REGIONAL NUMERICAL GROUNDWATER FLOW MODELLING AND PRELIMINARY LOCAL-SCALE WATER BUDGET ANALYSIS, HOLLAND RIVER WATERSHED, ONTARIO

Richard Gerber, Gerber Geosciences Inc., Toronto, Ontario, Canada
E.J. Wexler and Dirk Kassenaar, Earth*fx* Incorporated, Toronto, Ontario, Canada
Steve Holysh, Conservation Authority Moraine Coalition, Milton, Ontario
Don Goodyear, Lake Simcoe Region Conservation Authority, Newmarket, Ontario, Canada

ABSTRACT: Recent initiatives from various levels of government in Ontario require that detailed water budget analyses be conducted as part of the groundwater management process. For example, the Oak Ridges Moraine Conservation Act (ORMCA) requires that water budget analyses be conducted for all streams that originate on the Oak Ridges Moraine. These analyses require that the surface water and groundwater systems be characterized and that the components of the hydrologic cycle be quantified by means of numerical models. This paper describes water budget analyses conducted on a regional and watershed scale using a groundwater flow model developed for a rapidly urbanizing section of the ORM. Regional scale water budget analyses helped in the formulation of model inputs and the setting of calibration targets. Watershed scale modelling was conducted to obtain insight into the spatial distribution of flows and to assess the effect of municipal groundwater pumping and land use change on groundwater discharge to streams. Ultimately, the model will be used to manage the groundwater resource in a sustainable manner that minimizes potential impacts on the ecosystem

RÉSUMÉ

1. INTRODUCTION

The Oak Ridges Moraine (ORM) stretches 160 km across southern Ontario from the Niagara Escarpment in the west to Trenton in the east. Within the study area, which represents the west-central portion of the ORM (Figure 1), the moraine serves as the height of land separating southward flow draining towards Lake Ontario from northward flow draining towards Lake Simcoe. To effectively manage the water resources of the ORM, a quantitative understanding of the flow system is necessary. In 2001, the Province of Ontario released the Oak Ridges Moraine Conservation Act accompanied by the Oak Ridges Moraine Conservation Plan (ORMCP). The ORMCP requires that water budget analyses be conducted for all streams that originate on the ORM. These analyses must quantify the components of the hydrologic cycle and characterize the groundwater and surface water flow system using numerical models.

In 2000, the Regional Municipalities of Peel, York and Durham, the City of Toronto, and nine Conservation Authorities formed a partnership, referred to as the CAMC/YPDT team, to study and develop a detailed understanding of the groundwater systems associated with the ORM (Holysh et al, 2003). This understanding will form the basis for future management initiatives across the ORM. To date, the CAMC/YPDT Team has collated all water-related data and information into a water resources database to assist in resource management. These data include streamflow, climate, borehole, and water well information along with all available digital mapping. The database contains over 190,000 data points (e.g. boreholes, climate stations, and stream gauges), 4 million water levels, and over 13 GB of scanned reports and maps.

Another part of this investigation included the construction of three-dimensional numerical groundwater flow models including: (1) a 5-layer Regional Model that covers the entire ORM, and (2) a more detailed, eight-layer model, referred to as the Core model, which covers the central portion of the western half of the ORM.

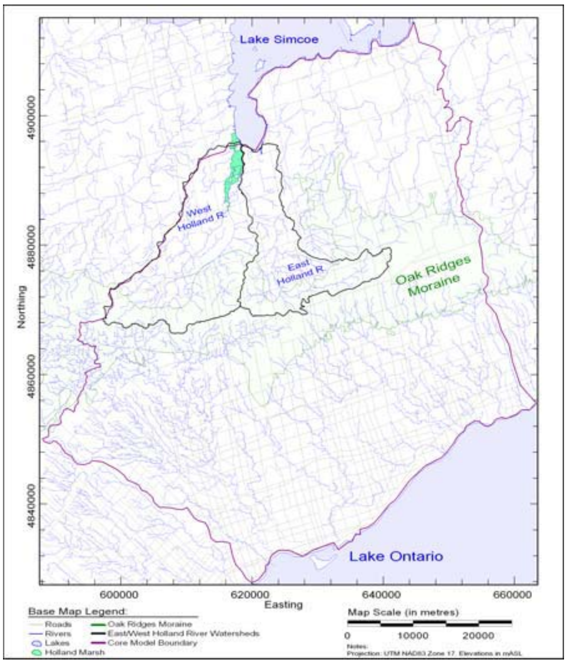

Figure 1: Core Model area.

The Core model area (Figure 1) covers all of York and parts of Peel and Durham Regions and the City of Toronto. It includes many of the significant watersheds within the Lake Simcoe Region Conservation Authority (LSRCA) and the Metro Toronto and Region Conservation (TRCA) areas. Development and application of the Core model is discussed in other papers (e.g. Earth*fx* *et al*., 2004).

