REGIONAL GROUNDWATER MODELLING OF THE OAK RIDGES MORAINE: AN INTEGRATED, DATA DRIVEN, GEOLOGY FOCUSSED APPROACH TO GROUNDWATER MODELLING

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ABSTRACT
The Oak Ridges Moraine (ORM) is a 160 km long ridge of sand, silt and gravel deposits oriented in an approximately east-west direction north of Lake Ontario. To better characterize the hydrogeological conditions of the ORM, a number of regional and local scale groundwater studies were initiated in 2001 to: a) compile and analyze the available geologic and hydrogeologic data and b) to create computer models of the groundwater and surface water flow system. The studies, which were directed by partnerships between municipal governments and Conservation Authorities, have developed an effective water management tool that is being used to assess the affects of land use change (including water allocations) on the groundwater flow system. The success of the project is attributed to four guiding principles: 1) a focus on data; 2) incorporation of geological interpretation, along with hard data, into the geological analyses; 3) a strong emphasis on understanding the link between the groundwater and surface water systems; and 4) an effective blending of a regional-scale approach with sufficient resolution and detail for local scale analyses.

RÉSUMÉ

1. BACKGROUND

The municipalities of York, Peel, Durham, and Toronto (YPDT) and the Conservation Authorities Moraine Coalition (CAMC), have together been leading coordinated regional-scale studies across a large portion of southern Ontario. The central focus of this partnership (Holysh *et al.*, 2003) has been the understanding and management of streams and aquifer systems originating on the Oak Ridges Moraine, a 160 km long ridge of sand and gravel deposits in southern Ontario (Figure 1). These studies have produced three significant products, including: 1) a comprehensive water-related database; 2) a detailed geological model (Kassenaar *et al*., 2003); and 3) a calibrated numerical groundwater model (Wexler *et al*. 2003). Each of these products are now being used for numerous practical applications, and continue to be refined to meet the growing needs of the partnership.

2. PURPOSE

The purpose of this paper is to present the key elements of the approach used for these large-scale interrelated studies. A strong emphasis on four key themes resulted in the principal findings and overall success of the project. This paper presents some of the challenges and insights associated with each of these themes. In addition, the issues and policies for maintaining and expanding the digital products are discussed.

The four key themes emphasized in these projects include: 1) a focus on data; 2) incorporation of geological interpretation, along with hard data, into the geological analyses; 3) a strong emphasis on understanding the link between the groundwater and surface water systems; and 4) an effective blending of a regional-scale approach with sufficient resolution and detail for local scale analyses.

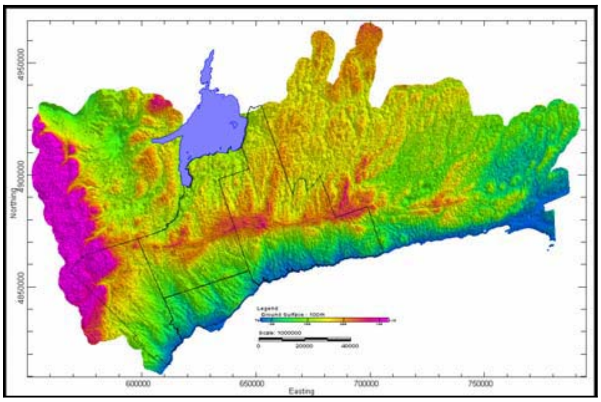

Figure 1: DEM of the Oak Ridges Moraine, Southern Ontario, Canada

3. COMPREHENSIVE WATER-RELATED DATABASE

In Ontario, as in many jurisdictions in North America, data, and in particular water and environmental data, have been neglected. Water-related studies are required for approval of land use change by government agencies at Provincial, Regional and local levels, and each of these studies tends to have a data acquisition component. Although data are constantly being collected in Southern Ontario (at a considerable cost), the information has never been assembled into a comprehensive, centralized database that can be used for future reference. Rather, data is collected by consultants, reported through various studies, and then simply lost in archived paper reports within the various agencies. In a similar fashion, individuals at many partner agencies have, as part of their on-going daily duties, collected water related data that now resides in files stored on one or two computers unknown and unavailable to others in the organization.

