REGIONAL AND SUB-REGIONAL GROUNDWATER FLOW MODELLING, OAK RIDGES MORAINE AREA OF SOUTHERN ONTARIO

E.J. Wexler, Earthfx Incorporated, Toronto, Ontario, Canada
Steve Holysh, Conservation Authorities Moraine Coalition, Milton, Ontario, Canada
Dirk Kassenaar, Earthfx Incorporated, Toronto, Ontario, Canada
Rick Gerber, Gerber Geosciences, Toronto, Ontario, Canada

ABSTRACT: Urbanization in the Greater Toronto Area (GTA) is encroaching on high recharge areas in the Oak Ridges Moraine (ORM). To predict impacts on groundwater and surface water, we developed a regional flow model of the ORM and a sub-regional model for the GTA core. MODFLOW was used to represent an area extending from the Niagara Escarpment eastward to the Trent River and southward from Lake Simcoe to Lake Ontario. 100-m wide cells were used in the sub-regional model to better represent stream/aquifer interaction and well drawdowns. The regional model was based on the Geological Survey of Canada’s 5-layer stratigraphic model; this was further refined to eight layers for the core model. Models were calibrated to observed heads and baseflow and provide regional water balances, refined recharge and aquifer property estimates, wellhead capture zones and valuable insight into the sensitivity of the groundwater and surface water systems to development-induced change.

RESUME: L'urbanisation dans le plus Grand Domaine de Toronto (GDA) empiète sur les domaines de haut recharges dans le "Oak Ridges Moraine" (ORM). Pour prédire les impacts sur l'eau souterraine et l'eau de surface, nous avons développé un modèle de flux régional du ORM et un modèle sous régional pour le noyau du GDA. "MODFLOW" a été utilisé pour représenter un domaine qui s'étend de l'est de l'Escarpement de Niagara jusqu'à la Rivière de Trent et vers le sud de Lac Simcoe jusqu'à Lac Ontario. Les cellules, larges de 100 m, ont été utilisées dans le modèle sous régional pour mieux représenter l'interaction entre le ruisseau et l'aquifer et l'abaissement du niveau de puits. Le modèle régional a été basé sur le modèle stratigraphique de cinq couches de la Commission Géologique du Canada (CGC). Celui-ci a été modifié à huit couches pour le modèle fondamental. Les modèles ont été calibrés aux têtes et base de flux observés et fournissent des équilibres d'eau régionaux, des recharges de raffinage et des estimations de propriété de aquifer, des zones de prise de tête de puits et un précieux aperçu dans la sensibilité de l'eau souterraine et les systèmes d'eau de surface au changement de développement induit.

.

1. BACKGROUND

The Oak Ridges moraine (ORM), a major physiographic feature in south-central Ontario, is an interlobate moraine that formed during the recession of the Wisconsinan glaciation about 13,000 years ago (Chapman and Putnam, 1984). It lies north of the Greater Toronto area (GTA), roughly midway between Lake Simcoe and Lake Ontario (Figure 1). The ridge formed by the ORM ranges in altitude from 405 metres above sea level (mASL) in the east to 305 mASL in the west and extends eastward from the Niagara Escarpment to the Trent River, a distance of over 160 km. Due to its predominantly sandy surface soils and hummocky topography, the moraine serves as the primary recharge area to underlying aquifers. While few streams are located on the moraine, spring discharge along the lower slopes of the moraine provides baseflow to streams that drain the till plains to the north and south.

Land use on the moraine has historically been agricultural, mostly crop, pasture land and forested areas (Chapman and Putnam, 1984). Land use is changing to low-density residential over much of the area. In the GTA core area more intense residential and commercial development has occurred. Recent efforts by the regional municipalities and the Ontario government have tried to control urban development on the ORM.

To better understand the impacts of development on groundwater and surface water systems in the ORM area, a coalition of four municipal governments and nine Conservation Authorities have initiated a number of studies of the geology and hydrogeology of the Oak Ridges Moraine. Primary among the studies were the development of a groundwater model for 1) the entire Oak Ridges Moraine, 2) the watersheds within the Toronto and Region Conservation Authority area (TRCA), and 3) for the Yonge Street Aquifer area in York Region. Objectives of these modelling studies were to develop an overall water balance for each study area, determine the sensitivity of the groundwater system to recharge variation, quantify impacts of increased water takings on stream flow, and provide a framework for detailed wellhead capture zone analysis.

Figure 1: Location of the Oak Ridges Moraine

Modelling progressed in two stages. A regional model was constructed based on the recent interpretation of the ORM hydrogeology by the Geological Survey of Canada. The regional model study area, shown in Figure 1, is about 250 km long and over 157 km wide. It extends beyond the ORM to reach natural hydrologic boundaries and was bounded by the Niagara Escarpment to the west and by the Trent River watershed to the east. Results from the regional model were used to develop a refined model for the GTA core. The process of developing the regional and sub-regional models and preliminary results are the subject of this paper.