York Region and the LSRCA have further enhanced the Core Model to produce detailed water balance estimates for the Holland River watershed (Figure 1) to meet the following objectives:

- quantify each component of the hydrologic cycle within the East and West Holland River subwatersheds;
- improve the understanding of the groundwater flow system within the Holland River watershed;
- identify locations where aquatic ecosystems are most sensitive to changes in the water budget;
- evaluate the availability of groundwater to meet the requirements of current and future water users and aquatic ecosystems;
- satisfy the requirements of the ORMCP; and
- provide local agencies with the tools necessary to effectively manage water resources.

2. PHYSICAL SETTING

Ground surface topography within the Holland River watershed ranges from approximately 219 metres above sea level (mASL) near Lake Simcoe in the north to approximately 380 mASL in the south along the crest of the ORM (Figure 2). The western part of the watershed is drained by the Schomberg River (also know as the West Holland River) and its tributaries, while the eastern part is drained by the East Holland River and its tributaries. The total drainage area of the Holland River watershed is approximately 586 km^2 (Vallery *et al*., 1982).

Physiographic regions within the study area include the Oak Ridges Moraine, the Schomberg Clay Plain, the Simcoe Lowlands, and till plains associated with the Peterborough Drumlin Field (Chapman and Putnam, 1984). The rolling hills of the Oak Ridges Moraine form the source area for the major streams that drain the watershed. The surficial sand and gravel deposits also form a major groundwater recharge feature within the watershed. The lower elevation portions of the watershed to the north of the ORM are dominated by lacustrine deposits and peats which are characterized by poor drainage and high water table conditions. The Holland Marsh occupies a broad valley emanating from Cooks Bay southwest towards Schomberg.

3. GEOLOGY

To describe the water budget for an area, it is important to first understand the underlying geology. This is especially true of the Holland River watershed where many towns obtain their municipal water supply from deep aquifer systems.

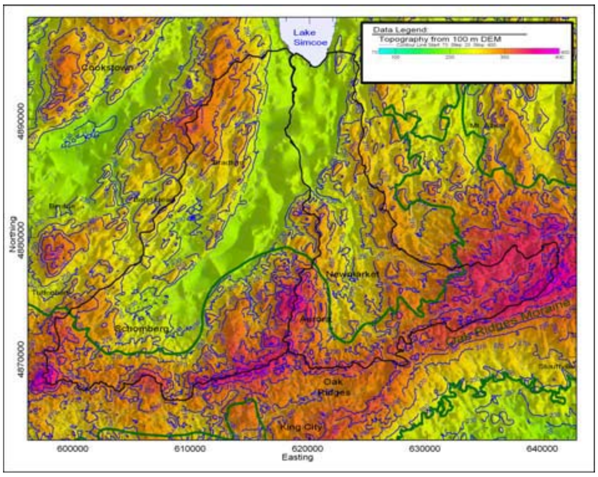

Figure 2: Ground surface topography and Holland River watershed (ORM planning boundary shown in green).

The geology of the study area is quite complex and consists of bedrock overlain by a succession of sediments deposited by glacial, fluvial and lacustrine processes over the last 135,000 years (Figure 3; Barnett et al., 1998). Details regarding the geology and hydrogeology of the study area are included in Earthfx *et al*., (2004), and only a brief description is provided here.

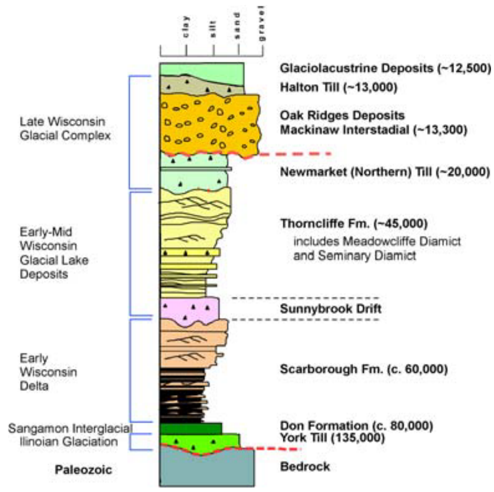

Figure 3: Quaternary deposits found within the study area (Figure from Eyles, 2002).

Shallow bedrock within the study area consists of limestone of the Middle Ordovician Simcoe Group in the north and shale of the Upper Ordovician Blue Mountain and Georgian Bay Formations in the south (Johnson *et al*., 1992). Fluvial action prior to glaciation eroded significant valleys into the bedrock surface. These valleys have subsequently been modified by glacial processes over the last 2 million years.

Bedrock topography, based on an analysis of borehole data, is shown in Figure 4. A major bedrock valley, known as the Laurentian channel, traverses the southwest portion of the watershed. This valley demarcates an ancient drainage system that extended from Georgian Bay to Toronto. Tributary valleys to the main Laurentian valley occur beneath the Holland Marsh and also extend from Mount Albert through Newmarket and Aurora to join the main valley south of the study area.