The YPDT groundwater study has put forward the idea that in this time of enormous computer power, sound data management is not only prudent, it is indeed a responsibility of public agencies. With this in mind, an early YPDT project set out to assemble a comprehensive digital database that would not only support groundwater flow model construction, but also form the foundation for long term groundwater management, including monitoring, model validation and refinement. A key element of the YPDT approach was to bridge agency boundaries and compile an integrated, comprehensive database covering geology, groundwater, surface water and climate related information. This broad scope recognizes that water management issues span a range of agencies and disciplines, and that a sound database is the foundation for credible decision making and effective long term resource management.

The goals of the database construction project included:

- Develop a comprehensive data model (database design or structure)
- Define a methodology for routinely incorporating data into the database;
- Provide ready access to data by all partner agencies;
- Ensure easy querying of data;
- Provide tabular, graphical, and mapping visualization tools

The data model (database design) was based on a refined version of the Earthfx Data Model. This groundwater database structure had over four years of development and refinement prior to selection for this project, however effort was made at the beginning of the project to optimize database structure and define clear data policies. Database design represents a balance between theoretical design, broad application, ease of use and practical performance. The chosen database design represented a significant technical advancement from commonly used, but outdated, structures. With time and training support, the advantages and layout of the new structure were accepted by the project team and related partner agencies (Figure 2).

3.1. Database Population

Once the structure of the data model was defined, the task of populating the database was initiated. Comprehensive databases such as the MOE's water well records were incorporated first. Following the initial growth with these established data sources, it became apparent that database population would continue to be a key long-term component of the database project. Not only was historical data in need of being captured, but considerable new information was coming forward.

For historical data, in order to assemble a comprehensive database, reports containing information needed to be accessible to the project team for long periods of time. The scanning and inventorying of reports became a key initiative. By having access to scanned electronic files of historical reports, the project team could systematically record and input data from the reports into the database. This process has been ongoing over the past three years with a focus having been put on key areas of interest. Capturing the data, as well as a reference to the source study (indexed, and spatially located digital report), will ensure that the database and the library are effectively linked.

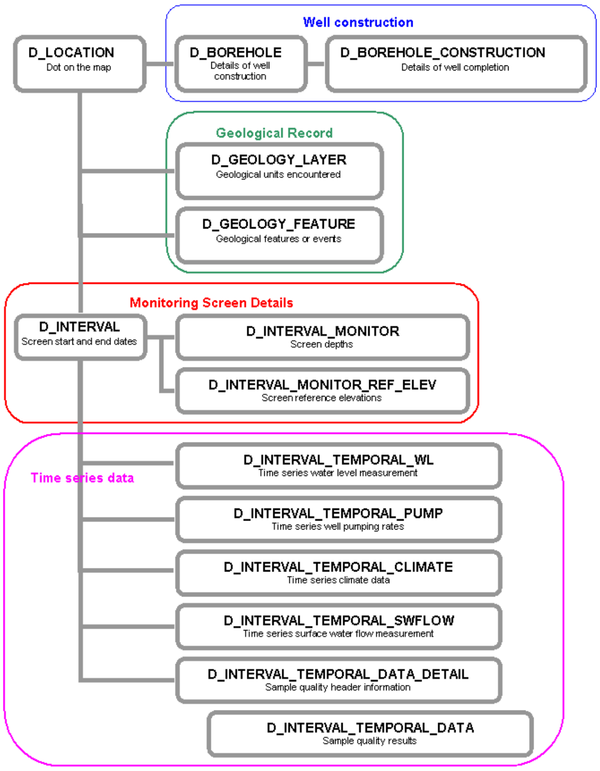

Figure 2: A portion of the data model

The database presently contains over 195,000 boreholes, including 45,000 geotechnical wells and the remainder primarily private water supply wells. Over 790,000 geologic descriptions and 4.3 million water levels and pumping rates have been compiled from these boreholes. In addition, data from over 1000 surface water monitoring stations (long term gauges and spot flow locations) and 520 climate stations are also included. Finally, over 1500 reports and over 2000 large format figures and maps were scanned and uploaded to the on-line report database and library. This central database is meeting the needs of a broad range of users, including field staff, data managers and numerical modellers.