2. PREVIOUS WORK

Several investigators have built numerical models for parts of the study area. These include Gerber (1999) who studied Duffins Creek watershed; Meriano (1999) who modelled the Rouge River basin; and Smart (1994) who studied the Humber, Don, Rouge, Duffins, and Lynde Creek watersheds. International Water Consultants, Ltd. (1991) developed a one-layer model for the Yonge Street Aquifer. The largest-scale study was by Mowatt (2001) who modelled an area similar to that of our sub-regional model. Most studies, with the exception of Mowatt (2000), used the regional groundwater divide in the ORM as a model boundary. The studies, except IWC (1991) considered three principle regional aquifers and two confining units as described below. The current study integrates and builds on these previous efforts.

Recent studies by the Geological Survey of Canada (GSC) and the Ontario Geological Survey (OGS) have significantly advanced the understanding of the key geological processes that contributed to the formation of the ORM (Barnett et al, 1998; Sharpe et al, 1999; Logan et al, 2001). The GSC provided digital mapping of key units used to build our regional model of the ORM. Refinement and subdivision of these units provided the basis for the sub-regional model of the GTA core

3. GEOLOGIC SETTING

3.1.1. Bedrock

The study area is underlain by Paleozoic limestone and shale of Ordovician age. The northern and eastern part of the study area is underlain by limestone of the Simcoe Group. In the south-central part of the area, the limestone is overlain by shales of the Georgian Bay group. In the west, the Georgian Bay shale is overlain by the softer Queenston shale. At the western end of the study area is the Niagara Escarpment, composed of the Lockport-Amabel Formation and the Clinton and Cataract Group.

The bedrock surface in the central part of the study area was deeply eroded by the historic Laurentian River, the pre-glacial drainage route of the Great Lakes basin. Tributary streams drained the more resistant limestone uplands and cut valleys through the shale to join the main channel. Other bedrock channels that drain the Precambrian bedrock to the north may have also cut narrow valleys through the limestone. Although dependent on the nature of the valley infill, the bedrock valley system can strongly influence flow patterns in the deeper overburden. The sediments could also be potential targets for future groundwater exploration.

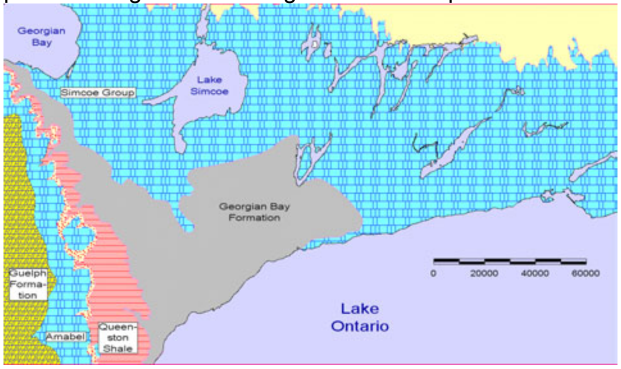

Figure 2: Bedrock Geology (after OGS, 1993)

3.1.2. Overburden Deposits

Overburden deposits in the ORM area are primarily of glacial origin and can exceed 200 m in thickness. Surficial geology for the study area is presented in Figure 3.

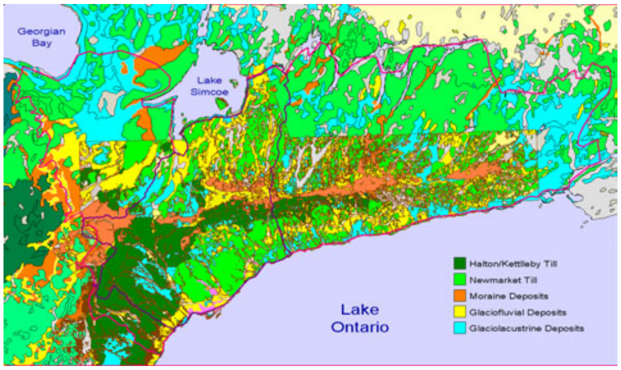

Figure 3: Surficial Geology (after OGS, 1998 and Sharpe et al, 1997)

The GSC (e.g. Logan et al, 2001) subdivided these deposits into five primary units: i) the Lower Deposits; ii) Newmarket Till; iii) ORM Sediments; iv) Halton Till; and v) glaciolacustrine and more recent deposits.

The Lower Deposits are formed of early to mid-Wisconsinan interbedded glaciolacustrine sediments and tills. These were combined by the GSC into a single regional layer while others (e.g. Gerber 1999) have subdivided this unit into several layers (Figure 4). The oldest of these layers is the Pre-Wisconsinan York Till, a thin bouldery deposit about 1 m thick, and the Don Formation comprised of alternating beds of sandy storm deposits and peaty muds (Eyles and Clark, 1988). These units are often thin or missing but may be more significant in the deeper bedrock valleys. Overlying the Don Formation is the Scarborough Formation (Scarborough Clay and Scarborough Sands). The Scarborough Sands are preserved in many of the bedrock valleys and provide a source of water to deep municipal wells. The Scarborough Sands are capped by the Sunnybrook Diamict, a unit of interbedded sand, diamict, and laminated clay. This unit is overlain by the Thorncliffe Formation, a more regionally-extensive, glaciofluvial stratified silt and sand deposit. The Thorncliffe formation is highly variable but can provide a significant source of water to municipal wells and private wells.