The thickness of the Quaternary sediments overlying bedrock is shown on Figure 5 and ranges from 50 m to 300 m. The thickest sediments occur within bedrock valleys and beneath the ORM. The thinnest overburden deposits occur adjacent to Lake Simcoe.

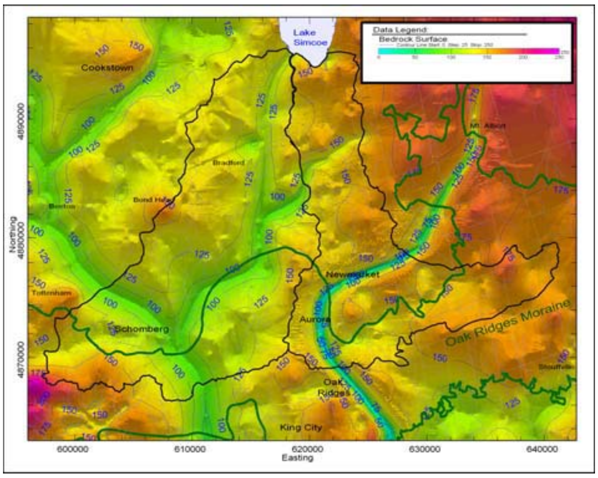

Figure 4: Bedrock surface topography.

The oldest Quaternary deposit of significant thickness within the study area is the Scarborough Formation or equivalent. This unit was formed by fluvio-deltaic processes and deposited mostly sand within the study area. This unit is mainly found within bedrock valleys and thins laterally away from the valleys. The Sunnybrook Drift (or equivalent) overlies the Scarborough Formation and consists of clast-poor silt and clay deposited by glacial and lacustrine processes. The Thorncliffe Formation (or equivalent) represents glaciofluvial

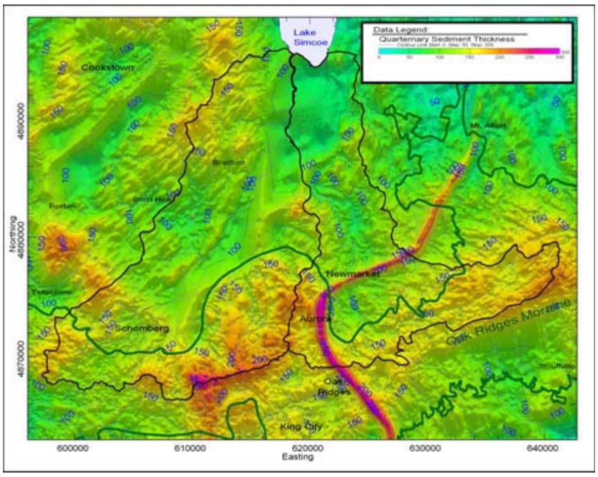

Figure 5: Quaternary sediment thickness

deposition of sand and silty sand generally within lows in the underlying stratigraphy. The type locations for these units are in the Scarborough bluffs area situated along the shore of Lake Ontario (Karrow, 1967). The term “or equivalent” is used to denote similar deposits considered coeval with those to the south.

The Newmarket Till is a dense diamict unit deposited when the Laurentide ice sheet was at its maximum extent, approximately 18-20,000 years ago. This unit can be up to 100 m thick but is generally 20-30 m thick. Subsequent to deposition, the upper surface of the till was eroded by glacial meltwater.

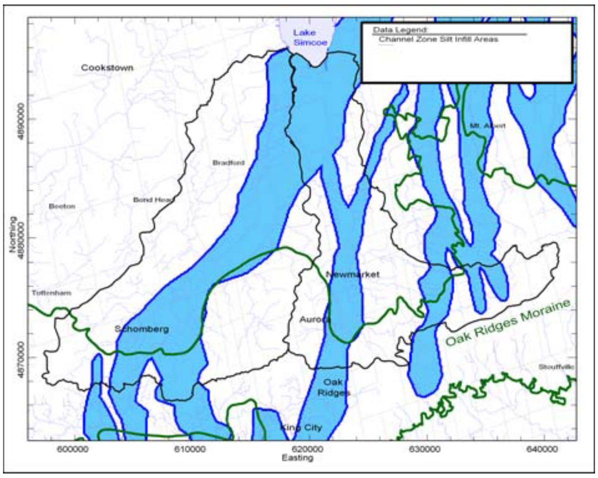

Figure 6: Erosional channel locations.

In some locations, sub-glacial erosional processes (sometimes referred to as tunnel channels) fully or partially removed the till. Locations of major tunnels, based on an extensive analysis of borehole data, are shown on Figure 6. These channels occur extensively throughout the watershed. Major erosional channels occur beneath the Holland Marsh extending from Lake Simcoe through Schomberg and through Newmarket, Aurora, and Oak Ridges. The tunnel channels were infilled by a fining-upward sequence of sands and silts deposited as meltwater energy waned.

