Natural Resources Canada / Ressources naturelles Canada

EARTH SCIENCES SECTOR
GENERAL INFORMATION PRODUCT 40

The Aurora-Maple Channel Aquifer System in the Oak Ridges Moraine Area, southern Ontario

Sharpe, D R; Russell, H A J

2000

Originally released as: The Aurora-Maple Channel Aquifer System in the Oak Ridges Moraine Area, southern Ontario, Sharpe, D R; Russell, H A J; 2000; 10 pages

Canada

The Aurora-Maple Channel Aquifer System in the Oak Ridges Moraine Area, southern Ontario

D.R., Sharpe, and Russell, H.A.J.,
Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8.

The original format of this document has been modified to facilitate electronic distribution.
Printed from the Oak Ridges Moraine Web site,
http://sts.gsc.nrcan.gc.ca/page1/envir/orm/orm.htm.
Contact Information: Dr. David Sharpe, Terrain Sciences Division, Geological Survey of Canada, 601 Booth St. Ottawa, Ontario, K1A 0E8, ph: (613) 992-3059,
fax: (613) 992-0190, e-mail: dsharpe@nrcan.gc.ca

INTRODUCTION

Background

Groundwater is an important source of domestic, industrial and municipal water supply across Canada and most of Ontario. In southern Ontario and the Greater Toronto Area (GTA), municipal groundwater sources have provided a clean, economical water supply enabling large population growth in many communities over the last 50 years. The Oak Ridges Moraine aquifer complex, in particular, has been an important groundwater resource in the GTA (Turner, 1977; Howard et al., 1996). Groundwater has proven to be a reliable resource, but its capacity is not well known, user conflicts are on the rise and new supplies have not been identified (Sharpe et al., 1996; 2000; Gartner and Lee, 1996). In short, the sustainability of the groundwater resource is uncertain due to inadequate mapping, monitoring and testing.

As a result of these concerns, aquifer management plans are increasingly being developed by area municipalities to address a range of groundwater resource and supply issues (e.g. Waterloo region; Terraqua, 1995; Robinson, 1999; Halton region; Holysh, 1995). An important component of aquifer management planning is the regional hydrostratigraphic framework, ie. a 3-dimensional depiction of aquifers and aquitards. A regional hydrostratigraphic framework developed for the ORM area (Sharpe et al., 1996) portrays a channel aquifer network that dissects a regional aquitard, potentially increasing inter-aquifer connection (e.g. Sharpe et al., 1998; Desbarats et al., 1998). Knowledge of aquifer connectivity is a key requirement in defining and protecting aquifer capture zones that contribute recharge to water-supply wells (e.g. Franke et al., 1998; Fogg et al., 1998). Recent hydraulic tests indicate inter-aquifer connection within the Aurora area (MOE, 2000; Gartner-Lee, 1998) and these obsevations are linked to new hydrostatigraphic data presented in this report.

Geological and hydrogeological setting from previous work

Regional geological mapping and digital elevation models reveal an extensive network of surface valleys (channels) north of ORM (e.g. Sharpe et al., 1997; Barnett et al., 1998; Kenny et al., 1997). The boundaries and uppermost fill of this surface channel network can be seen in the Aurora and Holland Marsh areas (Fig. 1). Recent stratigraphic data reveal an extensive buried channel aquifer network (Barnett et al., 1998; Pugin et al., 1999). For example, studies in this area (Fig. 1) link the Holland Marsh valley to a buried channel near Nobleton based on seismic profiles and continuously-cored boreholes (Pugin et al., 1999; Russell and Pullan, 1998; Sharpe et al., 1999b). Such channels can be 1-5 km across, 10's of km long and 50-100 m deep (Barnett et al., 1998). They are filled with gravel, sand and silt (Russell et al., 1998a) and these channel sediments form an essentially continuous sequence into the overlying Oak Ridges Moraine sediments (Gilbert, 1997; Russell et al., 1998a). Hence, channels form an important element in the hydrostratigraphy of the study area.