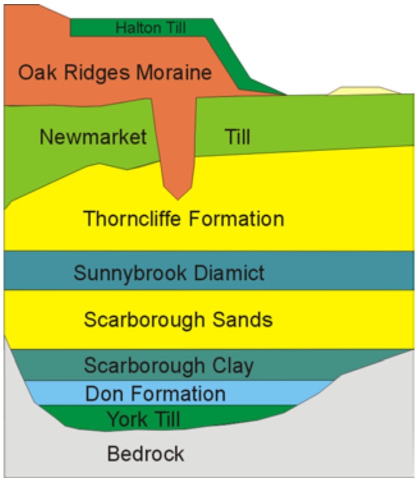

Figure 4: Simplified Stratigraphy of the ORM Area

The Newmarket Till was deposited during the late-Wisconsinan by the Laurentide ice sheet. It is a poorly-sorted sandy silt to sand till that forms an extensive regional confining unit. The upper surface of the Newmarket Till is drumlinized and has been eroded by a series of north-south trending sub-glacial tunnel channels (Barnett et al., 1998). The tunnel channels were formed by the flow of significant volumes of water beneath the ice. In some areas, the flows have removed all of the Newmarket Till and, in extreme cases (e.g. the Holland Valley), most of the Lower Sediments. The channels are tens of kilometers long, up to 4 km wide, and up to 150 m deep (Logan et al, 2001). Granular materials are often found near the base of these channels and are overlain by thick silt deposits. The tunnel channels can connect the surficial aquifer with the deeper aquifers although the thick silt layers may still impede groundwater flow.

The ORM deposits are mostly sands and gravels with local deposits of silts and clays. There are four large sediment wedges connected by narrow east-west trending ridges. Detailed descriptions of the sediments and the deposition environment are contained in Barnett et al. (1998). The ORM thickness can range from 0 to 150 m and is tapped by numerous private wells. Several highly productive municipal wells are screened in the ORM. Because the ORM sediments are so permeable, these wells are more susceptible to contamination.

A late re-advance of the ice placed the Halton Till along the south flank of the ORM and the Kettleby Till north of the ORM. The Kettleby Till tends to be patchy while the Halton Till appears as a wide east-west belt (Figure 3). Both are relatively thin sandy clay tills which tend to be more clay-rich to the west. Recent surficial geology mapping by the GSC (Figure 3) interprets the southern limit of the Halton Till as being close to the base of the moraine with the Newmarket Till at surface along the south slope down to Lake Ontario. Other interpretations postulate a more extensive Halton Till with a sand unit composed of outwash associated with the Mackinaw Interstadial sandwiched between the Halton and Newmarket Tills. Recent lake and shoreline deposits associated with glacial Lake Iroquois and Lake Algonquin form the uppermost surficial unit.

The sequence of units shown in Figure 4 is a very simplified picture of the complex geologic setting of the study area. The thickness of each unit is highly variable and, in many locations, one or all of the overburden units can be missing. For example, Halton Till is often found directly on bedrock in the western part of the study area, Newmarket till is often exposed at surface and overlies bedrock north of the moraine. ORM deposits may lie atop bedrock in the tunnel channels and great thicknesses of Scarborough sands form bluffs along the shore of Lake Ontario. This high variability in stratigraphy along with high variability in aquifer properties makes modelling the ORM particularly challenging.

4. MODELLING METHODOLOGY

4.1.1. Theory

Aquifer potentials are controlled by stratigraphy, the magnitude and spatial variation of hydraulic conductivity, and the rate and distribution of recharge and discharge. The mass balance equation describing steady-state groundwater flow is given by Bear (1979) as:

$$\frac{\partial}{\partial x}(h-b)\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}(h-b)\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{K'}{B'}(H_u-h)+N-W=0 \qquad eq.1$$

where:

K_{xx} = hydraulic conductivity in the x direction;
K_{yy} = hydraulic conductivity in the y direction;
h = hydraulic head or aquifer potential;
b = elevation of the unit bottom;
K' = vertical K of the underlying confining unit;
B' = thickness of the confining unit;
h_u = head in the underlying aquifer;
N = the rate of groundwater recharge; and
W = the rate of groundwater discharge.

Similar equations can be written for each aquifer in a layered sequence of layers and confining units with an additional term for leakage from the overlying aquifer. If an aquifer layer is always confined, the term $(h\text{-}b)K_{xx}$ can be replaced by the T_{xx}, the aquifer transmissivity. The leakage term can also be modified to represent vertical movement of water between sub-layers within an aquifer.

Equation 1 formed the basis of the mathematical model developed for the ORM and was solved to determine aquifer potentials. Finite-difference methods were used to solve Equation 1 because study area boundaries were irregular and aquifer properties and rates of recharge and discharge vary spatially over the study area.