Oak Ridges Moraine deposits occur above the Newmarket Till and largely consist of sand and gravel layers up to 150 m thick. Away from the ORM, sand units on the surface of the Newmarket Till have been categorized as belonging to the Mackinaw Interstadial deposits. The last glacial advance in the area, approximately 13,000 years ago, led to deposition of the Halton and Kettleby Tills which have a silt to clayey-silt matrix. Glaciolacustrine sand, silt, and clay associated with local ponding of glacial meltwater (e.g. Glacial Lake Algonquin) form a surface veneer over the till deposits.

4. HYDROGEOLOGY

4.1. Hydrostratigraphy

The classification of the geologic units described above into eight hydrostratigraphic units incorporated into the conceptual and numerical groundwater flow model is summarized in Table 1. The flow system generally consists of three principal aquifers. An upper aquifer system occurs within the deposits of the Oak Ridges Moraine and the Mackinaw Interstadial Unit. Two deeper aquifers occur within deposits of the Thorncliffe Formation (or equivalent) and the Scarborough Formation (or equivalent).

The upper aquifer is separated from the two deeper aquifers by the Newmarket till which acts as a regional aquitard. Horizontal permeabilities of the aquitards are generally an order of magnitude higher than the vertical values cited in Table 1. Where the Newmarket till has been eroded, the vertical hydraulic conductivity of the infill sediments determines the amount of leakage between the shallow and deep groundwater flow systems. It should be noted that much of the infill sediments appear in the water-well records as fining-upward sequences of sand and silt. Pumping tests conducted for municipal well exploration within the deep groundwater flow system generally indicate leaky-confined to confined aquifer conditions with boundaries. Regional modelling (Earthfx *et al.,* 2004) suggests that the hydraulic conductivity of the silt is approximately an order of magnitude more permeable than the Newmarket Till aquitard.

Table 1: Hydrostratigraphic units present within the Holland River watershed.

Layer	Classification	Hydraulic Conductivity
1. Surficial deposits and weathered till	Aquifer	Variable
2. Halton/Kettleby Till	Aquitard	~$5x10^{-7}$
3. ORM and Mackinaw Interstadial	Upper Aquifer	Variable
4. Newmarket Till	Aquitard	~$5x10^{-9}$
5. Thorncliffe Fm.	Middle Aquifer	Spatially variable
6. Sunnybrook Drift	Aquitard	~$5x10^{-9}$
7. Scarborough Fm.	Lower Aquifer	Variable
8. Weathered bedrock	Aquifer	Variable

4.2. Groundwater Flow

Groundwater flow directions within all three aquifers are mainly from south to north from the Oak Ridges Moraine towards Lake Simcoe (Figure 7 to 9). All three aquifer systems also exhibit a component of flow towards the Holland Marsh, which is considered a major groundwater discharge area. Within the Upper aquifer, groundwater flow patterns reflect ground surface topography with a significant component of flow towards the stream network. The surface water and groundwater divides appear to coincide; although some underflow into the watershed likely occurs in the northern half of the basin.

Groundwater flow within the deeper aquifers exhibit a similar pattern to the Upper aquifer with flow converging onto the lower reaches of the major streams. Excluding the Holland Marsh discharge area, vertical hydraulic gradients between aquifers are mainly downwards. The vertical gradients in both the Middle and Lower aquifers are also locally affected by municipal groundwater pumping. It should be noted that the potentiometric surface for the Lower aquifer is based on fewer data points than for the two overlying aquifers, which may explain the lack of clear channel flow systems in the observed data.

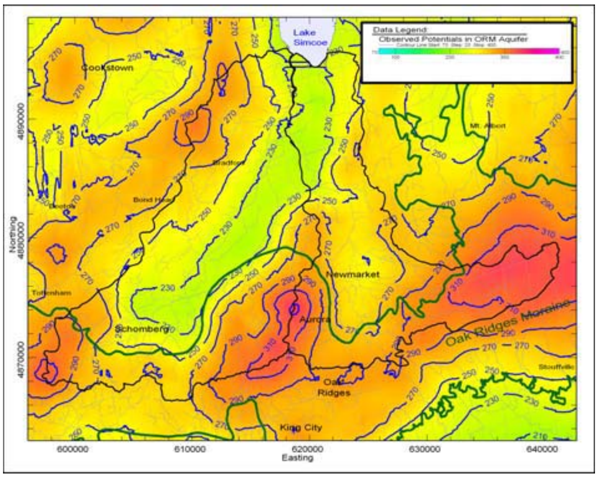

Figure 7: Observed potentiometric/water table surface for the Upper aquifer.