Processes are being established with the partner agencies to accommodate and transfer to the database new information as it is acquired. For example, data logger files of water levels from monitoring wells are being added to the database on an ongoing basis. Data access, for a broad range of users, is available through an interactive map web server, the desktop application Sitefx, and, for experienced users, directly through the SQL database interface. Database synchronization between agencies has proven to be a critical aspect of the ongoing growth of the database

3.2. Evolution of the Data Model

A key aspect of this project is that the database has been fully integrated into a broad range of applications, from routine monitoring to advanced flow modelling. It is only through active use that data quality can improve and opportunities are found for further optimization of the data model. Through the geological and numerical groundwater modelling studies, the database has been intensely used, thus providing the opportunity to correct errors as well as to alter the structure of the data model.

Despite extensive upfront database design work, some changes to the data model have been required over the last three years. Data model changes have significant and broad implications, particularly for advanced users who have developed complex queries based on the established data structure. Novice users have been protected from data model changes, as the Sitefx application (for data entry and reporting) ensures database structure consistency, and enforces a broad range of database policy rules and checks.

One such example is the recent evolution of the data model to incorporate a location quality table. This table provides the opportunity to incorporate advanced quality coding on any aspect of data stored in the data model. In early versions of the data model, QA codes for various data were captured in a cursory way in various database tables. Two key fields, the coordinate and the elevation QA codes simply evolved from the MOE water well record database structure and were carried in the main location table within the database. With long term use of the database over the past three years it was recognized that there was a need to move to a new method of organizing data quality information. The recently developed data quality table addresses data quality with respect to a number of aspects of the database. In addition to developing a more rigid policy for addressing well elevations and location coordinates, this table now provides quality codes that tie to such database components as geology, static water levels, etc. Other quality control aspects of the database can also be captured into this table in the future.

4. GEOLOGICAL MODEL CONSTRUCTION

The second major theme of the YPDT groundwater studies has been an emphasis on detailed geologic mapping and modelling. Given a large database, the temptation is to automate the geologic interpretation process by performing a series of complex database queries. Unfortunately, the results of such queries produce color contour maps that exhibit circular peaks and depressions that likely bear little relation to the geologic processes that controlled the deposition of the sediments.

Early on, the project team recognized that detailed visual interpretation was essential for: i) building a conceptual understanding; ii) learning about and checking the data; iii) identifying subtle and complex lithologic patterns;, and iv) interpreting conditions between data points.

A key aspect of the interpretation process was a strong focus on understanding the geological processes and the depositional setting of the Quaternary deposits that make up the area. In addition to simply kriging hard geological data from well records to construct geological surfaces, an emphasis was placed on incorporating “expert knowledge” in the form of digitized interpretation lines into the kriging process. This ensured continuity of valley systems, and allowed for layer pinch-outs to be effectively represented (Kasenaar *et al*., 2003).

The selected approach was to automate everything but the geologic interpretation. Software tools that could graphically present large volumes of data directly from the database were used with an emphasis on dynamic (moveable) cross section interpretation. In addition, the interpretation process was streamlined so that layer picking and manual contouring could be performed very efficiently. Rapid presentation and efficient capture of interpretation allowed the study team to visually interpret and correlate a large number of wells. Over 88,000 geologic layer picks have been made to date.

This visual interpretation approach identified key conceptual insights, data gaps, biases and patterns in the database (Kassenaar *et al*., 2004). For example, it was recognized that the well database is a biased record of aquitard materials, as most private wells are terminated in the top of the aquifer zones. Aquifer mapping thus depends on inferring aquifer zones from well screen placement and sand and gravel materials encountered in the bottom of the hole. Visual interpretation also identified lithologic patterns that appear as key indicators of the main aquifer and aquitard layers.