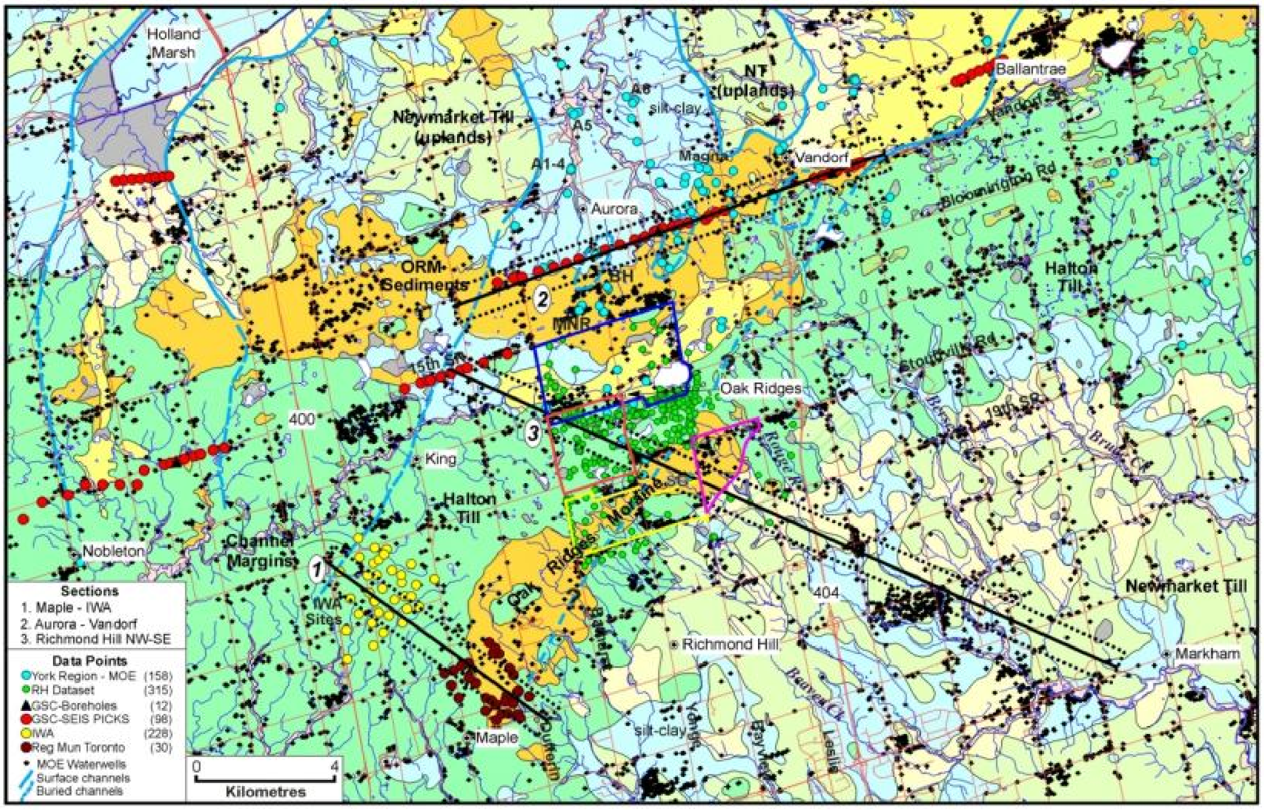

Figure 1: Geological map of Maple-Aurora area showing surface channels, projected buried channels, inter-channel uplands, location of major data sources in this part of the ORM, and, location of sections including the proposed Maple-Aurora channel system (Section 1, Fig. 3). Geology is indicated on the figure.

Six major strata in the ORM stratigraphic model (Fig. 2) provide a framework for investigating aquifer extent, geometry and connectivity. For example, Lower sediments are widespread throughout the GTA (Karrow, 1967; Eyles et al., 1985) and form so-called lower aquifers that provide significant municipal water supply (Sibul, 1977; Turner, 1977). Lower sediments consist of sandy Thorncliffe and Scarborough formation aquifers and fine-grained aquitard sediments. Each of these elements may be up to 50 m thick. Sandy (e.g. Scarborough Formation) aquifers can be recognized by their organic content (e.g. Aravena and Wassenaar, 1993). Overlying Newmarket Till, a dense, 30-40 m thick, sandy diamicton generally found above ~200 m asl, forms a regional marker bed based on high seismic velocities (Fig. 2; Hunter et al., 1998). This aquitard has bulk hydraulic conductivities of $\sim 10^{-9}$-10^{-10} m/sec (Fenco-McLarlen, 1994; Gerber and Howard, 2000). An irregular regional erosion surface, or unconformity (Fig. 2; Barnett et al., 1998; Pugin et al., 1999), consisting of drumlin uplands and channels, has in places eroded through Newmarket Till into Lower Sediment aquifers (Fig. 2). Sandy sediments found within buried channels (Russell et al., 1998a; Barnett et al., 1998) have hydraulic conductivities of $\sim 10^{-2}$-10^{-6} m/sec (Fenco-McLarlen, 1994), hence they may provide enhanced vertical connection between upper (ORM) aquifers and lower aquifers. In uplands, Newmarket Till may be leaky (e.g. Gerber and Howard, 1996),, allowing recharge to lower sediments at a rate of ~30-40 mm/year (e.g. Gerber and Howard, 1998), apparently related to small-scale structural heterogeneity (fractures). However, on a regional scale, heterogeneity and leakance from the ORM to lower aquifers is controlled by a network of channels cut into Newmarket Till (Desbarats et al., 1998; Sharpe et al., 1998; Fig. 2). Data listed above, show that channel sediments can have 4 orders of magnitude higher hydraulic conductivity than the regional aquitard, Newmarket Till.

There are indications of a channel system extending southward from Aurora to Maple (Fig. 1). It is defined by high-quality sub-surface data (seismic and continuously-cored borehole data) at Maple and Aurora, but similar data are lacking along a proposed channel reach in the Oak Ridges area (Fig. 1). In addition, high-quality subsurface data are required to characterize the geometry of buried channels and their sedimentary infills along channel reaches (Russell et al., 2000). Where such subsurface data are not available we make use of regional knowledge and the ORM stratigraphic data model (Logan et al., 2000).

Accordingly, the objective of this report is to provide detailed hydrostratigraphic understanding along a proposed Aurora-Maple channel aquifer system in the Oak Ridges Moraine area and to describe its hydrogeological significance.

Methods and Approach

Buried extensions of mapped surface channels across the ORM region have been detected using seismic profiling and coring. New subsurface data are used here to map the projected buried channels along Maple-Aurora channel system (e.g. Pugin et al., 1999) as will be demonstrated with two lithologic cross-sections. The extensive MOE water well records are helpful but they do not have the resolution or depth coverage to define buried channels (e.g. Russell et al., 1998) without additional knowledge. Thus, we have developed a regional data-driven, 3-D stratigraphic model (Logan et al., 2000) based on the ORM conceptual geological model (Fig. 2). This stratigraphic model integrates geological mapping, geotechnical and hydrogeological data as well as MOE waterwell data in a relational database and GIS (Russell et al., 1996; 1998b). A 3-D grid of coded stratigraphic points defines the regional data model that can be used to map particular stratigraphic architectures, such as the proposed Maple-Aurora channel system.