While aquifer potentials vary on a daily and seasonal basis due to fluctuations in the rates of precipitation and evapotranspiration, the models developed in this study assumed steady-state conditions. Transient effects were removed by using annual average values for net recharge (precipitation–evapotranspiration) and pumping. Although it cannot represent time-varying behaviour, the steady-state model provides a good representation of time-averaged groundwater conditions.

4.1.2. Selection of Computer Model

The regional and sub-regional groundwater flow models were developed using the U.S. Geological Survey (USGS) MODFLOW code. MODFLOW (McDonald and Harbaugh, 1988) is a three-dimensional, finite-difference code capable of simulating transient and steady state flow in confined or unconfined, multi-layered aquifer systems. In addition to MODFLOW, the USGS MODPATH code (Pollock, 1989) was used for backward particle tracking to determine capture and time-of-travel zones for municipal wells in York Region.

The study team used VIEWLOG to analyze and manage all hydrogeologic data. A Microsoft Access database was constructed to store borehole logs, water level data, and pumping information. Construction of the geologic model is described in a companion paper. Although primarily a data management tool, VIEWLOG contains pre-and post-processor functions for MODFLOW. These functions were used to facilitate model construction and to interpret and present model results.

5. OAK RIDGES MORAINE REGIONAL MODEL

5.1. Model Grid

The finite-difference method requires that the model area be subdivided vertically into several layers, each representing a hydrogeologic unit (such as an aquifer or aquitard). Each layer is then subdivided horizontally into a grid of small rectangular cells. Aquifer properties and top and bottom elevations for the layer are assigned to each cell and recharge and discharge rates are assigned to specific cells. Boundary conditions are specified for the cells along the physical boundaries of the flow system. In each model run, an algebraic approximation to Equation 1 is solved to determine the aquifer potential at the centre of each cell.

A grid consisting of square cells 240 m on a side was used to represent the study area. The model grid consisted of 1014 rows by 656 columns with five layers, for a total of over 3.3 million cells. MODFLOW works in a grid-based, coordinate system. A local origin, corresponding to the lower left corner of the model grid, was set at UTM coordinates 580,000 E and 4,825,000 N.

5.2. Model Boundaries

MODFLOW can represent three general types of boundary conditions: constant head, no-flow, and head-dependent discharge. All three boundary condition types were employed in the simulations. Locations of regional model boundaries are shown on Figure 5. Cells in the grid that fall outside the “active” model area were ignored in model calculations.

Figure 5: Model Grid and Boundary Conditions

5.2.1. Constant Head Boundaries

Constant head boundaries were applied at cells bordering Lake Ontario, Lake Simcoe, Georgian Bay, Rice Lake, Lake Scugog and the Kawartha Lakes to represent natural hydrologic boundaries at which aquifer potentials are known and remain constant. Potentials were set at 75.2 m above sea level (mASL) at Lake Ontario and 219.0 at Lake Simcoe. Smaller lakes were assigned elevations determined from topographic maps.

5.2.2. No-Flow Boundaries

No-flow boundaries were applied where the rate of lateral flow across a model boundary was assumed to be small or equal to zero. No-flow boundaries were set along the eastern edge of the regional flow model area to represent the surface water divide at the far end of the Trent River basin. A no-flow boundary was also set along the Niagara Escarpment. Recharge to sediment filled re-entrant valleys was applied as a specified flux. A no-flow boundary condition was implicitly set at the base of the lowest model layer. This assumed that the bedrock below a 5-m thick weathered zone was relatively impermeable and did not contribute significantly to groundwater flow.

Cells in the model can go “dry” during a simulation if the head drops below the base of the layer. The number of dry cells and their locations varied in response to changes in model inputs. The MODFLOW re-wetting option was used to allow a cell to re-activate if potentials in neighbouring cells rose above the base of the dry cell.

5.2.3. Head-Dependent Discharge Boundaries

MODFLOW uses several types of head-dependent discharge boundaries to simulate groundwater/surface water interaction where water is gained from (or lost to) a partially penetrating stream as leakage across a low-permeability streambed. MODFLOW “drains” were used in the regional model to simulate discharge to the groundwater-fed streams. The key assumption regarding “drains” is that leakage occurs in only one direction, (i.e., from the aquifer to the drain).

Leakage is proportional to the head-difference across the streambed. The “drain conductance”, a MODFLOW parameter equal to the streambed hydraulic conductivity divided by the streambed thickness times the wetted perimeter, was specified for each drain segment passing through a cell. Map lines representing stream reaches were each given a Strahler classification and assigned an average width and bed thickness. Hydraulic conductivities were assigned based on the parent soil material. Lengths of the drain segment within a finite difference cell were obtained by “intersecting” the model grid with each line segment representing a reach. Control elevations were assigned to each reach based on digital elevation data. VIEWLOG calculated the drain conductance values and created an input data file with over 270,000 drain segments. Drain conductances were adjusted during model calibration to better match observed baseflows.