The incorporation of expert intuition, through the use of constraint polylines, proved to be of considerable benefit in refining the geological surfaces. The project made extensive use of the 3D drawing and constrained gridding functions in the VIEWLOG software. These 3D lines constrain the gridding process, ensuring that the resulting geologic surfaces honour both the well picks, as well as the inferred position of bedrock valley systems and

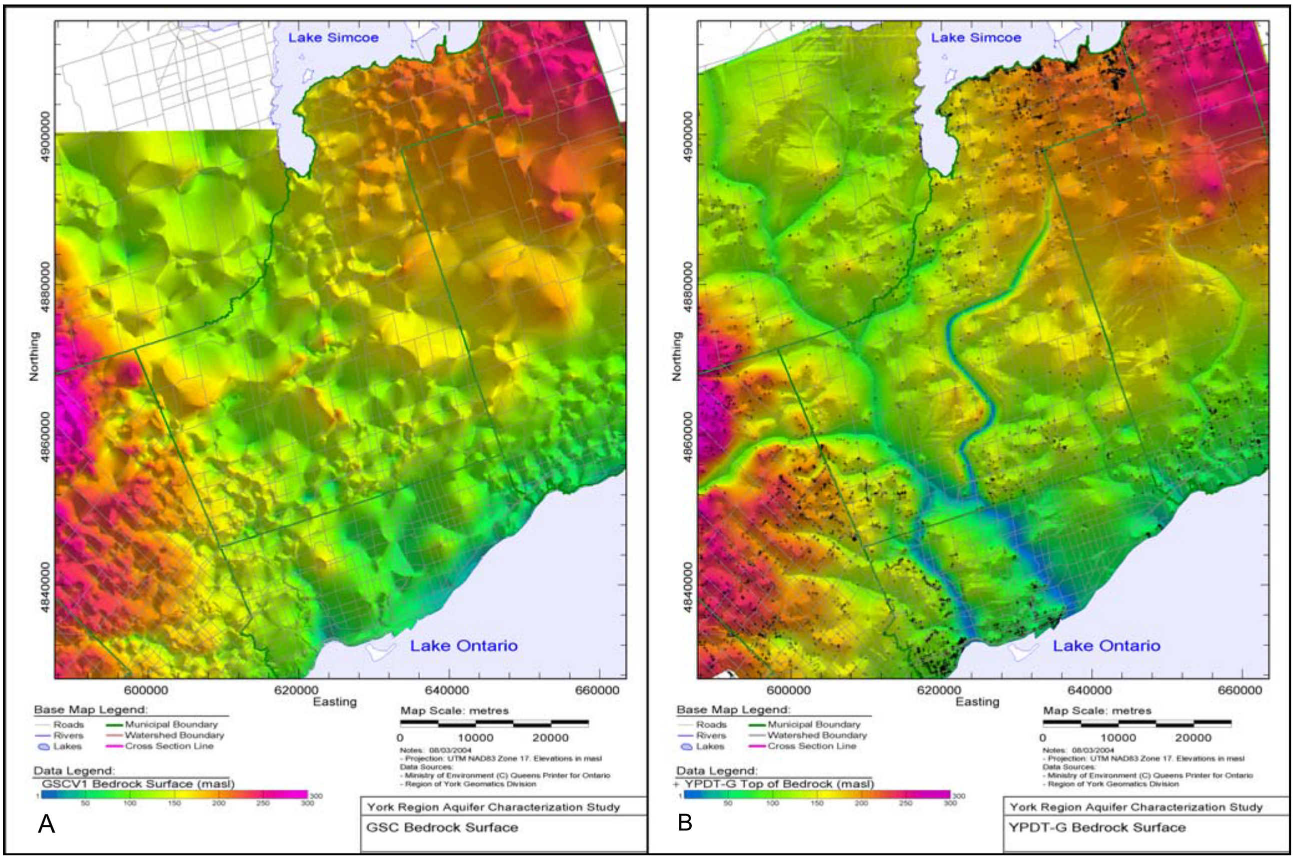

Figure 3: Comparison of unconstrained (left) and constrained (right) bedrock surface.

channels. Over 12,000 3D constraint polyline vertex points were used to constrain the surface gridding. Two examples that best demonstrate this approach lie in the development of bedrock valley systems, in particular the Laurentian River system, and in the development of the tunnel channel system within the overburden materials.