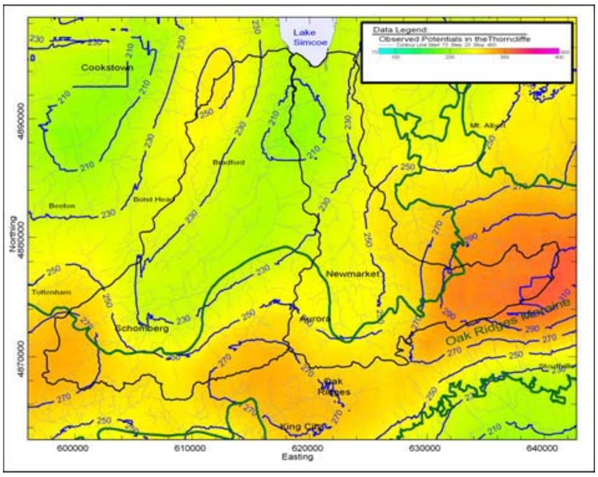

Figure 8: Observed potentiometric surface for the Middle aquifer within the Thorncliffe Formation.

4.3. Numerical Groundwater Flow Model

A steady state groundwater flow model was developed for the Core area (Figure 1) using the U.S. Geological Survey MODFLOW code. The model is described in detail in Earthfx *et al*., (2004); only a brief summary is provided here. The numerical model consists of eight layers, discretized horizontally using square cells 100 m on a side.

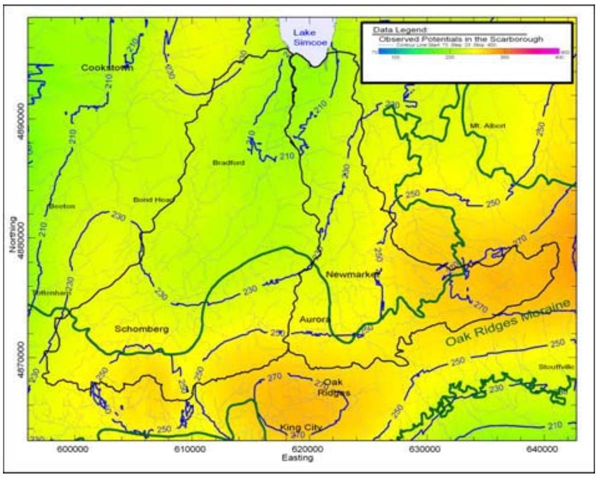

Figure 9: Observed potentiometric surface for the Lower aquifer within the Scarborough Formation.

Lake Simcoe and Lake Ontario were treated as constant head boundaries with elevations set at 219 mASL and 75.2 m mASL, respectively. No-flow boundaries were applied along the western side of the Core Model at the western edges of Mimico Creek, Humber River and Holland River watersheds. No-flow boundaries were also applied along the eastern side of the Core Model at the eastern edges of Duffins Creek, Carruthers Creek and Uxbridge/Pefferlaw Brook watersheds. The unweathered bedrock was assumed to be relatively impermeable and also formed a no-flow boundary.

Strahler classified stream segments were incorporated into the model to quantify the stream discharge. Upper reaches of streams were modelled as MODFLOW "drains" which allow discharge from the aquifer to the streams when the water-table rises above the streambed bottom elevation. The lower reaches of the streams are modelled as MODFLOW "rivers" which allow discharge to or from the stream to the aquifer depending on the difference between stream stage and aquifer head. A high resolution (10 m), hydrologically corrected, digital elevation model (DEM) was used to assign stream stage elevations to minimize model error in the deeply incised river valleys that occur within the Core model area.

Uniform values were assigned for the hydraulic conductivity of the aquitards based on available field data and results of previous modelling studies. Hydraulic conductivity for the aquifer units varied locally based on estimated values from aquifer performance tests, specific capacity data, and from lithologic descriptions. Initial estimates were adjusted during model calibration.

Groundwater recharge was estimated from land use, climate, and surficial geology mapping (Sharpe *et al.*, 1997). Values used in the calibrated model are summarized in Table 2 and shown on Figure 10. As would be expected, the highest recharge rates occur over the Oak Ridges Moraine area. High rates also occur on areas mapped as Halton Till with hummocky topography. Recharge rates over the till plains to the north and south of the ORM are generally less than half of the rates on the moraine.

Table 2: Annual average recharge values used in the calibrated Core Model.

Surficial Material	Recharge (mm/yr)
Glacial lake sands	180
Glacial lake silts and clays	90
Other recent deposits	160
Halton Till – hummocky topography	360
Halton Till – North of ORM	120
Halton Till – South of ORM	90
ORM deposits – hummocky topography	420
ORM deposits – non-hummocky	320
Newmarket Till	30
Lower Deposits/Weathered bedrock	30
Urban Areas – recharge value factor	0.6

Groundwater is extracted from the aquifers in the study area for municipal water supply, agricultural use, industrial use, golf course irrigation, and private (domestic) supply. Municipal wells within the Holland River watershed are shown on Figure 11. Actual water takings for the municipal wells were used in calibration runs; maximum permitted water takings were used in the water budget analyses. Withdrawal rates for other sources were obtained from water use studies commissioned by York Region.