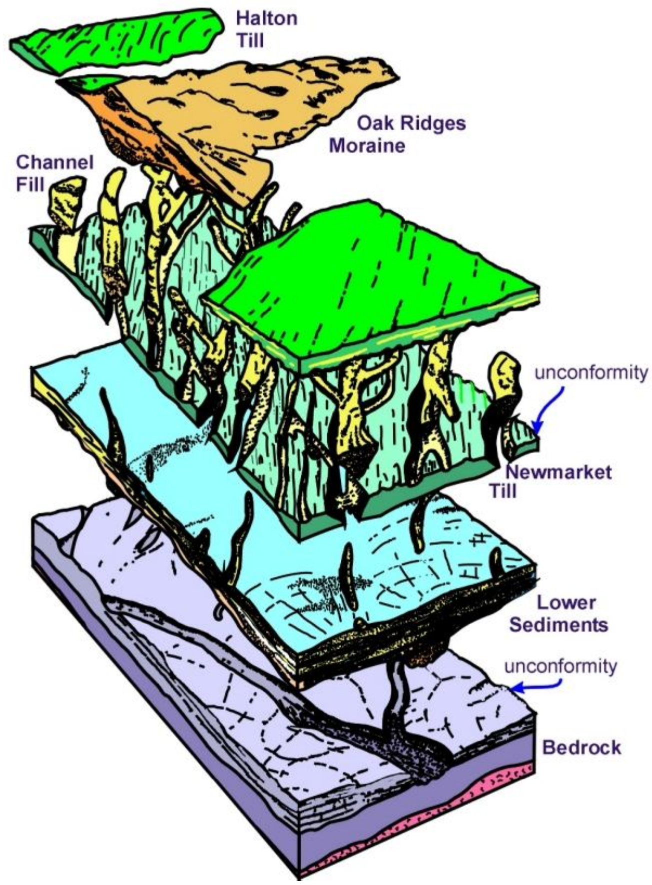

Figure 2: Geological model and hydrogeological framework for the ORM area.

From the ORM stratigraphic data model (Logan et al., 2000), we have drawn three stratigraphic cross-sections across the proposed Maple-Aurora channel system for comparison to lithologic sections. Each section is constrained by a different level of detail in terms of seismic, cored-borehole and water well data, which affects the resolution of channel geometry and channel sediments. Hence, the modeled sections represent the best available geological synthesis (Logan et al., 2000).

THE MAPLE-AURORA CHANNEL SYSTEM

1. Maple-IWA cross-section

The Maple-IWA lithologic section is oriented NW-SE across the southwesterly trend of the proposed Aurora-Maple channel and across the Maple spur of the Oak Ridges Moraine (Fig. 1). About 50 continuously-cored boreholes and seismic data, along a ~7 km long section, define the depth and lithology of a buried channel sequence (Fig. 3a). The seismic data, covering ~2 km of the IWA area (Fig. 3a), show an absence of high-velocity reflectors typical of Newmarket Till (e.g. Pugin et al., 1999). Hence, a significant gap occurs in the regional Newmarket Till aquitard where it has been eroded between 0-6 km (Fig. 3a). This defines a channel > 5 km wide and ~ 100 m deep that eroded into Lower sediments (Fig. 3a, 0.5-4 km). Two small channel segments occur beneath the Keele Valley Landfill and near Maple, where Newmarket Till is breached and sand and gravel is found at the base of these channels (Fig. 3a). Above an unconformity, channel and ORM sediments form a 150 m thick package overlain by 5-15 m thick Halton Till. Sediments within the Maple-IWA channel are predominantly sand with intervals of silt and minor clay, forming a channel aquifer complex (Russell et al., 1998a; Barnett et al., 1998). The lithology of the complete channel fill and overlying ORM sediments is intercepted by borehole V4D-158 (Fig. 3a). It displays two ~ 50 m sand packages separated by ~15-20 m of sand-silt-clay rhythmites. The rhythmite interval can be mapped across parts of the channel using continuous drillcores (Fenco-MacLaren, 1994). Bed by bed sediment logging of three cores within this interval indicates that the ~ 1-2 cm thick clay laminae are not correlatable and are probably discontinuous at distances greater than several hundred metres. Also, gravel intervals at the IWA site (Fenco-MacLaren, 1994), and at shallow levels beneath the Keele Valley site, suggest that coarser sediments may occur up-flow to the northeast. The abundance and distribution of high-quality data produces a good match between a well-constrained lithologic section (Fig. 3a) and the modeled stratigraphic section (Fig. 3b).