Figure 3a (left side) shows the bedrock surface constructed for an area extending north and west of the City of Toronto using only hard well picks. Figure 3b (right side), on the other hand, shows the same bedrock surface after a sub-aerial fluvial erosional system was interpreted to have acted upon the bedrock surface. Although Figure 3a strongly hints at a topographical low on the bedrock surface between Georgian Bay and Lake Ontario, it is only in Figure 3b that the full river system is interpreted. When incorporated into the numerical modeling exercise this fully developed Laurentian River bedrock system allowed for groundwater flow systems to develop in deeper aquifers that infill the bedrock low.

Figure 4 shows the location of the tunnel channel system north of and beneath the Oak Ridges Moraine in the York Region area. These channels have been delineated using a combination of the Geological Survey of Canada's tunnel channel interpretation (Russell *et al*. 2003), the ground surface as reflected in the DEM, and subsurface interpretation of the well records in the database.

5. NUMERICAL MODELLING AND STREAM/AQUIFER INTERACTION

The YPDT/CAMC group is a partnership of municipal governments and watershed conservation authorities. Traditionally the municipalities focused on groundwater supply investigations, while the conservation authorities focussed on surface water management. Regional groundwater assessments have rarely been undertaken in southern Ontario. The partnership recognizes the linkage between groundwater and surface water systems, and the importance of managing both resources in an integrated manner. The partnership approach has resulted in a modelling focus on stream/aquifer interaction.

Construction of a regional numerical groundwater model for the Oak Ridges Moraine, using the U.S. Geological Survey's MODFLOW code, was described by Wexler *et al*. (2003). That paper discussed aspects of the model such as the grid definition, model boundaries, model calibration, and preliminary model applications. The remainder of this paper builds on Wexler (2003), with a focus on the issues, benefits and importance of surface water/groundwater interaction processes in the YPDT model.

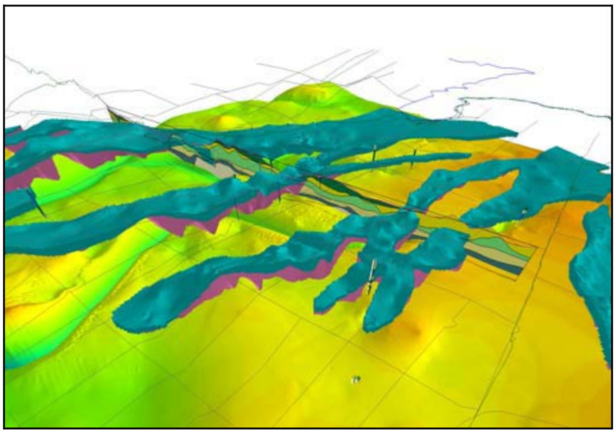

Figure 4: 3D view of tunnel channel deposits overlying bedrock surface (3D window size approximately 20 km).

Initial analysis of groundwater data showed that the streams in the ORM area exert a strong influence on water levels and flow directions. Accordingly, early in the modelling process it was recognized that considerable focus needed to be placed on developing a full representation of the linkage between the groundwater and surface water systems.

A number of factors were identified as critical to the simulation of groundwater/surface water interaction. Incorporating the numerous smaller stream reaches, including the headwater tributaries that emerge on the flanks of the moraine, rather than just the larger-order streams that discharge south into Lake Ontario and north into Lake Simcoe, required a considerable amount of time and effort. While narrow, these numerous small tributaries represent a significant “wetted area” of contact between the groundwater and surface water system. The Conservation Authorities, key partners in the project, have a mandate to understand and maintain aquatic freshwater ecosystems that thrive in the groundwater dependent headwater streams flowing out from the ORM. Because headwater streams only partly penetrate the water table, they tend to be extremely sensitive to small changes in the groundwater system, such as those caused by changes in land use. A water table decline, as a result of increased pumping or a decrease in recharge due to urban development, can shift the start-of-flow location in these streams by tens of metres, thus decreasing the habitat potential for many of the moraine’s freshwater organisms. With over 25,000 Strahler Class 1 stream reaches in the study area, it is clear that the cumulative impact on small streams can be significant.