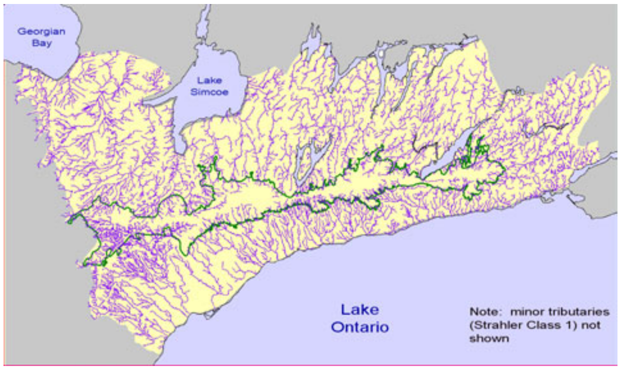

Figure 6: Streams Simulated in Regional Model

5.3. Model Layers

Hydrostratigraphy used in the regional model was based on the geologic layering defined by the GSC. Surfaces were modified slightly since MODFLOW requires that all layers be continuous. Where GSC layers were assigned a zero thickness, surface elevations were adjusted to assure a minimum 0.5 m layer thickness.

Land surface defined the top surface of the regional model. Land surface topography was obtained from a 10 m Digital Elevation Model (DEM) prepared by the Ontario Ministry of Natural Resources (MNR). The DEM was re-sampled to the model grid. A shaded relief map of land surface topography is shown in Figure 7.

Layers in the regional model included:

Layer 1: Oak Ridges Aquifer Complex (ORM)
Layer 2: Newmarket Till
Layer 3: Upper Part of Lower Sediments
Layer 4: Lower Part of Lower Sediments
Layer 5: Weathered Bedrock

The Lower Sediments were split into two to better represent the intermediate and lower aquifer (Thorncliffe and Scarborough equivalents). The vertical conductance between the two layers was modified to represent the Sunnybrook Diamict. The Halton Till was treated as a layer that capped the ORM deposits in a narrow band along the southern flanks of the Oak Ridges Moraine and primarily affected recharge rather than groundwater flow.

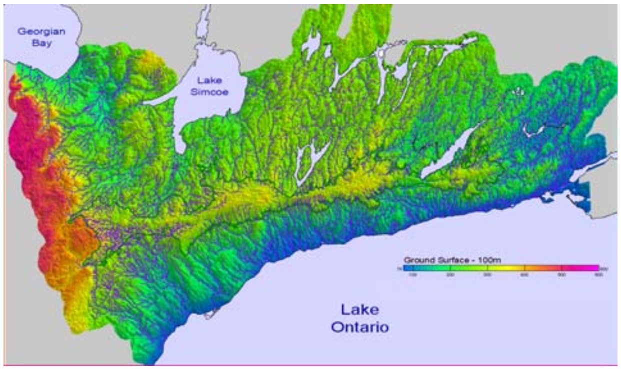

Figure 7: Land Surface Topography (after MNR)

5.4. Model Parameters

Uniform aquifer and aquitard properties were assumed in the early stages of model development based on results of previous smaller-scale studies. These property values were adjusted during model calibration.

5.5. Recharge and Discharge

Groundwater recharge is controlled by the spatial distribution of precipitation, soil properties, topography, and vegetation. Recharge was estimated based on results of previous groundwater modelling studies and on recent estimates for the TRCA watersheds. Recharge rates were assigned to zones based on surficial geology and were highest over the ORM due to the sandy soils and hummocky topography (360 mm/a) and lowest in areas covered with lake sediments or till (60 mm/a).

5.6. Calibration Targets

The regional model was calibrated by adjusting recharge rates and aquifer, aquitards, and streambed properties within reasonable ranges until a good match was achieved with observed heads and baseflows. Potentiometric surface and water-table maps were prepared using static water levels in the MOE well log database. Although measurements are distributed over a 40-year period and the accuracy of individual values is variable, the MOE water levels are the most comprehensive, areally-extensive data set. Our calibration effort focussed on matching the regional tends observed in the well log data as opposed to matching individual measurements. Baseflow estimates in the regional model were compared against calculated baseflows at select gauging stations (e.g. Duffins Creek).

5.7. Model Results and Conclusions

Simulated heads were obtained for each layer in the model. The simulated water table and potentials for Layer 4 are presented in Figures 8 and 9. Results indicated that (1) groundwater flow patterns were strongly influenced by streams and fine-discritization was needed to properly represent the stream network, (2) estimates of recharge and hydraulic conductivity produced reasonable matches to observed heads, gradients, and baseflows, and (3) model results were extremely sensitive to the permeability of the Newmarket Till which controlled aquifer heads both above and below the till layer.