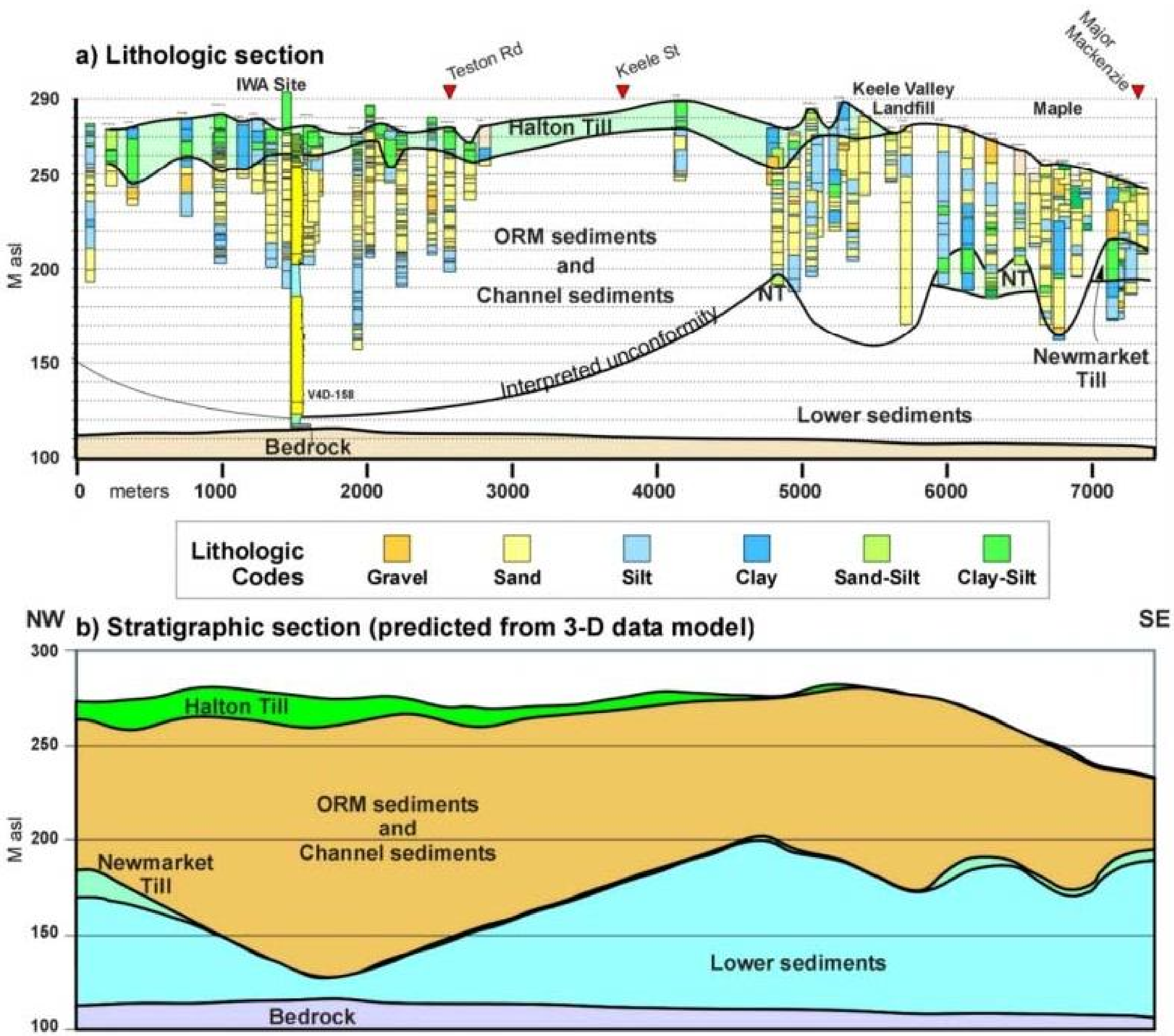

Figure 3: Maple-IWA cross-section.

a) Lithologic section based on ~50 continuously-cored boreholes and reflection seismic data. Borehole V4D-158 shows the lithology of the channel fill and overlying ORM sediments. Newmarket Till has been completely eroded except for small remnants in the Maple-Keele Valley area;

b) Stratigraphic section drawn from the ORM regional 3-D data model (Logan et al., 2000).

2. Aurora -Vandorf channel cross-section

The Aurora -Vandorf channel section was compiled from water well records and seismic profile data controlled by two deep (>125 m), continuously-cored, GSC boreholes (Fig. 1). The lithologic section reveals a ~ 10 km wide channel system consisting of three deep (~100 m) channels separated by uplands (Fig. 4a). Channel segments are 0.5-2 km wide, whereas the Newmarket Till uplands are ~2-3 km wide and 20-40 m thick. Smaller uplands (islands), or possible slump-blocks (Pugin et al., 1999), occur within channel segments where erosion was incomplete (Fig. 4a). Coarse sediments, including significant gravel aquifer intervals, are an important part of the channel sediments. Channel sediments generally fine upwards from gravel, sand, silt to minor clay. Coarse sediments occur in the Lower sediment aquifers in the area of the Magna channel (Fig. 4a), where ~ 80 m of sand and gravel occur at the base of borehole GSC-Aur-1997. In all three Aurora channels, sand and gravel occurs continuously over the interval ~150 to ~250 m asl, except for thin, clayey intervals at the base of Henderson channel (Fig. 4a). The cross-sections indicate a high potential for inter-aquifer connection between upper (ORM) and lower (channel and Lower Sediment) aquifers, particularly beneath the Magna and Vandorf east channels (Fig. 4). The channel sediments and Lower sediments are part of the Aurora municipal aquifer system (Gartner-Lee, 1998).