Small, upper-reach tributaries were simulated as MODFLOW “drains”, only allowing for one way movement of groundwater from the ground into the drains, while larger tributaries were simulated as MODFLOW “rivers” and could lose water back to the aquifers (Figure 5). Stream-aquifer geometry was also considered a critical factor controlling GW/SW interaction. The controlling stream level, or stage, was estimated from a high resolution 10 m Digital Elevation Model that had been hydrologically corrected. A precise estimate of the stage was critical for streams that are contained within deeply incised valley systems. Over-estimating the stage elevation of the smaller streams would effectively disable the model drains, causing a significant underestimate of the groundwater discharge to streams. Over-estimating the stage of the larger rivers would cause the opposite problem, resulting in un-realistic river leakage to the groundwater system. The stage was set as the DEM elevation from the 10 m DEM plus a specified amount depending on the stream classification.

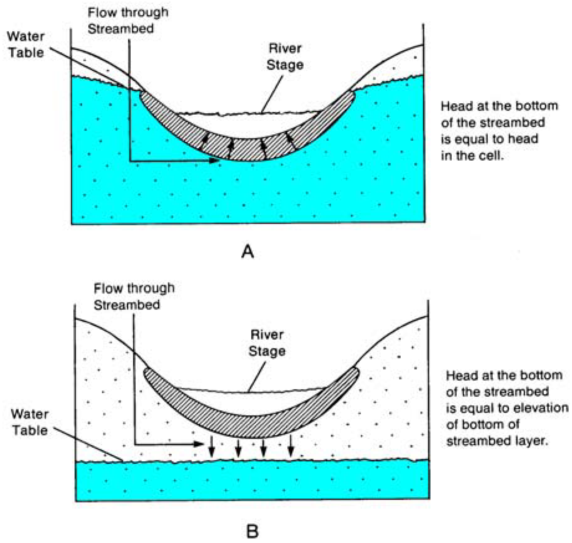

Figure 5: Stream-aquifer interaction processes. A = Discharge from ground to river. B = Recharge from river to ground

In addition to topographic influences, hundreds of cross sections were “cut” under the rivers to evaluate the stream-aquifer geometry. Stream conductance and interaction parameters were adjusted based on the insight provided by these cross sections.

A 100 m model cell size was selected so that each small tributary would be separated by several model cells. This allows local groundwater flow systems to develop between the streams and results in a significantly more realistic representation of the interaction between the groundwater and surface water system. Model resolution is further discussed in the following section.

To effectively calibrate the groundwater model, targets were set for the model to match both static groundwater levels and estimates of groundwater discharge from streamflow hydrographs for numerous streams that cross the model area. Several groundwater discharge (baseflow) separation techniques were applied to estimate the groundwater component of stream discharge on the gauged tributaries (Figure 6). The spatial distribution of groundwater discharge was calibrated to both the gauged

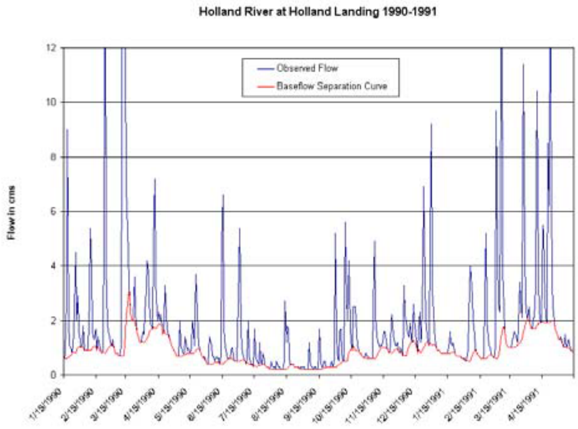

Figure 6: Baseflow separation estimates (red line) from total observer flow (blue line).

streams and additional spot low-flow measurements made by the GSC and the CA's.