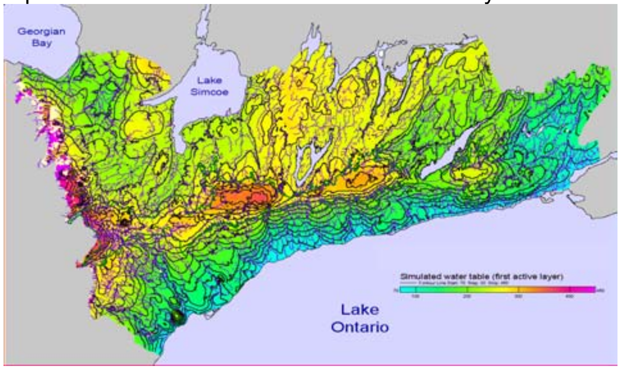

Figure 8: Simulated Water Table

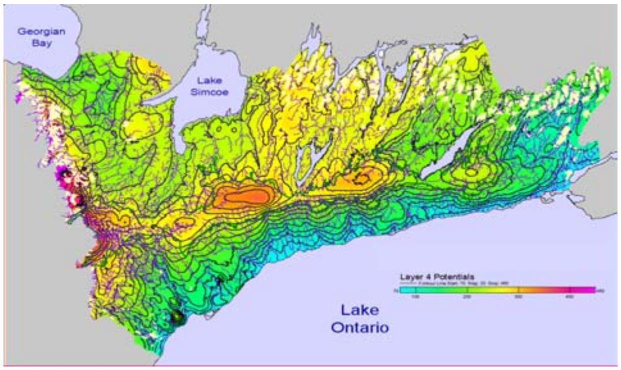

Figure 9: Simulated Heads in Layer 4 (Thorncliffe Aquifer)

Calibrated hydraulic conductivity values, shown below, did not vary greatly between aquifers and indicated that silts and fine sands are primary aquifer components. Properties agreed well with previous estimates by Gerber (1999) and Mowatt (2000). Hydraulic conductivity of the Newmarket Till is higher than test values from core samples. This agrees with Gerber (1999) who felt that fractures and sand bodies within the Newmarket till contribute to a higher effective vertical permeability. The presence of tunnel channels also facilitates exchange of water between the Lower Deposits and the ORM.

Unit	**Hydraulic Conductivity**
Oak Ridges Aquifer Complex	2.5×10^{-5} to 1×10^{-4} m/s
Newmarket Till (K_h) Newmarket Till (K_v)	5×10^{-8} to 1×10^{-7} m/s 2.5×10^{-8} to 5×10^{-8} m/s
Intermediate Aquifer	1×10^{-5} to2. 5×10^{-5} m/s
Lower Aquifer Layer 3 Lower Aquifer Layer 4	1×10^{-5} m/s 2.5×10^{-4} m/s
Weathered Bedrock (5 m thick)	1×10^{-5} m/s
Streambed	5×10^{-6} m/s

Although reasonable matches to the observed heads and flows were obtained, it was felt that more work was needed to map the bedrock valleys and tunnel channels and to better represent stratigraphy of the Lower Sediments if the model was to be used for predictive and management analysis. Refining of the stratigraphy is detailed in the companion paper. Efforts were also made to account for local variability of aquifer properties in the next phase of the study, as described below.

6. GTA CORE SUB-REGIONAL MODEL

The second phase of the study involved a more detailed assessment of the GTA Core Area and a refinement of the model. Many of the basic modelling assumptions remained the same as described above. The discussions below focus on where the approach differed.

6.1. Model Grid

The GTA core model included most of the TRCA watersheds and all of York Region as shown in Figure 10. The modelled area is bounded by the Humber and Holland Rivers to the west and by Duffins, Carruthers and Uxbridge Creeks to the east. The core model extends southward from Lake Simcoe to Lake Ontario.

Figure 10: Sub-regional Model Grid and Boundary Conditions

A grid (Figure 10) consisting of 100 m cells represented the core area. The small cell size was needed to better represent stream-aquifer interaction and drawdowns around the municipal wells. The model grid consisted of 840 rows by 1056 columns with eight layers, for a total of 7.1 million model cells. A local origin for the grid was defined at UTM coordinates 550665 E and 4810550 N.

6.2. Model Boundaries

Lake Ontario and Lake Simcoe were treated as constant head boundaries (Figure 10). A no-flow boundary was set along the Humber River to represent a flow line and along the eastern model boundary to represent watershed divides. Over 56,440 MODFLOW drain segments were used to represent groundwater-fed streams.

6.3. Model Layers

As described in a companion paper, a considerable effort was expended to redefine the bedrock surface and top surfaces of the aquifers and confining units. Because the GTA core model was being developed simultaneously, the surfaces of subunits within the Lower Deposits were approximated using a rules-based approach. Figure 11 shows a north-south cross section along Yonge Street from Lake Simcoe to Lake Ontario showing model layers in the current GTA core model which included:

Layer 1: Recent deposits
Layer 2: Halton Till
Layer 3: ORM
Layer 4: Newmarket Till
Layer 5: Thorncliffe Fm.
Layer 6: Sunnybrook Diamict
Layer 7: Scarborough Sands
Layer 8: Weathered Bedrock