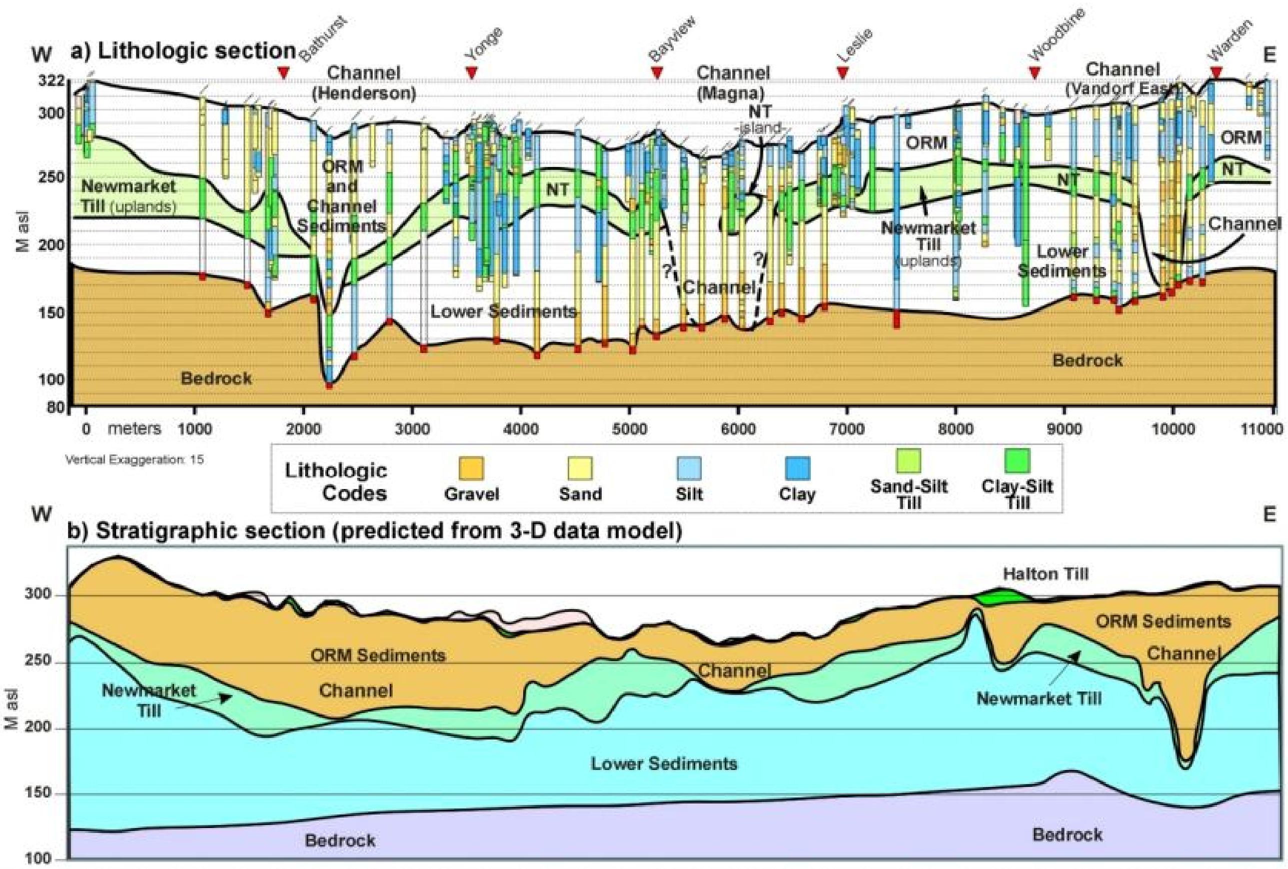

Figure 4: Aurora-Vandorf cross-section.

a) Lithologic section based on seismic data (logs extending into bedrock) and two GSC-cored boreholes. Channel segments occur at: 1) Henderson Road, 2) Magna, and 3) Vandorf east;

b) Stratigraphic section drawn from ORM 3-D data model (Logan et al., 2000).

3. Richmond Hill cross-section

The Richmond Hill cross-section runs northwest from the Newmarket Till plain south of the ORM, across the moraine to 15th Sideroad where seismic data define the western margin of the Aurora-Maple channel complex. Lithologic data from waterwell records in the area (Fig. 5a) are not adequate, by themselves, to evaluate the presence or absence of a channel connection between Aurora and Maple. The Richmond Hill stratigraphic section (Fig. 5b) predicts a ~ 5 km wide channel cut into the Newmarket Till aquitard and Lower sediment (0-5 km, Fig. 5). Channel and ORM sediments, ~ 150 m thick, fill and overtop the Aurora-Maple channel. Lack of reliable, continuously-cored, deep borehole and/or seismic data prevents definition of channel sediment lithologies and the extent of inter-channel "islands". Nevertheless, some "islands" can be inferred from individual well records (e.g. at MNR "Hospital wells", Summit Golf Course (SG) and Beacon Hall (BH), (Fig. 1) similar to islands mapped in the Aurora area.