Once calibrated, the model indicated that most groundwater discharges to streams rather than to the large lakes. Thus, an increase in groundwater withdrawals or decrease in recharge will result in an eventual decrease in baseflow (once local aquifer storage is depleted). Figure 7a shows the simulated discharge (color coded) to each of the 100 m cells along the headwater tributaries within a portion of the model area under baseline conditions. Simulated discharge to streams under different land use and pumping conditions were compared on a cell-by-cell basis to produce maps of per-cent change and absolute change in streamflow. Figure 7b shows the percent change in the flux to the streams after increasing pumping at a nearby municipal well. Only by incorporating all streams into the model and calibrating to observed baseflows is this level of stream impact evaluation possible. Conservation Authorities, armed with this information, can target specific tributaries or reaches of streams for further investigation, monitoring, and sensitivity analysis to assist in determining whether predicted changes are acceptable or not.

6. MODEL RESOLUTION AND SCALE

Early in the YPDT studies it was recognized that a wide range of issues were in need of assessment, ranging in scale from wellhead protection to regional watershed management. The final key theme of the YPDT studies is the effective blending of a regional-scale approach with sufficient resolution and detail for local scale analyses.

Traditionally, regional scale models have been created with simplified layer geometry and large, coarse resolution model cells. Local scale, detailed models were then created using techniques such as Telescopic Mesh Refinement (TMR), and additional site data. Early in the YPDT project it was also recognized that the resolution, or detail, of the subsurface borehole information rarely justified model cells smaller than 100 m in size. The 100 m cell size was also identified as sufficient to separate the numerous small tributaries that needed to be considered. A decision was made to model the entire core portion of the study area at a resolution of 100 m, and incorporate all available database information. Figure 7 shows the applicability of the regional mode to address a local scale issue. The area shown in Figure 7 represents less than 1% of the total model grid area. The results shown in Figure 7 demonstrate that the regional model can effectively address local scale issues.

In summary, the YPDT approach has produced a model that addresses both local and regional scale issues in a consistent and unified manner. With a uniform cell size of 100 m, the model has broad applicability throughout the YPDT area. The universal and comprehensive database also supports this approach, as all local scale data is included. This unique modelling approach negates the need for undertaking new more detailed or refined models for local scale projects. Commonly, government agencies have spent additional funding on "refining" previously built models to address specific issues. With the YPDT approach, unless new data or geological interpretations are brought forward, there is little benefit in refining the model. The approach allows for local scale analysis and understanding within a regional framework. Recent local scale applications have confirmed the usefulness of the model. These applications include:

- Delineation of wellhead protection areas;
- Assessment of dewatering impacts associated with large construction projects; and
- Water budget analysis on a watershed and subwatershed scale.

7. CONCLUSIONS

The YPDT project team set out with a goal of providing a more cost effective and integrated approach to understanding groundwater systems. In moving to this goal it became apparent that data, and in particular ready access to information, was a limiting factor restraining advancements in water resource management. Significant progress has been made to resolve this issue. Also apparent was the divergent focus of the two types of partner agencies, namely regional governments and conservation authorities. Although the root need of both agencies is a solid understanding of subsurface geological and hydrogeological conditions, regional governments continue to focus on municipal supply wells, whereas conservation authorities require information on the linkage between groundwater and surface water systems. This approach has brought all partnered organizations to a common point of understanding.