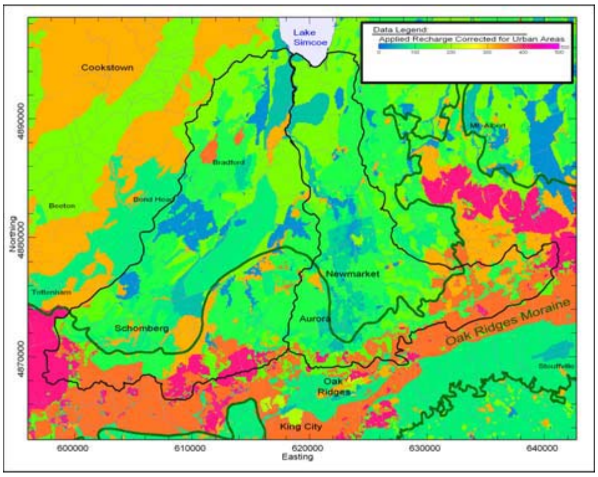

Figure 10: Estimated groundwater recharge.

Calibration targets for the model included: 1) static water levels; 2) estimates of groundwater discharge to streams from historical hydrographs; and (3) spatial patterns of groundwater discharge from low flow streamflow surveys. The Holland River watershed contains two active gauging stations – the Schomberg River near Schomberg (02EC010) and the Holland River at Holland Landing (02EC009; Figure 2). Calibration statistics and results of sensitivity analyses are described in Earthfx *et al*. (2004).

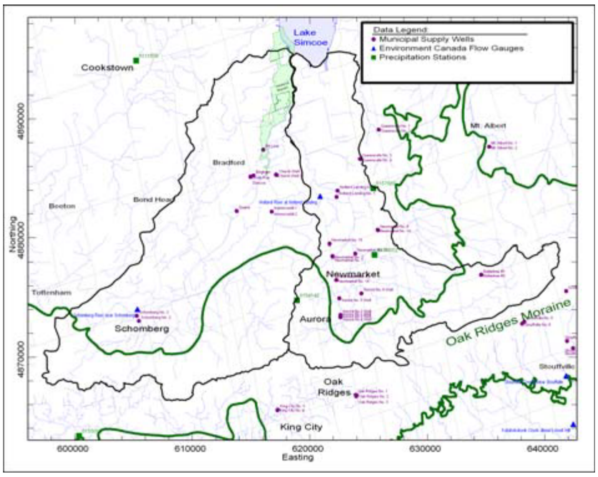

Figure 11: Municipal well, stream gauge, and precipitation station locations.

5. WATER BUDGET

Preliminary water budget estimates for the Holland River watershed were made from local climate and streamflow daily records, as described below. These provided an independent check on model results described in a following section.

5.1. Streamflow water budget

The watershed occurs within the Simcoe and Kawartha Lakes Climatic Region. Figure 2 shows the eight active Environment Canada climate stations situated near or within the Holland River watershed..

Table 3: Climate stations and annual average precipitation rates.

Station Name	Station ID	Precipitation (mm/yr)
Sharon	6157685	814
King Smoke Tree	6154142	826
Newmarket 3	615N002	804
Cookstown	6111859	825
Alliston Nelson	6110218	837
Albion Field Centre	6150103	785
Albion	6150100	799
Bolton North	615S004	841

All stations, except Bolton North and Newmarket 3, have a period of record greater than 20 years. The total annual precipitation for these six stations ranges from 785 to 837 mm/year (Table 3). Mean annual potential evapo-transpiration for the Simcoe and Kawartha Lakes Climatic Region is approximately 585 mm/year and the mean annual actual evapotranspiration is approximately 535 mm/year. It is estimated that the mean annual water surplus available for recharge and runoff is approximately 280 mm/year (Brown *et al*., 1980).
Total streamflow measured at the two active gauging stations is equivalent to about 200 mm/year over the drainage area; the estimated groundwater component of discharge amounts to approximately 100 mm/year over the drainage area. It should be noted that a large part of the Holland River watershed is not gauged. Groundwater discharge to the lower reaches, which may come primarily from the deeper aquifers, is not accounted for in the field measurements.

Figure 12 shows a cumulative discharge plot for the Holland River gauge at Holland Landing. Deviations from a straight line on the plot suggest the possibility of anthropogenic or other impacts affecting flow. Also shown is the total municipal groundwater pumping in the study area as measured by York Region. The trends of total streamflow and estimated groundwater discharge exhibit a slight change in slope prior to and following 1981 to 1982. This period corresponds to a general increase in municipal groundwater pumping, particularly from the Newmarket municipal wells but also corresponds to a change in the quantities of treated effluent being discharged to the East Holland River. Further study will establish whether municipal groundwater pumping is the primary factor affecting streamflow.