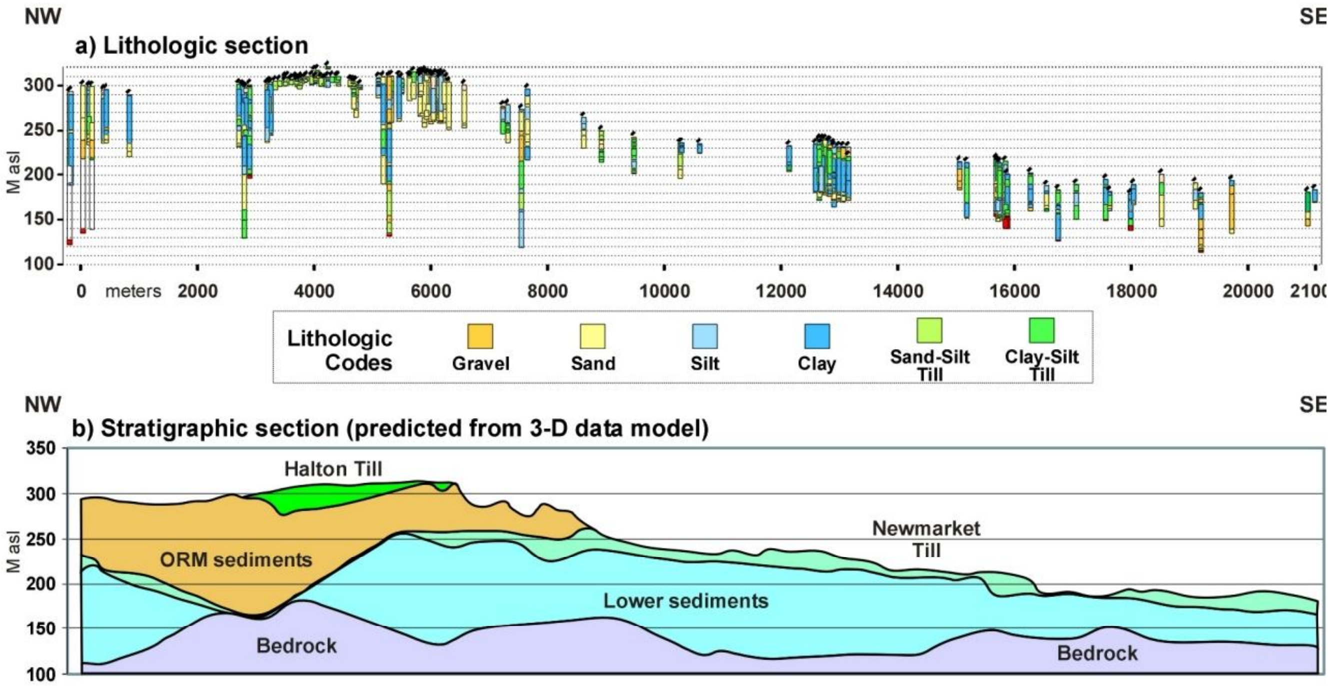

Figure 5: Richmond Hill cross-section.
a) Lithologic plot has too few deep records to complete an interpreted section.
b) Stratigraphic section is based on the 3-D stratigraphic model.

Regional channel information

Channels in the ORM area are 1-5 km wide, 10's of km long and 50-100 m deep (Barnett et al., 1998). The Aurora channel system is ~ 10 km across and consists of three 1-2 km wide channels with intervening islands of Newmarket Till. The Maple channel is 5-6 km wide and comprises one deep channel and two minor channels. It is likely that the channel continues for ~10 km or more. Based on examination of sediments within channels in the ORM region, both coarse-grained and fine-grained sediments occur (Sharpe et al., 1999; Russell et al., 2000). Channel sediments include: a) cross-bedded gravel, b) cross-bedded sand, c) massive sand, and, d) laminated sand, silt and clay. Sand sequences ~50 m and extending for many kilometres have been inferred (Pugin et al., 1999; Sharpe et al., 1999b). The Aurora channel segments contain gravel as part of each sedimentary infill, while downflow, the Maple channel reach is mainly a sandy infill. The Aurora-Maple channel system changes from a wide reach with several channels and coarse sediments up-flow (Aurora; Fig. 4a), to a single, deep channel with finer-grained sediments down-flow (Maple, Fig. 3a).

Sand and gravel channel sediments provide good vertical connectivity and inter-aquifer connection between upper, ORM aquifers, and channel aquifers (called the lower aquifer by some). Where the regional aquitard

(Newmarket Till) is missing, connection can occur between upper ORM / channel aquifers and aquifers within the Lower Sediments (Fig. 2). For example, sand and gravel of the Magna channel sequence (Fig. 4a), is directly connected to sand and gravel in the in Lower sediments.

Relationship to the Yonge Street Aquifer system

The Aurora-Vandorf cross-section allows assessment of the extent of the Yonge Street aquifer in the Aurora area. Coarse sediments, up to 80 m thick, extend for ~3 km between Bayview and Leslie (Fig. 4a) and they provide potential stratigraphic connection between upper (ORM and channel) and lower (Lower sediments) aquifers. The channel and lower aquifer system comprise part of the deep municipal Yonge Street aquifer in the Aurora-Newmarket corridor at elevations of ~140-230 m asl. These sediments extend northwest from the Aurora cross-section (Magna channel) for ~3 km to Aurora production wells (A5, A6, Fig. 1; Gartner-Lee, 1998). A similar sediment sequence extends for ~ 4 km from A5 and A 1-4 Aurora production wells southwest to the Henderson Road channel (Fig. 4).

Recent hydraulic tests in this area indicate horizontal connection along the lower aquifer system and vertical connection between upper ORM and lower (channel) aquifers (MOE 2000; Gartner-Lee, 1998). Aquifer pump tests show horizon connection within channel and Lower sediment aquifers between Aurora production wells and wells on the Magna property (Gartner-Lee 1998), located immediately north of the Aurora cross-section (Fig. 1). Pump test results and related chemical data at the Magna property (Gartner-Lee, 1998) indicate vertical connection between upper (ORM) aquifers and lower aquifers (Yonge Street aquifer). This connection is achieved in the presence of clayey aquitard layers in the Magna channel, north of section 3 (Fig. 4; Gartner-Lee, 1998), similar to the connection implied in the Maple channel where clay beds are shown to be discontinuous. Lateral and vertical connection is achieved despite the occurrence of ~40 m of Newmarket Till in a channel wall (Fig. 4a, west of Leslie), and thus evidence of channel erosion and deposition needs to be carefully assessed in areas of Newmarket Till.

Significance of the channels

Knowledge of aquifer connectivity is a key requirement of defining and protecting aquifer capture zones that contribute recharge to water-supply wells (Franke et al., 1999). Channels that are part of the Oak Ridges aquifer complex have eroded regional aquitards and they contain coarse-grained sediments along extensive channel reaches (e.g. Barnett et al., 1998; Russell and Pullan, 1998; Pugin et al., 1999). Therefore, the ORM channels likely provide significant inter-aquifer connectivity (Sharpe et al., 1996; Sharpe et al., 1998) due to the much greater hydraulic conductivities in channels compared to Newmarket Till. On the other hand, recent hydrogeological models of the ORM area (e.g. Howard et al., 1997; Gerber and Howard, 2000) have not recognized the presence or significance of these channels, so their relationship to groundwater flow patterns within the ORM area needs further definition. Accordingly, recent work indicates that leakance (thickness x hydraulic conductivity) through channel systems is the most significant mechanism that contributes flow between upper and lower aquifers (Desbarats et al., 2000). The Maple-Aurora channel aquifer system, which includes part of the deep municipal Yonge Street aquifer (Gartner-Lee, 1998), supplies groundwater to ~125,000 citizens (MacViro, 1998) in the Aurora-Newmarket corridor. Recent hydraulic tests indicate connection between upper (ORM) and lower (channel) aquifers in the area around Aurora (MOE, 2000; Gartner-Lee, 1998), thus, supporting the hydrostatigraphic data presented here. Considering the high potential for aquifer connectivity, downward groundwater fluxes from near-surface channel sediments are expected to provide recharge to domestic and regional municipal wells.