The complex hydrostratigraphy of the Oak Ridges Moraine and the surrounding area provides many challenges to the construction of a regional numerical groundwater flow model. The success of the YPDT projects in addressing this complex area is largely due to an emphasis on four key themes. The selected approach

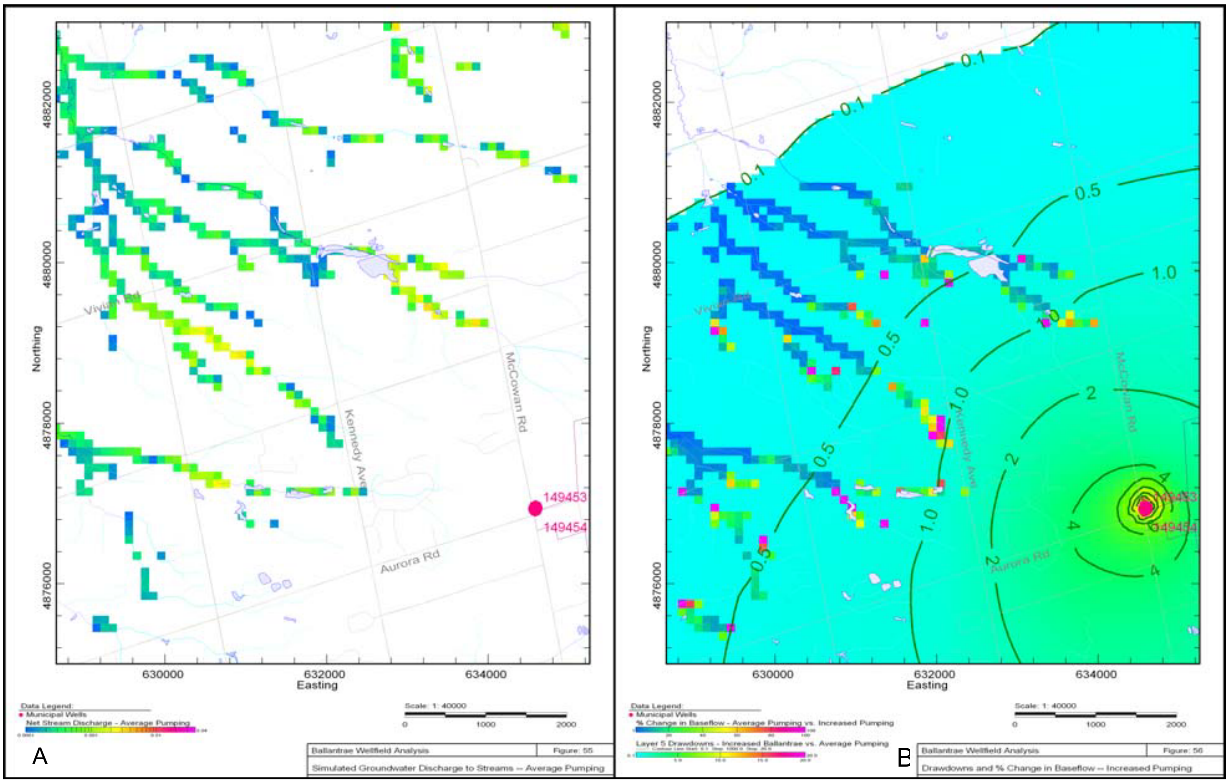

Figure 7: (A) Stream baseflow, (B) Percent change in baseflow due to pumping.

recognizes that modelling requires a solid database foundation, as well as detailed visualization and geologic analysis phases during which key conceptual insights can be obtained (Figure 8).

The approach takes groundwater modeling well beyond simply defining capture zones, emphasizing the role of groundwater modeling as an essential tool to be used in day to day land use management decisions. Each of the three products, the database, geologic model, and flow model, are recognized as key parts of the foundation for water management in the YPDT study area.

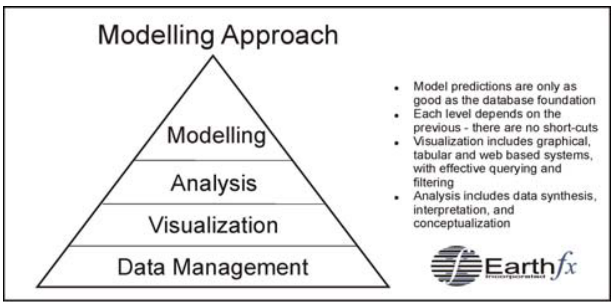

Figure 8: Predictive modelling requires a solid foundation of database compilation, visualization and geologic interpretation.

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