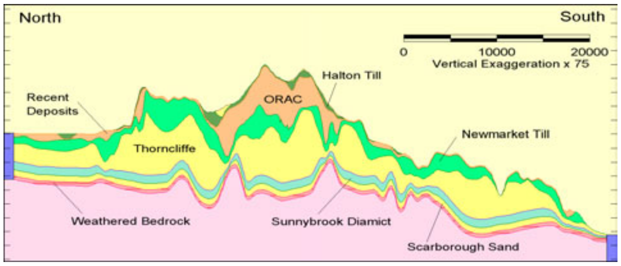

Figure 11: North-South Cross Section

A rules-based approach was also developed to adjust layer surfaces and assign aquifer properties where layers pinched out. For example, if the Halton Till was at mapped at surface and was lying directly on Newmarket Till, then the upper 2 m were included in Layer 1 and cells were assigned properties for weathered till while cells in Layer 2 were assigned unweathered till properties. Layer 3 was given a minimum 1 m thickness by pushing down the top of Layer 4 and cells in Layer 3 were assigned Newmarket Till properties. Although these types of adjustments were more complex than simply assigning each unit a minimum thickness, it ensured layer continuity while not artificially adding units that did not exist. Tunnel channels were treated by assigning silt-layer properties to Layer 4 instead of Newmarket Till properties.

6.4. Model Parameters

Several methods were evaluated for assigning hydraulic conductivities (K's) to aquifer layers. These included interpolating sparse aquifer test data, using K's estimated from specific capacities, and assigning K's based on lithology described in drillers' logs. While all methods produced reasonable results, assigning hydraulic conductivity based on lithology was most consistent. Values were assigned to each possible combination of primary and secondary materials (e.g. clay with gravel). Equivalent vertical and horizontal K's were calculated based on the assigned K values and thickness of each lithologic unit.

Aquitards were assigned uniform properties that were adjusted during model calibration. Net recharge was assigned primarily based on surficial geology. Pumping was assigned to York, Peel, and Durham Region municipal wells based on their maximum permitted rates. Data on industrial, agricultural, domestic and recreational pumping was provided through water-use surveys.

6.5. Calibration Targets

Potentiometric surface and water table maps from the MOE static water levels were revised based on the re-interpreted layering. Observed drawdowns at York Region monitoring wells were compared against predicted drawdowns. Baseflow estimates were prepared by hydrograph separation for 20 years of flow data at Environment Canada gauging stations. Spot flows were also measured at ungauged streams across the ORM.

The model was first calibrated in the Duffins Creek area and compared to results of Gerber (1999). Next, it was calibrated in the Yonge Street corridor, an area with a large amount of available hydrogeologic data, and finally over the entire GTA Core area.

6.6. Model Results

Simulated heads were obtained for each layer in the model; potentials for Layer 5 are presented below. Model results confirmed that (1) groundwater flow patterns were strongly influenced by the streams, by local variation in aquifer properties, and by the presence of bedrock valleys and tunnel channels.

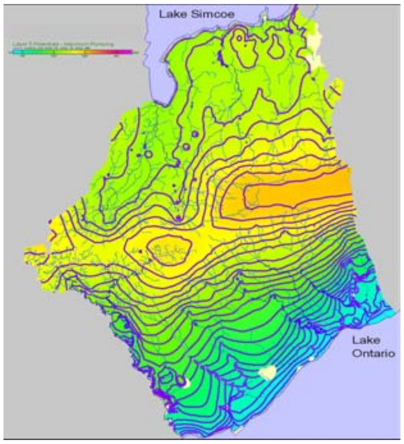

Figure 12: Simulated Heads under Maximum Pumping Conditions

Predicted groundwater discharge was compared against baseflow at gauges; results for Black River are shown in Figure 13. While the model cannot match monthly flows, it does match annually averaged flow.

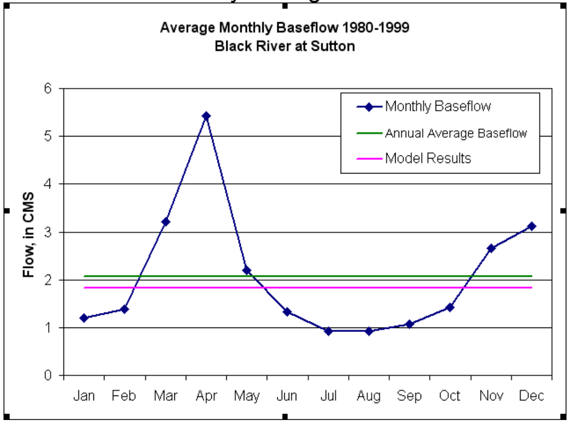

Figure 13: Simulated vs. observed flow at Black River

Model calibration was felt to be sufficiently good that predictive scenarios could be run. For example, capture zone analyses were conducted using backwards particle tracking to determine time-of-travel zones for the York Region municipal wells. These are shown in Figure 14.