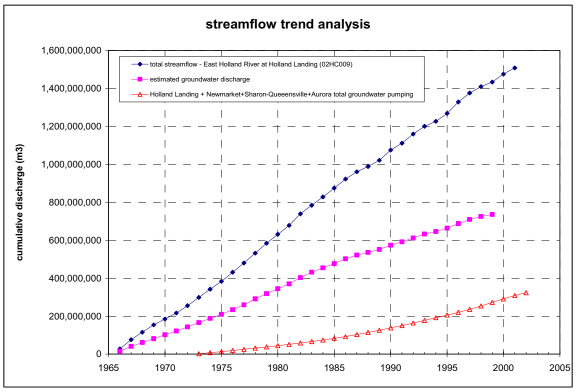

Figure 12: Cumulative mass curves for streamflow, estimated groundwater component of streamflow, and municipal groundwater pumping.

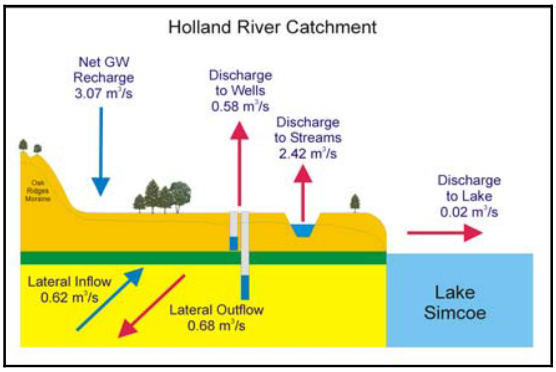

Figure 13: MODFLOW calculated mass balance estimate for the Holland River watershed.

5.2. MODFLOW Water Budget

Output from the calibrated numerical groundwater flow model was analyzed to determine a groundwater mass balance for the East and West Holland River catchments. The model simulated groundwater discharge to streams but did not account for runoff and streamflow processes.

Model results indicate that the groundwater divides for many of the larger stream catchments generally follow surface water divides. Locally, lateral flow occurs at different rates and directions along these boundaries. The mass balance summaries show both lateral inflow and lateral outflow rates, rather than just net lateral flow.

Figure 13 presents an overall water balance for the Holland River catchment. While simplified, this figure points out several features of the study area including 1) net flow across the lateral boundaries of the Holland River catchment was negligible 2) discharge to Lake Simcoe is also a small component of the overall flow; municipal and other large-scale pumping account for less than 20% of the available recharge (and associated discharge). The numbers do not sum to exactly zero because of the small mass balance model error.

More detailed breakdowns of model mass balances for the West Holland and East Holland River catchments are shown in Figure 14 and Figure 15, respectively. Some additional explanation is provided below.

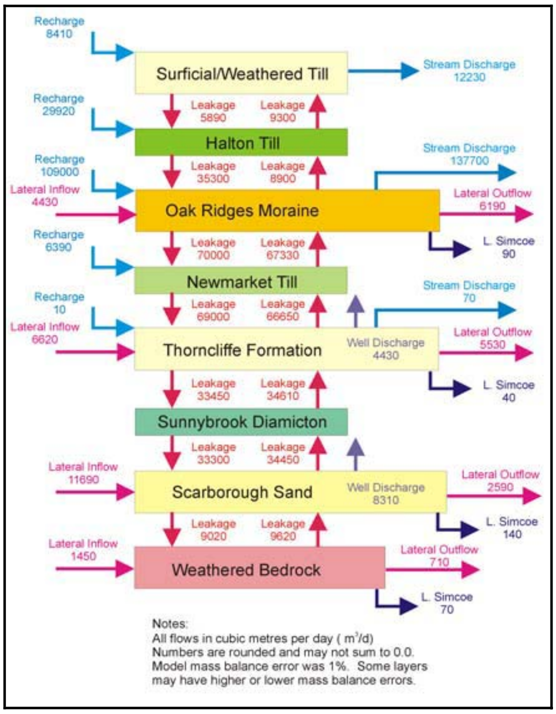

Figure 14: MODFLOW calculated mass balance estimates for the West Holland River catchment.

The model is a steady-state model and uses estimates of annual average net recharge as input to the model. The distribution of applied recharge was shown previously in Figure 10. The recharge is initially applied to Layer 1. If this layer is absent or if the model cells go dry in that layer during the simulation (i.e. the simulated water-table drops below the base of the layer), the recharge is passed on to the next layer down. The allocation of recharge to the different layers shown in Figure 14 and 15 was determined from the final distribution of recharge in the calibrated model.

Discharge to streams is the summation of discharge to MODFLOW river and drain segments. The model indicated that groundwater discharge was evenly distributed between the drain and river segments. Recharge from the river to the aquifer was less than 1% of the total simulated stream/aquifer water exchange.

