single model during the final model creation step resulting in the removal of these wedges.

3. WHERE DO WE GO FROM HERE?

The OGS has moved from program development to production mode as it strives to model priority areas of the province. An improved conceptualization of glacial history and depositional environments associated with important aquifer complexes has resulted from recently completed and ongoing studies. This knowledge has translated into improved predictive capability and associated efficiencies. To date, the OGS has mapped approximately 5400 square kilometers with an additional 2850 square kilometers in progress. Two full-time Quaternary geologists are dedicated to this program with support staff available to assist with geophysical surveying, database management and GIS mapping functions. With limited staffing and funds, completion of detailed 3D mapping of all of southern Ontario will likely take several decades. There has been an attempt to produce a standardized product that will allow for merging of models. With this in mind, it is important to create models with similar conceptualizations of geology and easily correlatable units. Detailed sampling of cored boreholes for grain size analysis will assist with the assigning of hydraulic properties to the modelled units and hence more reliable groundwater flow models. The OGS has attempted to partner with municipalities and conservation authorities to convert as many cored boreholes as possible into long term monitoring wells. Static water levels, water chemistry and isotope analysis to determine water age will assist with better understanding groundwater flow paths and identifying windows in aquitards. Short term pump tests to better characterize transmissivity of aquifers and their associated recovery rates will undoubtedly assist with the modelling of aquifer extent in the subsurface. The OGS continues to pursue alternative subsurface imaging and characterization technologies to assist with 3D mapping. Refinements to the modelling protocols developed to work with Datamine Studio software are ongoing as well. New visualization products carrying a wider appeal to a diverse client base continue to be developed.
Figure 2. Residual Bouguer gravity profiles superimposed on regional bedrock topographic surfaces derived from water-well records for the Rockwood buried bedrock valley (left) (Burt and Rainsford, 2010) and the Laurentian buried channel (right) (Bajc and Rainsford, 2010). Anomalous negative residual responses are shaded in blue (left) and black (right).

4. REFERENCES