SUMMARY

Vertical hydraulic connection between ORM and channel sediments, and Lower sediment is likely in the Aurora and Maple areas. Further, horizontal connection along the Aurora-Maple channel system is likely due to the continuity of coarse channel sediments. It is possible to achieve aquifer connectivity in sandy channel sediments between islands of Newmarket Till and beds of low-permeability clay in the Aurora-Vandorf channel system.

This is comparable to aquifer connectivity identified in fluvial sediments containing both sandy and clayey sediments, afforded by sand-body connectivity (Fogg, 1986). Hydrostratigraphic units in the Maple-IWA portion (Fenco-MacLaren, 1994) of the Maple-Aurora channel system have a large proportion of high-permeability sediment and an absence of continuous Newmarket Till aquitard (Fig. 3). Channel sediments provide up to 4 orders of magnitude increase in vertical hydraulic conductivity compared to the regional aquitard, Newmarket Till. Hence, the potential is high for horizontal and vertical connection in this portion of the channel system. The Richmond Hill cross-section is not as well constrained as the two other sections but the regional 3-D stratigraphic model implies similar potential for significant inter-aquifer connection and connection to the Yonge Street aquifer based on the presented hydrostratigraphic cross-section (Fig. 5).

In conclusion, the extent, heterogeneity and inter-connection of shallow and deep hydrogeological units, within channels, are difficult to decipher without geophysical surveys, continuous drill cores and pump test data. In the absence of these data, modelled stratigraphic sections provide important information for assessing regional hydrostratigraphic setting and evaluating whether detailed site investigation is warranted or not.

References

Aravena, R., and Wassenaar, L.I. 1993. Dissolved organic carbon and methane in a regional confined aquifer, southern Ontario, Canada: carbon isotope evidence for associated subsurface sources. Applied Geochemistry, 8: 483-493.

Barnett, P.J., Sharpe, D.R., Russell, H.A.J., Brennand, T.A., Gorrell, G., Kenny, F.M., and Pugin, A. 1998. On the origin of the Oak Ridges Moraine, Canadian Journal of Earth Sciences, 35 (10): 1152-1167.

Desbarats A, Hinton M, Logan C, Russell, H.A.J., and Sharpe, D.R. 1998. Geostatistical modeling of leakance in the Newmarket Till aquitard, Oak Ridges Moraine, Ontario. Abstract with program, Geological Society of America, annual meeting, Toronto, Oct. 1998.

Desbarats, A.J. Hinton, M.J. Logan C.E. and D.R. Sharpe, 2000. Geostatistical Mapping of Leakance in a Regional Aquitard, Oak Ridges Moraine Area, Ontario. Vignette published on the GSC ORM website: http://sts.gsc.nrcan.gc.ca/orm/index.asp

Eyles, N., Clark, B.M., Kaye, B.G. Howard, K.W.F., and C.H. Eyles. 1985. The application of basin analysis techniques to glaciated terrains: an example from the Lake Ontario basin, Canada. Geoscience Canada, 12: 22-32.

Fenco-MacLaren. 1994. IWA landfill site search, Metro/York region: Step 6 hydrogeological report sites V3B, V4A, V4D. Interim Waste Authority Report, *Prepared by* M. Gomer, Fenco MacLaren Inc., January 1994.

Franke, O.L. Reilly, T.E. Pollock D.W. and J.W. LaBaugh, 1998. Estimating areas contributing recharge to wells; Lessons from previous studies, by U.S. Geological Survey, USGS Circular 1174.

Gerber, R.E., Howard K.W.F., 1996. Evidence for recent groundwater flow through Late Wisconsinan till near Toronto, Ontario. Canadian Geotechnical Journal 33: 538-555.

Gerber, R.E., and K.W.F. Howard, 1998. Groundwater Balance for the Duffins Creek Drainage Basin: 3-D Flow Model Approach. In: Proceedings of Groundwater in a watershed context; Canadian Water Resources Association, Burlington, Ontario, December 2-4, CD-ROM, p.187-194.

Gerber, R.E. and Howard, K., 2000. Recharge through a regional till aquitard: Three-dimensional flow model water balance approach; Ground Water: 38(3): 410-422.

Gartner-Lee Ltd., 1996. Long-Term Water Supply for the Regional Municipality of York, Ground Water Resources. Prepared for Regional Municipality of York.

Gartner Lee Limited, 1999. Water Supply Study of Magna Golf Course Aurora, Ontario; Prepared for: MI Developments Inc.

Gilbert, R., 1997. Glaciolacustrine environment of part of the Oak Ridges Moraine, southern Ontario. Geographie physique et Quaternaire, 51: 55-66.

Holysh, S., 1995. Halton Aquifer Management Plan Phase 1 Report Background Hydrogeology, Regional Municipality of Halton.

Howard K.W.F., Eyles N., Smart P.J., Boyce J.I., Gerber R.E., Salvatori S.L., Doughty M., 1996. The Oak Ridges Moraine of Southern Ontario: A Groundwater Resource at Risk. Geoscience Canada 22 (3): 101-192.

Hunter J.A., Pullan, S.E., Burns, R.A., Good, R.L., Harris, J.B., Pugin, A., Skvortsov A., Goriainov, N.N., 1998. Downhole seismic logging for high resolution reflection surveying in unconsolidated overburden. Geophysics 63(4): 1371-1384.