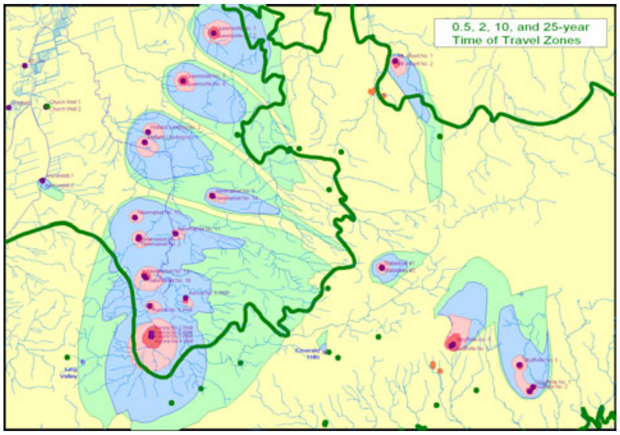

Figure 14: Time of Travel Zones for Wells in York Region Pumping at Maximum Rates

6. CONCLUSIONS

The complex hydrostratigraphy of the Oak Ridges Moraine provided many challenges to the construction of regional and sub-regional groundwater flow models. Foremost was how to model an extremely large and complex area without sacrificing the fine scale detail needed for stream-aquifer interaction and wellhead protection. Through detailed analysis of the available data, we developed highly detailed models of the groundwater flow system that matched observed water levels, flow directions and groundwater discharge to streams. The models provide a powerful tool for water balance analysis, quantifying impacts of increased water takings on water levels and streamflow, and detailed wellhead capture zone analysis.

7. REFERENCES

Barnett, P.J., Sharpe, D.R., Russell, H.A.J., Brennand, T.A., Gorrell, G., Kenny, F., and Pugin, A., 1998, On the origins of the Oak Ridges Moraine: Paper on GSC website modified from Canadian Journal of Earth Sciences, vol. 35, pp. 1152 – 1167.

Bear, Jacob, 1979, Hydraulics of Groundwater: McGraw Hill, New York, 567 p.

Chapman L.J. and Putnam, D.F., 1984, The Physiography of Southern Ontario: Ontario Geological Survey, Special Volume 2, 270 p.

Eyles, N. and Clark, B.M., 1988. Last Interglacial sediments of the Don Valley Brickyard, Toronto, Canada and their paleoenvironmental significance: Canadian J. of .Earth Science, V.25, p. 1108-1122.

Gerber, R.E., 1999, Hydrogeologic behavior of the Northern till aquitards near Toronto, Ontario: Ph.D. Thesis, Dept. of Geology, University of Toronto,

Logan, C., Russell, H.A.J., and Sharpe, D.R., 2001, Regional three-dimensional stratigraphic modelling of the Oak Ridges Moraine area, Southern Ontario: Current Research–2001-D1, Geo. Survey of Canada.

McDonald, M.G. and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: USGS Techniques in Water Resources Investigations Book 6, Chapter A1, 586 p.

Meriano, M., 1999, Hydrogeology of a complex glacial system, Rouge River-Highland Creek watershed, Scarborough, Ontario: M.Sc. Thesis, Dept. of Geology, University of Toronto, 86 p.

Ontario Geological Survey, 1993, Bedrock geology, seamless coverage of the province of Ontario: Ontario Geological Survey, ERLIS Data Set 6

Ontario Geological Survey, 1997, Quaternary geology, seamless coverage of the province of Ontario: Ontario Geological Survey, ERLIS Data Set 14

Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: USGS Open File Report. 89-381, 188 p.

Russell, H.A.J., T.A. Brennand, C. Logan, and D.R. Sharpe, 1998, Standardization and assessment of geological descriptions from water well records, Greater Toronto and Oak Ridges Moraine areas, southern Ontario. Geological Survey of Canada – Current research 1998-E, pp.89-102.

Sharpe, D.R., Barnett, P.J., Brennand, T.A., Finley, D., Gorrell, G., Russell, H.A.J., and Stacey, P., 1997. Surficial geology of the Greater Toronto and Oak Ridges Moraine Area, southern Ontario: Geo. Survey of Canada, Open File Report 3062, Scale 1:200,000.

Sharpe, D.R., Barnett, P.J., Russell, H.A.J., Brennand, T.A., and Gorell, G., 1999, Regional geological mapping of the Oak Ridges Moraine, Greater Toronto Area, Southern Ontario: Current Research – 1999-E, Geo. Survey of Canada, pp. 123 -136.

Smart, P.J., 1994, A water balance numerical model analysis of the Oak Ridges Aquifer Complex, South Central Ontario: M.Sc. Thesis, Dept. of Geology, University of Toronto, 154 p.

Mowatt, G.D., 2001, A finite element groundwater flow model analysis of the glacial stratigraphy of the Greater Toronto Area: M.Sc. Thesis, Dept. of Geology, University of Toronto, 151 p.

International Water Consultants Ltd, 1991, Regional Municipality of York, aquifer performance assessment, Oak Ridges, Aurora, Newmarket, East Gwillumbury and Bradford: IWC, 52 p.

Ontario Geological Survey, 1997, Quaternary geology, seamless coverage of the province of Ontario; Ontario Geological Survey, ERLIS Data Set 14