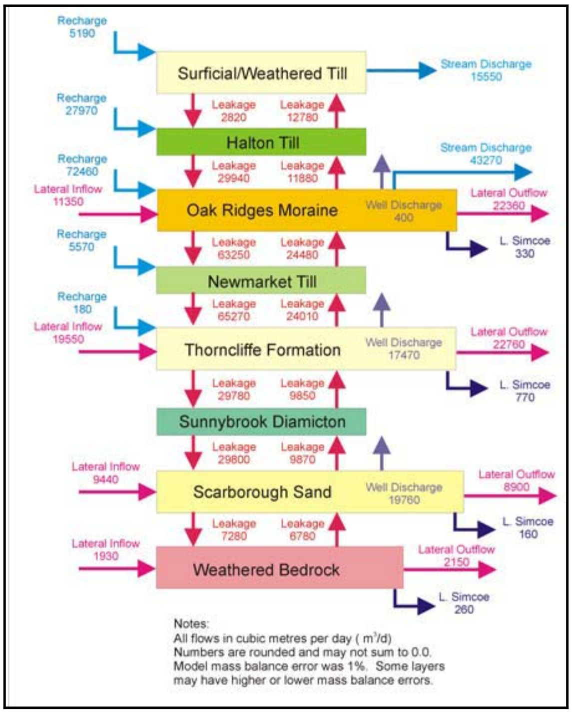

Figure 15: MODFLOW calculated mass balance estimates for the East Holland River catchment.

Leakage occurs between aquifer layers at rates dependent on the hydraulic gradient, aquitard hydraulic conductivity, and thickness of the confining units. For example, high rates of downward leakage occur between the ORM aquifer and the Thorncliffe aquifer beneath the Oak Ridges Moraine, while high rates of upwards leakage occur in the vicinity of streams within the tunnel channel valleys where the Newmarket Till is thin or absent. Both upward and downward leakage rates (rather than just net leakage) have been shown in the mass balance summaries. Leakage out the bottom of one layer is equal to the leakage in the top of the next layer down.

The deeper aquifer system (Middle and Lower aquifers within the Thorncliffe and Scarborough Formations, respectively) is recharged by leakage through the

Newmarket Till and through the silt deposits that infill the tunnel channels. Downward leakage through the channel infill silt deposits is much greater than through the Newmarket Till. The quantity of leakage from the Upper aquifer system to the deeper aquifers varies spatially, as shown on Figure 16, and depends on the vertical hydraulic gradient and the hydraulic conductivity of the intervening aquitard (Newmarket Till and channel infill silt deposits).

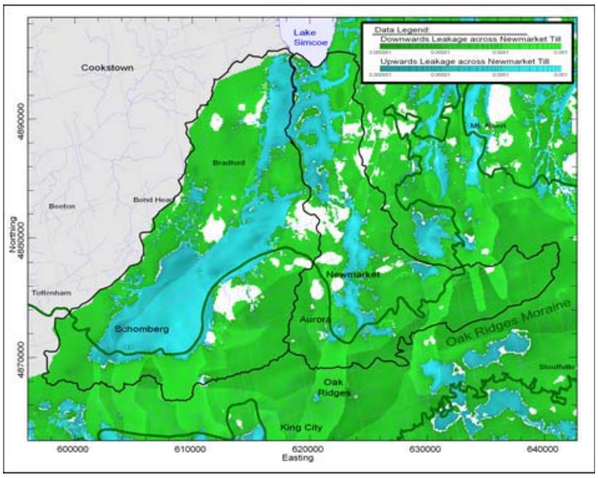

Figure 16: Leakage through the Newmarket Till and tunnel channel deposits to the deeper aquifers.

Overall mass balance error (water coming into the entire model area by recharge minus water leaving the model via discharge to streams, lakes and wells) is about 2%. The error can be somewhat larger within individual model layers. The error is due primarily to round-off errors that accumulate during the large number of calculations performed in the mass balance analysis and when large inflows are subtracted from large outflows. Refinement of the model is continuing to reduce mass balance errors.

6. CONCLUSIONS

Many water budget analyses simply quantify the average amount of water present within each reservoir of the hydrologic cycle (e.g. soil zone, groundwater system, and surface water bodies). The average volumes are obtained by differences in the water flux in and out of each reservoir. Water budgets being conducted as part of the YPDT Groundwater study seek to use water budget analyses as a part of a broader analysis framework being developed ultimately to provide an understanding of the entire flow system. A key component of the water budget is therefore the MODFLOW model itself rather than a simple quantification of coarse water budget numbers. YPDT derived water budgets estimate the amount of water present within each reservoir and also include an estimate of the spatial and temporal distribution of water movement within both the surface and subsurface reservoirs. It is only through a detailed understanding of how the flow system operates both spatially and temporally can effective management of the water resource be achieved.

7. REFERENCES

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