Kenny, F., 1997. A chromostereo enhanced Digital Elevation Model of the Oak Ridges Moraine Area, southern Ontario; Geological Survey of Canada and Ontario Ministry of Natural Resources, Geological Survey of Canada Open File 3423, scale 1:200 000.

MacViro Consultants Ltd., 1998. Introduction of Surface Water to Aurora/Newmarket. Transportation and Works Department, York Region, 3780.

MOE, 2000. Ministry of the Environment Groundwater stakeholders meeting, Feb. 23, 2000.

Fogg, G.E., Noyes, C.D., and Carle, S.F., 1998. Geologically-based model of heterogeneous hydraulic conductivity in an alluvial setting, Hydrogeology Journal 6(1): 131-143.

IJC, 2000. Protection of the Waters of the Great Lakes. Final Report to the Governments of Canada and the United States. International Joint Commission, February 22, 2000.

Logan, C., Russell, H.A.J., and Sharpe, D.R., 2000. Regional 3D geological modeling of the Oak Ridges Moraine area, southern Ontario. Vignette on ORM website: http://sts.gsc.nrcan.gc.ca/orm/index.asp

Karrow, P.F. 1967. Pleistocene geology of the Scarborough area. Ontario Department of Mines, Geological Report 46.

Pugin, A., Pullan, S.E., and Sharpe, D.R. 1999. Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario; Canadian Journal of Earth Sciences, 36(3): 409-432.

Robinson, J., 1999. Waterloo Aquifer Management Plan, presented to the Dorset Groundwater workshop, Sept. 1999.

Russell, H.A.J., Logan, C., Brennand, T.A., Hinton, M.J., and Sharpe, D.R., 1996. Regional geoscience database for the Oak Ridges Moraine project; Geological Survey of Canada, Current Research 1996-E, 191-200.

Russell, H.A.J., and Pullan, S.E., 1998. Stop 2.4 Nobleton borehole in the Laurentian Channel. *In*: Sharpe, D.R., Hinton, M., Russell, H.A.J., and Barnett, P.J. 1998. Regional geology and hydrogeology of the Oak Ridges Moraine area, southern Ontario; Field Trip Guide 7, Geological Society of America, Annual Meeting, Toronto, Ontario, Canada.

Russell, H.A.J., Sharpe, D.R., and Arnott, R.W.C., 1998a. Sedimentology of the Oak Ridges Moraine, Humber River watershed, southern Ontario; *In* Current Research 1998-C; Geological Survey of Canada, p 155-166.

Russell, H.A.J., Brennand, T.A., Logan, C., and Sharpe, D.R. 1998b. Standardization and assessment of geological descriptions from water well records: Greater Toronto and Oak Ridges Moraine Areas, southern Ontario; *In* Current Research 1998-E; Geological Survey of Canada, p 89-102.

Russell, H.A.J., Pullan, S.E., Barnett, P.J., and Sharpe, D.R. 2000. Channel form and sedimentary fills beneath the Oak Ridges Moraine, southern Ontario: the Holland Marsh-King City channel system, Oak Ridges Moraine, southern Ontario. Geological Survey of Canada Open File 3841.

Sharpe, D.R., Dyke, L.D., Hinton, M.J., Pullan, S.E., Russell, H.A.J., Brennand, T.A., Barnett, P.J., and Pugin, A., 1996. Groundwater prospects in the Oak Ridges Moraine area, southern Ontario: application of regional geological models; Geological Survey of Canada, Current Research 1996-E, p 181-190.

Sharpe, D.R., Barnett, P. J., Brennand T. A., Finley, D., Gorrell, G., Stacey, P., and Russell, H.A.J., 1997:. Surficial Geology of the Greater Toronto and Oak Ridges Moraine area, southern Ontario; Geological Survey of Canada Open File 3026, scale 1:200,000.

Sharpe, D.R., Barnett, P.J., Russell, H.A.J., Brennand, T.A, Gorrell, G., Dyke, L.D., Hinton, M.J., Pullan, S.E., Pugin, A., 1998. Channel aquifers of the Oak Ridges Moraine area, Southern Ontario. Geological Society of America Annual meeting 1998, Toronto.

Sharpe, D.R., Barnett, P.J. , Russell, H.A.J., Brennand, T.A., and Gorrell, G. 1999. Regional geological mapping of the Oak Ridges Moraine-Greater Toronto area, southern Ontario; *In* Current Research 1999-E; Geological Survey of Canada, p 123-136.

Sharpe, D. R., Russell , H.A.J., and Pullan, S.E., Pugin, A. Brennand, T.A, and Barnett, P.J. 1999b. Channel form and sediment fill of tunnel channels beneath the Oak Ridges Moraine, southern Ontario. Geological Society of America Annual Meeting, Denver, Colorado. October 27-30, 1999.

Sharpe, D.R., Hinton, M.J., and Russell, H.A.J., 2000. Groundwater Resources in the Oak Ridges Moraine, Greater Toronto Area. Geological Association of Canada Annual Meeting, Calgary, May 2000. Vignette on ORM website: http://sts.gsc.nrcan.gc.ca/orm/index.asp

Sibul, U., Wang, K.T., and Vallery, D. 1977. Ground-Water Resources of the Duffin Creek-Rouge River Drainage Basins. Ministry of the Environment Water Resources Report 8.

Terraqua Investigations Ltd. 1995. Study of the hydrogeology of the Waterloo Moraine. Unpublished report to the Regional Municipality of Waterloo, Ontario, Canada.

Turner M.E., 1977. Oak Ridges Moraine Aquifer Complex. Ontario Ministry of the Environment, Water Resources Branch, Hydrogeological Map 78-2.

Acknowledgements

Charles Logan derived all the cross-sections and figures and Paul Stacey re-formatted the document for PDF release. We thank Marc Hinton and Harvey Thorleifson for review comments.